PATHS FORWARD

for Exploring Ocean Iron Fertilization

EXOIS
EXPLORING OCEAN IRON SOLUTIONS

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ACRONYMS

AV .... autonomous vehicle
BGC-Argo.... Biogeochemical-Argo
CDR .... carbon dioxide removal
mCDR........ marine carbon dioxide removal
ExOIS .... Exploring Ocean Iron Solutions
Fe:C........ iron to carbon ratio
GHG .... green house gas
Gt .... gigaton (one billion tonnes or one trillion kg)
HNLC........ high-nutrient low-chlorophyll
LNLC .... low-nutrient low-chlorophyll
MRV........ monitoring, reporting, verification
eMRV .... MRV for ecological and environmental impacts
OIF .... ocean iron fertilization
OIOs .... ocean iron observatories
OSSE........ Observing System Simulation Experiments
SERIES .... Subarctic Ecosystem Response to Iron Enrichment Study

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EXECUTIVE SUMMARY

We need a new way of talking about global warming. UN Secretary General António Guterres underscored this when he said the "era of global boiling" has arrived. Although we have made remarkable progress on a very complex problem over the past thirty years, we have a long way to go before we can keep the global temperature increase to below 2ºC relative to the pre-industrial times. Climate models suggest that this next decade is critical if we are to avert the worst consequences of climate change. The world must continue to reduce greenhouse gas emissions, and find ways to adapt and build resilience among vulnerable communities. At the same time, we need to find new ways to remove carbon dioxide from the atmosphere in order to chart a "net negative" emissions pathway. Given their large capacity for carbon storage, the oceans must be included in consideration of our multiple carbon dioxide removal (CDR) options (1).

This report focused on ocean iron fertilization (OIF) for marine CDR. This is by no means a new scientific endeavor. Several members of ExOIS (Exploring Ocean Iron Solutions) have been studying this issue for decades, but the emergence of runaway climate impacts has motivated this group to consider a responsible path forward for marine CDR. That path needs to ensure that future choices are based upon the best science and social considerations required to reduce human suffering and counter economic and ecological losses, while limiting and even reversing the negative impacts that climate change is already having on the ocean and the rest of the planet.

Prior studies have confirmed that the addition of small amounts of iron in some parts of the ocean is effective at stimulating phytoplankton growth. Through enhanced photosynthesis, carbon dioxide can not only be removed from the atmosphere but a fraction can also be transferred to durable storage in the deep sea. However, prior studies were not designed to quantify how effective this storage can be, or how wise OIF might be as a marine CDR approach.

ExOIS is a consortium that was created in 2022 to consider what OIF studies are needed to answer critical questions about the potential efficiency and ecological impacts of marine CDR (http://oceaniron.org). Owing to concerns surrounding the ethics of marine CDR, ExOIS is organized around a responsible code of conduct that prioritizes activities for the collective benefit of our planet with an emphasis on open and transparent studies that include public engagement (2; see inset pg. 3).

Our goal is to establish open-source conventions for implementing OIF for marine CDR that can be assessed with appropriate monitoring, reporting, and verification (MRV) protocols, going beyond just carbon accounting, to assess ecological and other non-carbon environmental effects (eMRV). As urgent as this is, it will still take 5 to 10 years of intensive work and considerable resources to accomplish this goal.

We present here a "Paths Forward" report that stems from a week-long workshop held at the Moss Landing Marine Laboratories in May 2023 that was attended by international experts spanning atmospheric, oceanographic, and social sciences as well as legal specialists (see inside back cover). At the workshop, we reviewed prior OIF studies, distilled the lessons learned, and proposed several paths forward over the next decade to lay the foundation for evaluating OIF for marine CDR. Our discussion very quickly resulted in a recommendation for the need to establish multiple "**Ocean Iron Observatories**" where, through observations and modeling, we would be able to assess with a high degree of certainty both the durable removal of atmospheric carbon dioxide—which we term the "**centennial tonne**"—and the ecological response of the ocean.

In a five-year phase I period, we prioritize five major research activities:

1. **Next generation field studies**
   Studies of long-term (durable) carbon storage will need to be longer (year or more) and larger (>10,000 km^2) than past experiments, organized around existing tools and models, but with greater reliance on autonomous platforms. While prior studies suggested that ocean systems return to ambient conditions once iron infusion is stopped, this needs to be verified. We suggest that these next field experiments take place in the NE Pacific to assess the processes controlling carbon removal efficiencies, as well as the intended and unintended ecological and geochemical consequences.
2. **Regional, global and field study modeling**
   Incorporation of new observations and model intercomparisons are essential to accurately represent how iron cycling processes regulate OIF effects on marine ecosystems and carbon sequestration, to support experimental planning for large-scale MRV, and to guide decision making on marine CDR choices.
3. **New forms of iron and delivery mechanisms**
   Rigorous testing and comparison of new forms of iron and their potential delivery mechanisms is needed to optimize phytoplankton growth while minimizing the financial and carbon costs of OIF. Efficiency gains are expected to generate responses closer to those of natural OIF events.
4. **Monitoring, reporting, and verification**
   Advances in observational technologies and platforms are needed to support the development, validation, and maintenance of models required for MRV of large-scale OIF deployment. In addition to tracking carbon storage and efficiency, prioritizing eMRV will be key to developing regulated carbon markets.
5. **Governance and stakeholder engagement**
   Attention to social dimensions, governance, and stakeholder perceptions will be essential from the start, with particular emphasis on expanding the diversity of groups engaged in marine CDR across the globe. This feedback will be a critical component underlying future decisions about whether to proceed, or not, with OIF for marine CDR.

Paramount in the plan is the need to move carefully. Our goal is to conduct these five activities in parallel to inform decisions steering the establishment of ocean iron observatories at multiple locations in phase II. When completed, this decadal plan will provide a rich knowledge base to guide decisions about if, when, where, and under what conditions OIF might be responsibly implemented for marine CDR.

The consensus of our workshop and this report is that now is the time for actionable studies to begin. Quite simply, we suggest that some form of marine CDR will be essential to slow down and reverse the most severe consequences of our disrupted climate. OIF has the potential to be one of these climate mitigation strategies. We have the opportunity and obligation to invest in the knowledge necessary to ensure that we can make scientifically and ethically sound decisions for the future of our planet.

GUIDING PRINCIPLES

For ocean carbon dioxide removal studies

1. Prioritize collective benefit for humans and the environment
2. Establish clear lines of responsibility to oversee studies
3. Commit to open and cooperative research, including risk assessments
4. Perform evaluation and assessment in an iterative and independent manner
5. Engage the public in consideration of climate intervention options

1 INTRODUCTION

Disruptions to our climate system driven by carbon dioxide and other greenhouse gases (GHGs) are causing great harm to our planet and increasing human suffering. There is broad agreement that we need both immediate emissions reductions in GHGs and deployment of carbon dioxide removal (CDR) to reverse this trend. Given the ocean's large capacity for carbon storage—more than 50 times larger than the atmosphere and 15-20 times larger than all land-based plants and soils—enhancing the ocean's natural ability to store carbon dioxide (CO_2) needs to be considered.

There are many different approaches to marine CDR (mCDR), of which ocean iron fertilization (OIF) has the longest history of study and field testing (1). Such studies have confirmed that the addition of small amounts of iron is particularly effective at stimulating phytoplankton growth in many parts of the ocean. As a consequence, CO_2 can be more effectively removed from the atmosphere and some fraction of the carbon can be transferred to durable storage in the deep sea, thus speeding up the natural biological carbon pump and potentially mitigating the impact of climate change. However, these earlier studies were not designed to adequately quantify how effective, durable, or wise, OIF might be as an mCDR approach.

ExOIS is an umbrella grtoup that originated in 2022 to share ideas regarding OIF studies that are needed to constrain mCDR efficiencies and ecological impacts (https://oceaniron.org/). Furthermore, ExOIS is organized around a responsible and ethical code of conduct that prioritizes activities for the collective benefit of our planet with an emphasis on open and transparent studies that include public engagement (2; see insert page 3).

As outlined in the ExOIS white paper (https://oceaniron.org/our-plan/), the overall goal of ExOIS is to conduct research to evaluate if OIF is an efficient and responsible approach to reducing atmospheric CO_2. The metrics for success would be to achieve net increases in durable (>100 years) carbon storage in the deep sea that can reach Gt CO_2 per year levels at a cost of less than $100 per tonne of CO_2 sequestered. These metrics need to be weighed against the intended and unintended ecological consequences, and against the consequences of taking no, or different, climate intervention actions. To reach this goal, there are scientific as well as social and governance issues to consider.

We are concerned that commercialization of CDR is moving ahead faster than the science needed to assess efficiencies and ecological impacts. **Ultimately, ExOIS is seeking to establish open-source conventions for implementing OIF for mCDR that can be assessed with appropriate monitoring, reporting, and verification (MRV) protocols, going beyond just carbon accounting to assess ecological and other non-carbon environmental effects (eMRV).** This will take 5-10 years and considerable funding. ExOIS is not a commercial company nor a start up, so we are not seeking venture capital by selling shares in a new company. ExOIS will not be raising funds based upon sale of carbon credits for financial gain, as we are assessing OIF, not marketing a product.

We need both immediate emissions reductions in GHGs and deployment of carbon dioxide removal

The overall goal of ExOIS is to conduct research to evaluate if OIF is an efficient and responsible approach to reducing atmospheric CO_2

The ideas in this report came out of a one-week workshop held at the Moss Landing Marine Laboratories in May 2023, and attended by about 30 top experts (see appendix 1). We summarize prior OIF studies and outline a path forward towards implementing multiple "Ocean Iron Observatories" (OIOs) where, through observations and models, we can assess with a high degree of certainty the durable removal of atmospheric CO_2—which we term the "centennial tonne"—and the ecological response of the ocean. **A centennial tonne is defined as 1000 kg of carbon isolated from atmospheric ventilation for at least 100 years** (see Section 3.2.4 and Figure 4.1).

The report emphasizes the five major research activities needed in Phase I to reach this Ocean Iron Observatories vision, and the five-year timeline and costs to reach these goals. These activities include: 1) field studies in the NE Pacific; 2) regional, global and field study modeling; 3) testing various forms of iron and delivery; 4) advancing MRV and eMRV; and 5) advancing social science and governance issues. Following the discussion of these five activities, a flexible management plan and program office structure is also presented for managing and obtaining the resources required to accomplish these goals, while representing the collective ideas and efforts of ExOIS to the larger mCDR communities as well as public, policy, and commercial interests.

We end this report with a discussion of a second five-year Phase II that would include larger and longer assessments of OIF using an Ocean Iron Observatories (OIO) framework (see Section 4. Modeling) designed to target additional sites using optimized forms of iron delivery, and improved models and advances in MRV and eMRV. Both phases are needed to develop the knowledge to guide decisions about if, when, where, and under what conditions OIF might be responsibly implemented for mCDR.

In summary, the science, engineering, and modeling activities laid out in this report can inform on the effectiveness of OIF, how it feedbacks on climate, and the costs at larger scales; but these are not the only criteria for moving ahead. Attention to social dimensions, governance considerations, and public perceptions of OIF are needed from the beginning, including expanding the diversity of groups engaged in mCDR across the Global North and South. The consensus of this workshop and this report is that we have the opportunity and obligation to invest in the knowledge necessary to ensure that we can make scientifically and ethically sound decisions for the future of our planet.

2 SITE COMPARISONS

It is well established that iron is the primary limiting nutrient of phytoplankton growth in 30-40% of the world's oceans, including high-nutrient, low-chlorophyll (HNLC) regions of the Equatorial Pacific, Southern Ocean, and Subarctic North Pacific (3, 4). Prior deliberate ocean iron fertilization (OIF) experiments (n=13) have been performed in HNLC regions and another in the North Atlantic Ocean, which is a low-nutrient, low-chlorophyll (LNLC) region. **These experiments have demonstrated that iron additions can stimulate phytoplankton growth**, providing the potential for net carbon removal (5, 6). To apply OIF as a mechanism for marine carbon dioxide removal (mCDR), iron additions should not only stimulate phytoplankton growth but would need to lead to net increases in the durable removal and sequestration of carbon at depth, with known and acceptable ecological and biogeochemical consequences.

It is important to note that **prior experiments were not designed to understand whether OIF is an effective and durable mCDR technique suitable to offset the effects of climate change.** To assess this potential, additional field trials are necessary to address the technological feasibility of OIF as an mCDR strategy, the durability of resulting carbon sequestration, ecological and non-carbon impacts, and the risk of 'unintended ecological' consequences, as well as to address social and political concerns (7). This short comparison of possible OIF sites comes out of a discussion involving scientists familiar with OIF, as well as experts from social sciences, governance, and policy fields who were part of a multidisciplinary ExOIS workshop held in May 2023. This section of the report is intended to summarize the current knowledge of each study site and potential challenges for implementing OIF as an mCDR method, with findings largely presented in two tables and references therein.

The efficacy and durability of OIF will depend largely on the baseline environmental conditions (physical and biogeochemical) of the targeted study areas. Feasibility assessments will also need to consider the site-specific logistics for large-scale ship-based experiments as well as the unique social and governance dimensions for each potential site. Figure 2.1 shows a conceptual framework of key considerations for OIF site selection to assess OIF as a potentially viable and effective mCDR method. We have outlined baseline conditions and feasibility across four ocean regions for OIF field study, including three major HNLC regions, but also a LNLC region—the subtropical Pacific where iron additions may potentially stimulate new production driven by the activity of nitrogen-fixing microbes (diazotrophs) (Tables 2.1 and 2.2). The subarctic North Pacific and Southern Ocean were further classified into west-east regions and north-south regions of the Antarctic Circumpolar Current, respectively, depending on longitudinal and latitudinal gradients in oceanic environmental conditions.

In Table 2.1, baseline conditions include physical, chemical, biological, and geological mechanisms that control the magnitude of carbon exported and its durability. Each region has its specific advantages and challenges. For example, both west and east regions of Subarctic Pacific have long-lived eddies, low eddy kinetic energy, and relatively high durability of carbon export (8), with excess macronutrients and diatom-dominated communities that may lead to rapid export when iron limitation is relieved. The Equatorial Pacific has similar advantages of low eddy kinetic energy, sufficient light, and good durability of carbon export, however this region is co-limited by iron and silicate and shows strong solubility-driven outgassing of CO_2. This outgassing means that a major portion of the carbon capture will be signaled as a decrease in outgassing, which has both advantages and disadvantages for carbon MRV.

The site-specific feasibility conditions, including prior OIF experimental results, potential side effects, monitoring and modeling capacities, engineering feasibility,

TABLE 2.1. BASELINE CONDITIONS

	PARAMETERS	SUBARCTIC PACIFIC		EQUATORIAL PACIFIC	SUBTROPICAL PACIFIC	SOUTHERN OCEAN	
		WEST	EAST			NORTH	SOUTH
Physics and chemistry	Circulation and mesoscale activity	intermediate waters can be formed; long lived eddies; high wind speeds	low EKE; eddies are long lived; surface currents are slow; high wind speeds	low wind speed; low EKE; ENSO	frequent mesoscale activity (≈30%)	upper limb of MOC; high EKE; strong shear-driven vertical mixing; ENSO & SAM	lower limb of MOC; lower EKE; ENSO & SAM
	Water column	shallow MLD (≈20-120 m); shallow permanent pycnocline	shallow MLD (≈10-100 m); shallow permanent pycnocline	shallow MLD (≈10-30 m); shallow permanent pycnocline	permanent stratification, shallow MLD (≈20-100 m), deep euphotic zone (≈125 m)	deep MLD (strong mixing; 100->400 m)	relatively shallow MLD (high density gradient; 20-150 m)
	Solar irradiance	limiting in winter; seasonal variation		light not generally limiting in upper euphotic zone	not limiting; seasonal variation	limiting in winter; seasonal variation	
	Surface T	cold (2-12°C)	cold (4-13°C)	warm (24-28°C)	warm (23-28°C)	cold (2-12°C)	very cold (-1.85-3°C)
	Air-sea gas flux	reasonable air-sea CO_2 disequilibrium time scales (couple months long)		seasonal CO_2 outgassing	well understood; little upwelling of CO_2	limited air-sea equilibrium: short surface residence times; possibility of high gas exchange with high wind	limited gas exchange due to sea ice
	Carbonate system	high seasonal DIC drawdown, OA evident	seasonal DIC drawdown	seasonal outgassing of DIC	OA evident; limited mixing into nutricline	relatively high revelle factor, aragonite undersaturated	high revelle factor, aragonite undersaturated
	O_2	relatively shallow O_2 minima	low O_2 subsurface	shallow and spreading OMZ	regionally variable mesopelagic suboxic water masses	hypoxia not evident	
	Limiting nutrients	high N and Si; high Si:N; Fe-limited	high N; high Si:N ratio; Fe-limited	Fe and Si	low macronutrients; N limiting for non-diazos, N_2 fixers limited by Fe, P, trace metals	Fe (co-limited by Si and Mn)	Fe
	Regional Fe source	aerosol depositon; continental shelf	volcanic inputs	undercurrent; upwelling; low aerosol deposition	hydrothermal, aerosol deposition	aerosol depsotion; islands downstream	ice sheet melting
Biology and geology	Biology and geology	phytoplankton biomass and diversity	seasonally variable chl *a*; Diatom-dominated	low chl *a*; Diatom-dominated	medium chl *a*; dominated by picoplankton	low chl *a* (< 0.15 mg m^{-3}); dominated by picocyanobacteria	low chl *a*; Diatom-dominated (*Phaeocystis* in some regions)
	PP	strongly seasonal; spring bloom	strongly seasonal; spring bloom	low to moderate; low seasonality	low; relatively weak seasonality (≈ 2x change)	high; highly seasonal; Nov. to Mar.	high; highly seasonal with ice edge retreat; Dec. to Feb.
	Grazers	seasonally variable copepods; high micro-zooplankton effect	seasonally-variable large copepods and salp blooms	mesozooplankton	microplankton dominant	copepods	large krill and salps
	C export	grazing roles for C-export is still largely unknown	grazing roles for C-export is still largely unknown; durable sequestration since once particles sink, degradation slows	f-ratio of 15-30; thorium estimates (5%), potential advective transport of surface DOC to subtropic	good understanding; based on traps, O_2/Ar, mass balance and tracers	shallow C export/ High ANCP (45-50°S; 4 to 6 mol C m^{-2} yr^{-1}); late export in bloom	high C export (at 100 m) during seasonal blooms; late export in bloom
	Durability of C export	durability is very good in the Subarctic Pacific, comparatively		uncertain	ca. 500 m for 30 years; less than 5 yrs >100-200 based on CFCs	uncertain	
	Dominant C export process	BGP dominant; DVM a factor; MLP less important on daily scales	BGP and DVM important; MLP less important on daily scales	MLP evident; shallow subduction; vertical migration of mesozooplankton; BCP (4-25%)	BGP dominant, lesser role of DVM	large MLP but relatively lower BCP	very large and efficient BCP (dominated by Krill fecal pellets)

Abbreviations: Fe: iron; **SST**: sea surface temperature; **MLD**: mixed layer depth; **BGP**: biological gravitational pump; **BCP**: Biological C pump; **DVM**: diel vertical migration; **MLP**: Mixed layer pump; **NP**: North Pacific; **EKE**: eddy kinetic energy; **P**: phosphate; **LC/LP**: London Convention, London Protocol; **CH4**: methane; **ETNP**: Eastern tropical North Pacific; **OA**: ocean acidification; **NPP**: Net primary production; **CFC**: chlorofluorocarbons; **OMZ**: oxygen minimum zone; **ANCP**: annual net community production

TABLE 2.2. FEASIBILITY CONSIDERATIONS

	PARAMETERS	SUBARCTIC PACIFIC		EQUATORIAL PACIFIC	SUBTROPICAL PACIFIC	SOUTHERN OCEAN	
		WEST	**EAST**			**NORTH**	**SOUTH**
OIF experimental results	Experiments	SEEDS-1 and SEEDS-2	SERIES	IronEx-1 and -2	no experiments conducted	EisenEx; EIFEX; SOFeX-N; SAGE; LOHAFEX	SOIREE; SOFeX-S
	Biological response	SEEDS-1 - massive diatoms; SEEDS-2 - Copepod increases drove down phytoplankton biomass	diatoms	pennate diatom dominated; low mesozoo grazing		diatom dominated blooms (exceptions of LOHAFEX and SAGE)	diatom dominated bloom; heavily silicified diatoms
	C export	SEEDS-1 - 13% of fixed C lost from surface	C and Si export observed in sediment trap at 125 m; C export observed by optics	shallow export		modest C export (smaller cells, more remineralization); EIFEX - deep C export (with diatom aggregates, krill fecal pellet export, less remineralization)	SOFeX-S - Increase in export (at 100 m)
Potential impacts from OIF	Fisheries, higher trophic levels	fisheries present	important habitat for salmon	fisheries; potential benthic impacts	fisheries present	migrating whales	effects on the large higher trophic level biomass
	HAB impacts	*Pseodonitzchia* blooms would be anticipated		DA production	low concern	community changes to *Pseodonitzchia*	
	Nutrient robbing	low concern, source water intermediate water	low concern	high concern	no issues	high concern (preformed nutrient subduction, 50+ yr)	source water for bottom water (1000 yr)
	Deoxygenation	potential alteration of OMZ	potential alteration of OMZ	potential alteration of OMZ	ETNP: increased productivity comes with a risk of deoxygenation	Source water of OMZ	Largest oxygen decrease in bottom and deep waters
	Other climate-relevent gases	no significant increase in DMS	increase in nanoplankton and DMS, decreasing DMS during diatom bloom	potential enhancement of denitrification (N_2O)	minor CH_4 production known	Increase in DMS but insignificant change in N_2O	Significant increase in N_2O and DMS
Monitoring & models	Long-term monitoring?	KNOT/K2 others; C-PROOF gliders	Line P / Station P; C-PROOF gliders; NOAA PMEL buoy	TPOS; BCG-Argo	Hawaii Ocean Time Series; several long term sites in the western subtropical pacific (Japanese/Korean stations - see IGMETS)	SOLOMON; SOCCOM	BCG-Argo
	Relevant models	regional models not yet capable of integrating experiments; insufficent ecological models; insufficent remote sensing data assimilation capabilities		well defined physical models (requiring biogeochemistry incorporation)	ROMS; DARWIN; satellite NPP and export	SOSE; Possibility for novel nested regional domains	

Abbreviations: SOLOMON: Southern Ocean Long-term Observation and MONitoring; **SOCCOM**: Southern Ocean Carbon and Climate Observations and Modeling project; **OIF**: ocean iron fertilization; **C**: carbon; **HAB**: harmful algal bloom; **OMZ**: oxygen minimum zone; **DMS**: dimethyl sulfide; **Si**: silica; **DA**: demoic acid; **N_2O**: nitrous oxide; **TPOS**: Tropical Pacific Observing System; **BCG**-Argo: biogeochemcial Argo; **ETNP**: Eastern Tropical North Pacific; **CH_4**: methane; **ROMS**: regional ocean modeling system; **DARWIN**: Darwin Project ; **NPP**: net primary production; **SOSE**: Southern Ocean state estimate; **KNOT**: Kyodo North Pacific Ocean Time-series; **C-PROOF**: Canadian-Pacific Robotic Ocean Observing Facility; **SEEDS**: Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study; **SERIES**: Subarctic Ecosystem Response to Iron Enrichment Study; **EIFEX**: European Iron Fertilization Experiment; **SoFeX-N**: Southern Ocean Iron Experiment - North; **SAGE**: SOLAS Air-Sea Gas Exchange; **LOHAFEX**: Indo-German Iron Fertilization Experiment; **SOIREE**: Southern Ocean Iron Release Experiment; **SOFeEx-S**: Southern Ocean Iron Experiment - South; **IGMETS**: International Group for Marine Ecological Time Series

TABLE 2.2. FEASIBILITY CONSIDERATIONS (CONTINUED)

	PARAMETERS	SUBARCTIC PACIFIC		EQUATORIAL PACIFIC	SUBTROPICAL PACIFIC	SOUTHERN OCEAN	
		WEST	EAST			NORTH	SOUTH
Engineering feasibility	Vicinity to ports	easy to access; stage out of Japan	easy to access; stage out of CA, Canada	easy to access; stage out of Lima	NPSG easy to access; stage out of Oahu or West Coast of U.S.	remote	remote; ice strengthened ships required
	Area considerations (monitoring)	inside of the Western subarctic gyre targeting mesoscale eddies is an option	Endeavor ridge provides possibility to support powered moorings; likely success for patch-mode	requiring a larger patch size; high advection rate; possibility of shorter patch duration (<2 month)	gyres are big, can be remote	requiring a larger patch size; high advection rate	requiring a larger patch size; high advection rate
	Deployment costs	moderate; tracking/sampling eddies would be ieal		high gear expense; larger sampling array; aerosol deposition of Fe with daily squalls (logistically difficult from an operations POV at scale)	detection limits for nitrate, other nutrients and biomass; small changes over large scales may be difficult to detect	high (challenge of navigating autonomous assets)	
	Unique challenges for MRV	estimates of zooplankton biomass and grazing	satellite info limited; estimates of zooplankton biomass and grazing	good satellite coverage	calm weather and good satellite coverage	satellite info limited with high cloud cover	
Social and Governance	Governance issues	LC/LP		LC/LP	LC/LP	LC/LP	LC/LP; ATS; CCAMLR
	Presence of Exclusive Economic Zone (EEZ) or Marine Protected Areas (MPA)	around the Kuril and Aleutian island are EEZs of Russia and US	reserves are related to seamounts	Ecuadorian EEZ (Galapagos)	national monuments in the North Pacific around the Hawaiian Island chains	Antarctic EEZ	
	Identified stakeholders	international except EEZ	consultation with coastal First Nations would be required and could be complicated due to prior Fe experiments (esp. Haida Nation)	island nations (local adjacent states); staging operations (Lima, Ecuador); negative perception for experimenting in the "Global South"	Pacific Islanders	island nations; CCAMLR and ATS (south of 60°S)	CCAMLR and ATS

Abbreviations: MRV: measurement, reporting, verification; **LC/LP**: London Convention/London Protocol; **Fe**: Iron; **POV**: point of view; **EEZ**: Exclusive economic zone; **NPSG**: North Pacific Subtropical Gyre; **CCAMLR**: Convention on the Conservation of Antarctic Marine Living Resources; **ATS**: Antarctic Treaty System

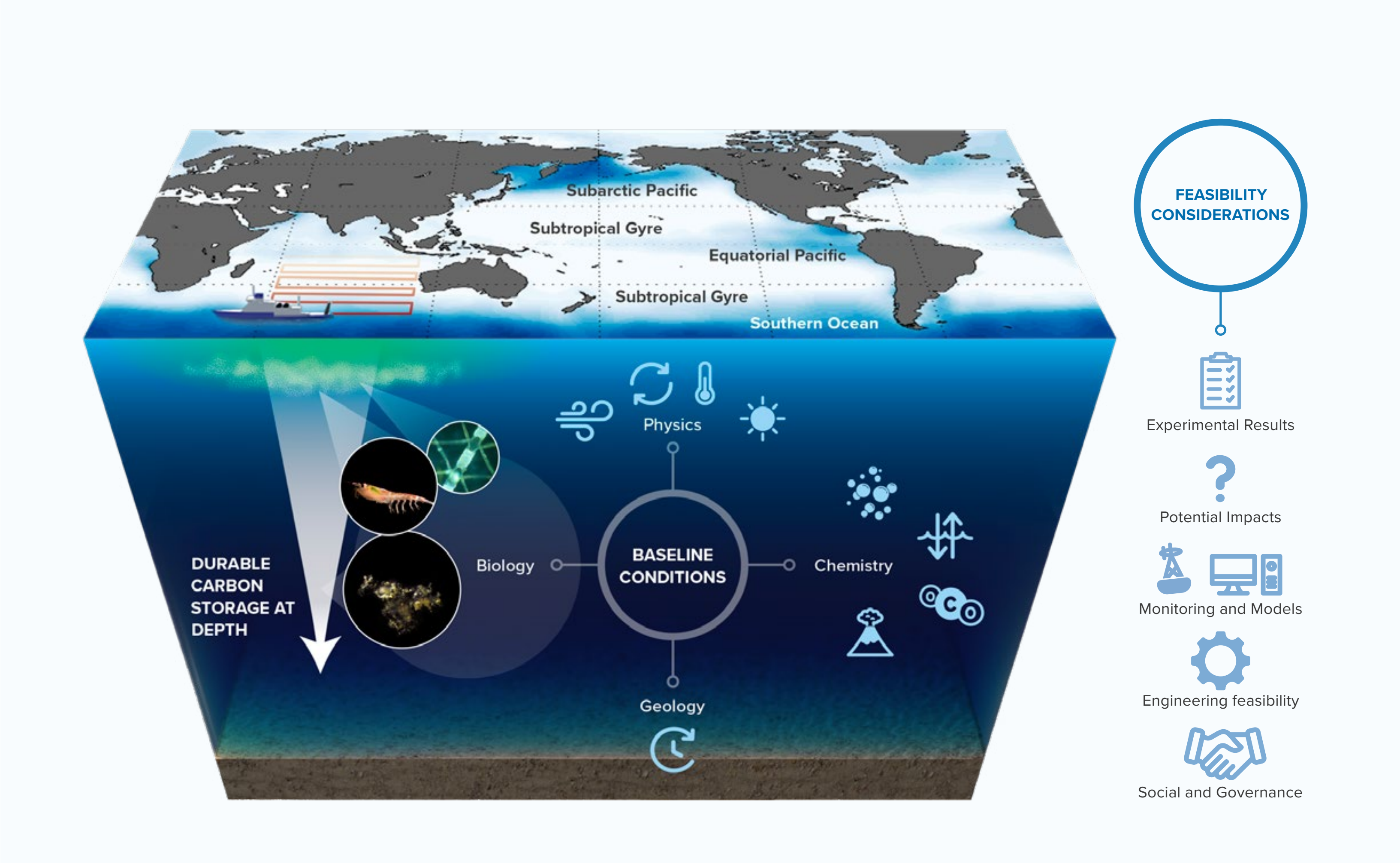

Figure 2.1. Conceptual diagram of considerations for OIF

and social and governance issues, are summarized in Table 2.2. For example, a number of field trials have already been conducted in the Southern Ocean, many of which recorded a significant increase in carbon export. Yet this region is remote, deployment of autonomous platforms and ships would be challenging with very high costs, and the issue of long-term enhanced nutrient consumption in waters that supply other ocean regions may pose more significant risks at downstream regions more so than for the other sites. In contrast, the Subarctic Pacific is more accessible, the possibility of downstream nutrient depletion is lower, and costs for autonomous tracking and sampling are deemed more moderate. Ultimately, the decision of where and when to conduct OIF trials will need to consider both baseline conditions at the time of implementation as well as the unique feasibility considerations for each site.

3 NEXT GENERATION OF FIELD STUDIES

3.1 Field studies needed to assess OIF for mCDR

Global ocean iron fertilization (OIF) studies demonstrate that iron addition enhances phytoplankton biomass and carbon sequestration in many regions of the world ocean (6), suggesting a potential for OIF as a marine carbon dioxide removal (mCDR) strategy. However, these previous studies do not address the complex scientific, technical, economic, governance, social, and moral concerns surrounding the implementation of OIF at scale for mCDR (7). Chief among the scientific uncertainties are issues of efficacy (how much carbon can be sequestered for how long in different locations—a question not addressed in previous work), and potential negative ecological consequences. One of the key outcomes from the Moss Landing Marine Laboratories workshop was the recognition of the urgent need to address these uncertainties by conducting well-designed field studies with a specific focus on generating necessary data to constrain these uncertainties. This foundational knowledge is necessary to assess whether or not OIF is a scientifically sound and socially acceptable strategy for mCDR. Thus, the central question here is not should it be done, but rather how effective would it be and at what environmental cost.

Insights surrounding the efficacy and potential ecological consequences of OIF have been generated by *in situ* experiments in high-nutrient, low-chlorophyll (HNLC) regions, all of which greatly enhanced phytoplankton growth (largely diatoms) but the limited time and space scales were too small to quantify carbon export (5, 6). Global ocean biogeochemistry and ecosystem models (e.g., 9) broadly suggest that OIF has the potential to sequester ≈0.5-1 Gt of carbon per year (1 tonne is equal to 1000 kg, thus 1 Gt is equal to 1 billion tonnes or 1 trillion kg), although the resultant nutrient redistribution ("nutrient robbing") could generate downstream ecological and economic consequences that need to be better accounted for (e.g., 10). However, these models are constrained by a fairly limited set of *in situ* observations that do not capture the true complexity of the ocean's biological carbon pump, which controls iron and carbon export in natural ecosystems (11), so both field and modeling assessments need improvement (see Section 4. Modeling). None of the prior *in situ* experiments were designed to rigorously study and quantify carbon sequestration or evaluate the ecological consequences of OIF, leaving critical knowledge gaps (5, 6). Among the greater unknowns are whether strategies for OIF can be "tuned" to alter the biogeochemical and ecological outcomes. This knowledge gap could be addressed with the following hypotheses using field studies:

- **Hypothesis 1** – Pulse inputs of iron are more likely to lead to direct algal aggregation and high carbon fluxes in contrast to continuous inputs (over some time) which lead to increased heterotrophic grazing responses and their associated impacts on carbon flux via increases in fecal flux and vertical migration.
- **Hypothesis 2** – The additional magnitude of carbon export and its efficiency will increase with longer and larger iron additions.

Neither of these simple but key hypotheses can be addressed with data from prior experiments, so the factors impacting the variability in the biological response to iron fertilization (bloom formation and export) remains poorly constrained. Addressing outstanding questions about the efficacy and ecological outcomes of OIF CDR will require new field and model studies. We do know from the 13 OIF experiments thus far that there have been no recorded or observed instances of major long-term, quantifiable ecological consequences, similar to the much larger natural events that deliver episodic pulses of iron to the ocean (e.g. volcanic eruptions, fires).

3.2 Key Areas of Effort

3.2.1 PRIMARY OBJECTIVES, CHALLENGES, AND OPPORTUNITIES

A primary scientific objective for the next generation of OIF field studies is to first robustly quantify the additionality of carbon removed (how much more carbon is removed by iron amendment) and the durability of this carbon sequestration (how long before this carbon returns to the atmosphere). The second primary objective is to assess the ecological and environmental response to OIF (eMRV) with a key focus on the major perceived risks (i.e. derisking). We will begin to address questions of variability (seasonal or other) in these responses through multiple experiments conducted at a single site. To meet these primary objectives, **experiments will be significantly larger (>10 times larger spatial scales and sampling areas) and longer in duration (one year instead of one month) than previous mesoscale iron enrichment studies.**

This next generation of ocean OIF trials must be designed, simulated, and sampled using existing, but currently imperfect, tools and models. To accommodate this ambitious experimental scale, we anticipate that the core set of measurements taken will need to be scaled down and more targeted than some previous experiments, meaning that obtaining full sets of rate and stock measurements with traditional oceanographic approaches likely will not be feasible (see Table 3.1). Fortunately, advances over the past decades in autonomous platforms, sensor technologies, ocean ecosystem modeling, and molecular-based methods mean that deeper insights at longer and larger scales will be possible relative to that of previous OIF experiments. With this in mind, along with lessons learned from previous OIF experiments, several design considerations for the next generation of field studies need to be considered.

3.2.2 FIELD STUDY DESIGN CONSIDERATIONS

Various site-agnostic aspects surrounding the design of the field studies that need consideration include the size (km^2) of the initial patch of iron-fertilized surface seawater, the form of iron delivered, the method of iron delivery (e.g., ship-based deployment vs. aerosol), the frequency and quantity of iron delivery, the anticipated rates of patch diffusion, tracking of the amended patch, and the size of the areas to be monitored. Several of these considerations were factored into the proposed initial field site in the NE Pacific as discussed below.

Iron Delivery – Prior experiments used ship-based deployment of iron (II) sulfate (5), with the inert tracer SF_6 added to facilitate tracking of the iron-amended patch. A disadvantage of using large additions of this form of iron is its rapid (temperature dependent) oxidation to insoluble iron (III) species and subsequent rapid precipitation and loss from the euphotic zone. This loss not only represents a "system" inefficiency but leads to vast overestimates of the iron quotas (Fe:C) required to stimulate a phytoplankton bloom (see 3.2.2.). The iron-to-carbon ratio (Fe:C) is a metric that describes how much carbon is exported per unit of iron added (12). Furthermore, using ships to deliver the iron limits the rate at which a patch can be fertilized, which places practical limitations on the patch size and uniformity. However, the key advantage of iron (II) sulfate here is the ample prior demonstration of its efficacy in stimulating blooms in multiple HNLC regions. The consistency of these responses would allow more focus on the primary scientific objectives (measuring carbon export and ecological/environmental responses), justifying at least the initial use of iron (II) sulfate for the next generation of OIF field studies. Many new iron forms and iron delivery methods are being evaluated (see Section 5. Iron) to improve the Fe:C export efficiency of engineered blooms, some of which would be tested in future field studies. As suggested in Hypothesis 1, the rate of delivery would lead to different biogeochemical and ecological responses—with short-term additions generating a rapid pulse of aggregative export more similar to a diatom bloom in the spring and longer additions over a growing season leading to more heterotrophically driven carbon export—leaving open the question of which has potentially greater durability. Testing these strategies in the open ocean is essential to evaluate these differences. The addition of a stable iron isotope, iron-57, is also being considered to directly assess if the carbon at depth can be attributed to the iron that was added.

Patch Size Considerations and Tracking – Initial patch sizes of prior *in situ* surface iron amendments have ranged from 25-300 km^2 (6), which have been large enough to detect the phytoplankton growth response with satellite remote-sensing, but small enough to facilitate sufficient sampling and monitoring of the "in-patch" and "out-patch" water parcels. Smaller patches are practical from an economic and logistical point of view, since fewer assets (ships, ship time, moorings, drifters, autonomous vehicles, etc.) are needed both for initial iron delivery and then to cover the area to survey the outcome.

However, lateral mixing processes lead to dilution and patch inhomogeneity (5), which challenge the ability to adequately track and effectively sample the patch with the coarse resolution of shipboard sampling. In addition, dilution of the patch reduces particle aggregation rates (e.g., 13), hence the export of carbon would be reduced. These factors lie at the crux of Hypothesis 2, which suggests that carbon export will be enhanced as patches become larger and observations longer, as proposed here. We suggest broadly increasing both by a factor of 10 or more, so time from one month to one year (and longer), and study areas increasing from 100 km^2 to >10,000 km^2 scales, which are still small relative to natural episodic iron additions, such as from volcanic eruptions and forest fires (14).

In addition to impacting carbon efficiencies, larger and longer scales may lead to unexpected dynamics of the biological response. For example, larger patch sizes may be important for altering vertical migration and foraging behavior of mesozooplankton or small fishes in ways that could alter export efficiencies and ecological structures. There are other possible biological responses that are not currently captured in biogeochemical or ecosystem models.

Larger patch sizes also improve the ability for robust detection of carbon export because subsurface assets like sediment traps (moored or neutrally buoyant) or other technologies (e.g. BGC-Argo floats, 15) may miss export pulses from smaller scale features originating from surface waters. A larger size will include multiple samplings well beyond the fertilized waters, ensuring that both in-patch (iron-driven) and out-patch (baseline) impacts are adequately sampled, which is critical to determine additionality of OIF for mCDR. Observing System Simulation Experiments (OSSEs) will be a valuable tool to guide the implementation of needed sampling strategies (e.g., asset coverage, timing, etc.) for a given patch size (see OSSEs in Section 4. Modeling). A preliminary assessment indicates that a 50 x 50 km patch size in the NE Pacific within a larger (100 x 100 km) area would allow for adequate sampling (see below). Patch tracking would likely include addition of an inert tracer SF_6 (or its replacement SF_5CF_3; 16) and as the patch evolves, changing biogeochemical proxies, such as chlorophyll, Fv/Fm, CO_2 drawdown, and dissolved iron (all of which can be measured underway from ships and some from subsurface gliders and/or surface autonomous vehicles; AVs).

Ultimately, the field studies we propose should be small enough that the biogeochemical and ecological outcomes can be robustly captured while minimizing the risks of long-term ecological damage, but large enough that the perturbation would yield similar outcomes as OIF operations at mCDR-relevant scales. This latter point is crucial if these findings are to guide future decision-making about the efficacy and wisdom of utilizing OIF for mCDR.

3.2.3 SITE SELECTION - THE NE PACIFIC

It is well established that iron is the primary limiting nutrient of phytoplankton growth in 30-40% of the world's oceans, including HNLC regions of the Equatorial Pacific, Southern Ocean, and Subarctic North Pacific (3, 4). Prior deliberate OIF experiments (n=13) have been performed in HNLC regions, and in the North Atlantic Ocean, which is a low-nutrient, low-chlorophyll (LNLC) region. These experiments have demonstrated that iron additions can stimulate phytoplankton growth, providing the potential for net carbon removal (5, 6). Iron additions also have been shown to stimulate new production in the subtropical Pacific by increasing the activity of N_2-fixing microbes (diazotrophs; 17), but the ability of diazotrophs to sequester carbon is still an open question (18).

A recent multidisciplinary ExOIS workshop held in May 2023 included discussions about possible OIF sites among scientists familiar with OIF, as well as experts from social sciences, governance, and policy fields. The baseline conditions as well as some of the site-specific logistical and feasibility constraints for OIF field work have been summarized in Tables 2.1 and Section 2.1 of this report. Based upon these considerations, we suggest that the best location for the next generation of OIF field studies is in the NE Pacific (Figure 3.1). The NE Pacific has low eddy kinetic energy, allowing for the patch to remain coherent over timescales of several months, which is needed to lead to efficient aggregation and carbon export (Figure 3.2). The depths to which carbon needs to sink to reach our centennial tonne timescale is also relatively shallow in the NE Pacific (around 500 m, Figure 3.3). Modeling of the physical environment also suggests that drift of the patch center relative to the maximal signal in particulate organic carbon flux at 200 m will be small, 10-20 km scales, even after 90 days (Figure 3.4a). The site is at the end of the large-scale ocean overturning circulation, i.e. the great conveyor belt, and thus downstream impacts and nutrient robbing concerns are low. Accessibility is also good, given the location of US and Canadian ports, and no island nations are in the study region, though outreach and discussion with regional fisheries and coastal indigenous groups would be important in the early stages of planning the experiment as discussed in Section 7 (Social and Governance). Finally, we know from one prior OIF experiment, SERIES, that adding iron will stimulate diatom-dominated communities and export (19). There is a wealth of scientific background knowledge not just from SERIES but from long-term time series at Ocean Station P (OSP; 20, 21) and associated studies in the area, including the more recent NASA EXPORTS study (22), that will assist in the planning of the experiment as well as assessments needed for permits under the London Protocol (See Section 7).

3.2.4 KEY METRICS AND MEASUREMENTS

Several key field measurements will be critical to assess the efficacy and ecological impact of OIF for mCDR. These measurements must generate information about carbon sequestration and ecological impacts that can be compared across both terrestrial and other marine CDR systems. This will be difficult, given the need to use vastly different techniques to quantify these impacts in different settings. In addition, the ocean is characterized by highly dynamic physical, chemical, and biological processes, all of which influence carbon sequestration and occur across a variety of spatial and temporal scales. While advances in MRV and eMRV technologies are needed (see Section 6. MRV), we have the tools in hand to make these measurements as part of the field studies proposed here.

MRV for Carbon and the Centennial Tonne – Quantifying mCDR will be a function of additional (additive) carbon export, the depth of carbon sequestration, and the site location. To be "removed" from surface waters, carbon must be transported below the depth horizon of the main thermocline (pycnocline), as otherwise winter mixing will allow it to return to the atmosphere. Site location then becomes very important because the depth of the main pycnocline varies widely across ocean regions (≈100-1000 m; 23). Even then, the advection of subsurface water masses leads to different timescales before returning to the surface (8, see durability discussion in Section 4. Modeling). In addition, any drawdown of CO_2 needs to consider not just how much dissolved CO_2 decreases in the surface, but how quickly the surface waters re-equilibrate with the atmosphere prior to sinking (24). A combination of observation and modeling are thus essential for MRV for carbon.

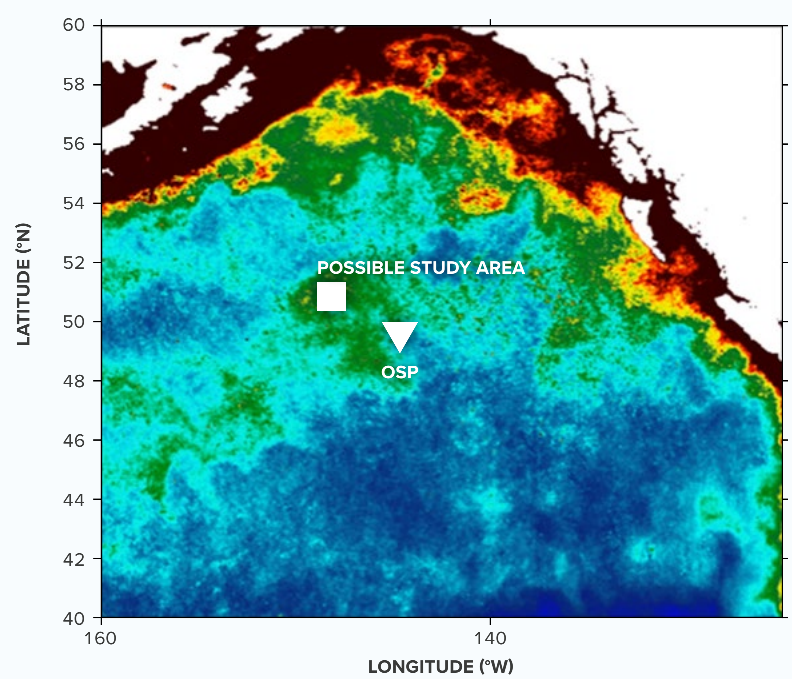

Figure 3.1. Map of the nominal location of the next generation of field studies in the NE Pacific. Also shown is the location of the Ocean Station P (OSP) long term time-series monitoring site. Map background is chlorophyll.

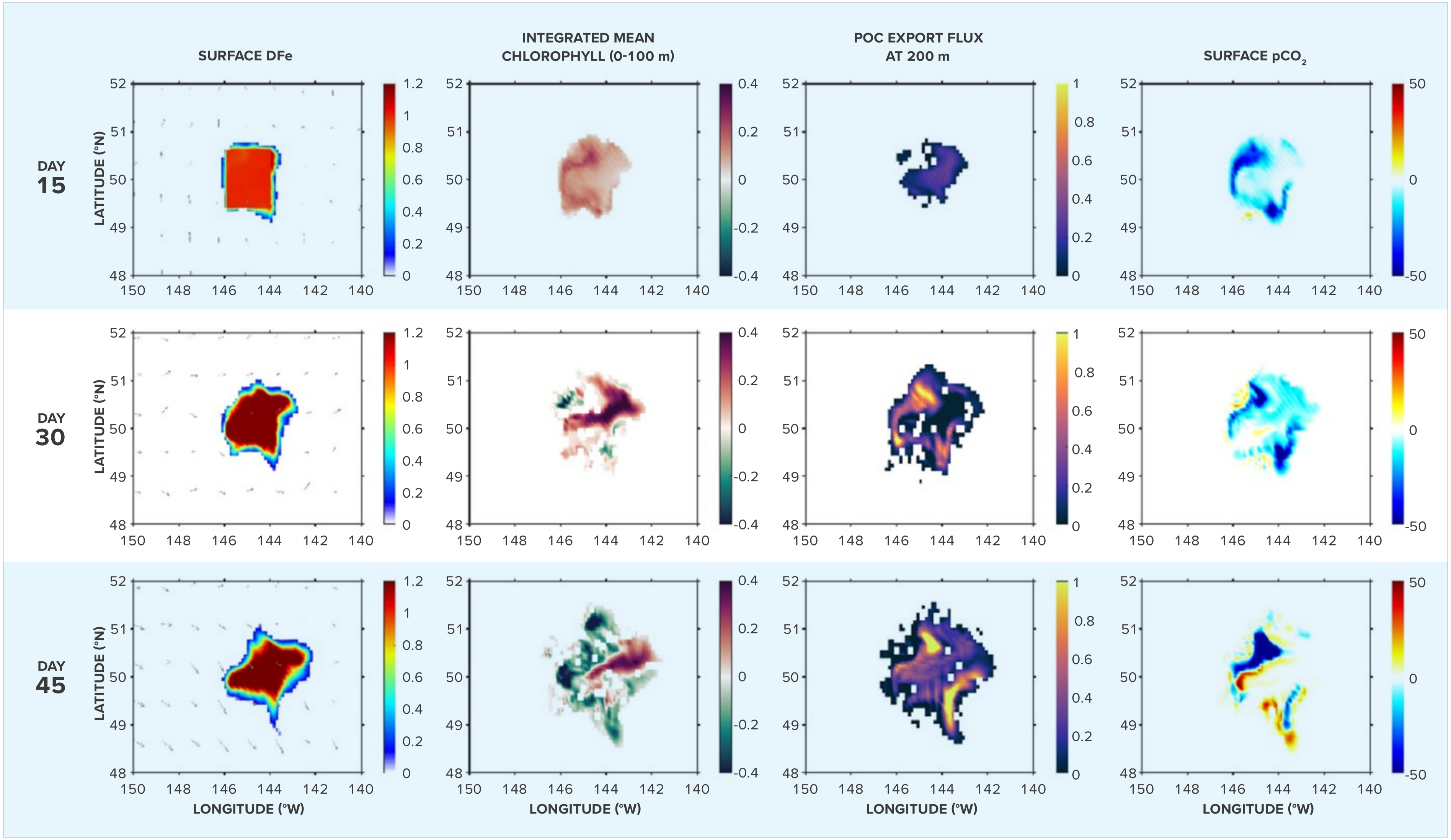

Figure 3.2. Model of biogeochemical response to OIF addition in NE Pacific. Panels arranged top to bottom for projections on day 15, 30, and 45 after iron addition. Panels include (left to right) surface dissolved iron; integrated chlorophyll; particulate organic carbon flux at 200 m; and surface pCO_2. Initial modeled patch size is 200 x 200 km. Details in text. Figure provided by F. Chai et al. (personal communication).

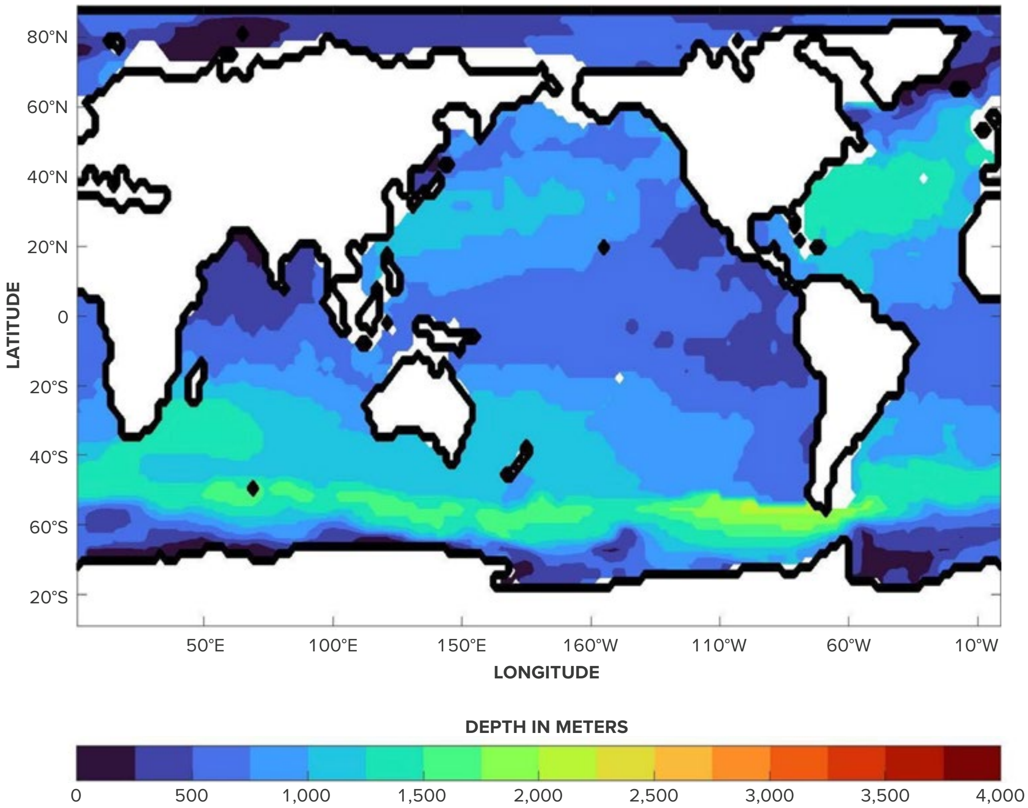

Figure 3.3. Map showing depth at which 50% of the carbon would be sequestered, or isolated from return equilibration with the atmosphere for on average one hundred years. Adapted from a model in Siegel et al. (8).

To grapple with this issue, the concept of the centennial tonne is proposed, which would represent a metric used to quantify the additive mass of carbon removed from the atmosphere for at least a century – 1000 kg of carbon isolated from atmospheric ventilation for at least 100 years (see Section 4. Modeling and Figure 4.6). In this way, the depth horizons used to quantify mCDR durability would vary with site location and be independent of seasons. The rationale for a century timescale is pragmatic and based on the anticipation of carbon markets and durability around carbon credits and climate solutions. Removal does not have to be permanent for mCDR to be an effective tool in reducing human and environmental losses due to climate change.

Ecological and Environmental MRV (eMRV) – OIF will have substantial ecological and biogeochemical consequences, some of which (e.g., increased diatom production) are well known, others that are less well defined, and both of which can generate undesirable outcomes. **Monitoring, reporting, and verification of these environmental and ecological effects (eMRV) is arguably as important as the more straightforward MRV for carbon accounting**. Some of the known potential impacts that need to be studied include, but are not limited to, "downstream" effects from nutrient removal, greater deoxygenation of mid-depth waters, and enhanced growth of potentially toxic phytoplankton or species known for fish-killing. As such, experimental designs must also encompass vigilance to observe unexpected outcomes in these complex systems. Combined, these eMRV findings will be essential for assessing the risks of large scale, prolonged OIF strategies. They also will be a key input for the next stages of experimental planning, and eMRV assessments likely will have to evolve as the experiments progress and findings come in. The proposed field studies will be of sufficient duration to inform on these outcomes, but not long enough to permanently alter ecosystems in the test regions.

Core parameters – A core subset of parameters is under development (Table 3.1). Central to this list is the ability to track CO_2 drawdown in the surface (and with models the re-equilibration of surface waters with the atmosphere) and the amount of carbon that reaches the depth of our centennial tonne. In addition to this data on carbon durability and additionality, the remineralization of sinking carbon, iron, and other macronutrients and minerals (N, P, biogenic silica, particulate inorganic carbon) needs to be measured to better understand their relative removal pathways and depth of penetration, which impact their individual return times to the surface and downstream impacts. For eMRV, we need to measure changes in surface plankton communities (stocks and species), taking advantage of advances in optics, imaging, and genomics. Out of concern for harmful algal blooms, domoic acid production would be monitored and subsurface changes in geochemical properties, such as O_2 levels and production of other greenhouse gases measured (N_2O, CH_4, dimethyl sulfide). Of course in such a study, careful attention needs to be paid to physical parameters and models required to track and understand the fate of any iron-induced bloom. Remote sensing is not specifically called out in this Table, but certainly key for monitoring the evolution of the patch size, shape, and its biological characteristics (community structure, particulate inorganic carbon, particle size, etc).

We are confident that the type of measurements in Table 3.1 can be made by current oceanographic methods, tools, and platforms, but will become easier as new technologies under development mature. We plan and organize these experiments in an open and transparent process, and can thus more readily invite other groups to participate, testing new MRV and eMRV technologies, verifying what we are already measuring, and measuring components we are not tracking. For example, while we do not think these experiments will induce large scale fisheries shifts or changes to benthic biogeochemical conditions, other groups would be welcome to bring in such components. Details of the sampling plans and core parameters would be decided at the field-planning workshop.

3.3 Timeline

The IPCC AR6 Synthesis Report highlighted the extreme urgency for the development and testing of CDR strategies, which argues for accelerated efforts toward field studies evaluating the efficacy of OIF as a carbon sequestration strategy. **We do not have the luxury of waiting for perfect or ideal tools.** With funding commitments in hand, we could be ready for the first field studies in 2025. This is an aggressive timeline for traditional oceanographic field experiments and there are many steps needed to reach this goal. First, the plans summarized in this report

The proposed field studies will be of sufficient duration to inform on these outcomes, but not long enough to permanently alter ecosystems

TABLE 3.1. ESSENTIAL MEASUREMENTS

ESSENTIAL MEASUREMENTS	PLATFORMS/SAMPLER	COMMENTS
Dissolved CO_2 & carbonate system	Ship CTD, floats, gliders, surface AVs	On board & AVs
Gravitational C export	Sediment traps, radionuclides	(3 depths min) What remains above 500 m, at "centennial tonne" depth (approx 500 m) and 1000 m
Macronutrients	Ship CTD, floats, gliders	Ship N, P, Si; floats/gliders nitrate sensors
Iron- dissolved + particluate	Underway ship, CTD	Dissolved: <0.45 um, particulate >0.45 um, underway to track patch
Particulate C, N, P, bSi, PIC	CTD and in-situ pumps	Bottle and size-fractionated on pumps; PIC and bSi as needed
Bio rates- NPP, NCP	CTD and incubations	Reduce number of rate studies needed
Imaging- UVP, shadowgraph, etc	CTD, towed, floats, gliders	Maximize imaging to reduce use of nets for eMRV
Biooptics- beam c, acs, PAR, bbp	Ship CTD, floats, gliders	Flow through and as possible vs depth
Gases- O_2, N_2O, CH_4, DMS	CTD	On board
HABS- particulate domoic acid	CTD	Ship-board ELISA plus shore based on a subset for verification - moored if essential
Bio-plankton and bacteria	CTD	Chlorophyll, microscopy and flow cytometry shipboard, limited sampling for others eDNA, omics, Fv/Fm.
Bio-fish	Ship accoustics	Invite fisheries scientists- separate ship/nets
Physical & bio conditions	Fixed OSP moorings for winds, weather	NOAA mooring for local weather
Physical	Gliders, floats, towed	PO modeling essential
Tracking patch	Ship, AVs, remote sensing	SF_5CF_3 (SF_6 alternative) and as bloom develops, surface Chl, Fv/Fm, dissolved Fe and DIC
Spatial and temporal mapping	Remote sensing	Physical and biological properties at surface

are notional, and a dedicated field-planning workshop will be needed in fall/winter 2023 to lay out in more detail the site-specific scale of deployments, measurements to be made, social license issues, and costs, including fully scoped and descoped options. Partners will need to be established and a path and responsibilities assigned for organizing platforms, permits, and mechanisms for opening up the experiment to core participants who are funded with new resources, inviting in those who are participating with their own resources, and reaching out to groups to add in measurements that might not be covered in the core ExOIS field project (which depends in large part on total funds in hand). The workshop would include experts on key aspects of the experiment implementation and observations. These more detailed planning activities could begin in early 2024 to find collaborators and raise funds for a specific set of field experiments.

This timeline could lead to the next generation of field studies in the NE Pacific as early as 2025. A tentative plan would be using paired experiments with spring and late summer iron additions in year one, with measurements and a second pair of iron additions in year two, i.e. 4 OIF deployments. Post-cruise data analyses and synthesis modeling would be done by the core teams after each experiment, with multiple workshops for sharing data. Presentation of these field plans and the subsequent experimental findings to the larger ocean sciences and mCDR community, as well as the public, would need to be established from the start.

3.3.1 MILESTONES AND DELIVERABLES

The field plans would be finalized by the end of year one, AVs, ships, science teams at the ready, and considerable outreach to the public and regional stakeholders

TABLE 3.2. CHARACTERISTICS OF A FIELD STUDY SITE IN THE NE PACIFIC

PILOT STUDY CONSIDERATIONS	PLANNED STUDY ATTRIBUTES	COMMENTS
Patch size initial	50x50 km (2500 km^2)	SERIES was 77 km^2
Location	150 km from OSP (to not influence time series)	SERIES was 50 km NE of OSP (OSP at 50°N 145°W)
Observational grid initial	100x100 km	Multiple sites in & out; OSP is "out" as well
Two 90 day deployment periods	Approx May 1 and Aug 1	Reset to original location for second deploymnet
Total study period	March-November	SERIES was 25 days
Target iron surface 10 m	1 nM	
Approx. Fe added as $FeSO_4$	10 tonne	SERIES 0.5 tonne

underway. Each cruise becomes a milestone with an ambitious two deployments per year over two years as the goal. Major findings, such as CO_2 balances, chlorophyll growth, additional carbon reaching depth and ecological and other assessments would be presented in preliminary format at international scientific gatherings, and in short form to the public and funders on a regular basis to fulfill our stated goal of open and transparent studies. Data would be made publically available within 6 months of any cruise using a suitable data management team that would need to be contracted, ideally one that is pre-existing and funded out of the ExOIS Program Office. As noted, assessing the risks of OIF and public perception of the outcomes are important goals and deliverables so that we can build up the trust that ExOIS has the appropriate governance, standards, protocols, and qualifications to lead these studies.

3.3.2 CHALLENGES

Quantifying the impact of OIF on atmospheric CO_2 will require coupling model experiments with field experimental data to provide early insights into the potential efficacy of OIF strategies for CDR (see Section 4. Modeling). If the study findings show potential, then it will become increasingly important moving forward to develop better optimized forms of iron that are readily deliverable, longer-lived in surface waters, and more bioavailable (see Section 5. Iron), as well as improved practical and lower-cost strategies for MRV and eMRV (see Section 6. MRV). The project goal then is to build the protocols and MRV and eMRV that can quantify durably removed carbon, i.e. the “centennial tonne” along with its associated uncertainties using models. This goal will require running ocean studies at orders-of-magnitude larger spatial and temporal scales than previous mesoscale iron enrichment studies, using the best tools and models available. These field studies are a measured step towards the larger “ocean iron observatories” concept that will evolve out of these studies if the findings are encouraging. These advancements will be coupled tightly with social science studies and evolving progress in governance (see Section 7. Social and Governance), with ExOIS setting an example for all in the mCDR community to follow.

3.4 Priorities and Costs

While the field experimental plans have a clear set of goals and preliminary hypotheses (see Section 3. Field Studies), they have not been planned out in detail. Decisions on measurement protocols, sampling choices in space and time, how many groups and partners, etc. will all impact cost. What is presented here is a budget based upon prior experiences in similar ocean studies and a set of assumptions for a fully scoped and operational set of field and model studies.

Our cost estimate plans for a spring and summer field study deploying on the order of 10 tonnes of iron over a 50 x 50 km patch of the NE Pacific, several hundred km distant from the time series site Ocean Station P and the prior SERIES OIF experiment (Table 3.2). Initial modeling shows that Lagrangian monitoring a 100 x 100 km region centered on the patch would enable inside/outside patch assessments, and that there would be sufficient nutrient resupply to support a second bloom in the same late summer season (Figure 3.4b). These deployments would be repeated in the second year. Cost estimates use current off-the shelf available platforms and sensors to meet the key measurement requirements as laid out in Table 3.1. This budgeting uses a calculation scheme set up by the NASA EXPORTS project (https://oceanexports.org/; see Table 6 in EXPORTS implementation plan), which allowed several scoping and descoping options to be assessed and budgeted. We assume the total support is coming from one source (no in-kind partner contributions). In this scenario, one ship would be used for deployment and recovery of autonomous assets and two better-equipped science vessels would be needed for the main observation periods (two 30-day cruises, ocean class ships, UNOLS rates) with another ship specific to the deployment of iron (two times per year). Autonomous assets would include multiple Argo-type biogeochemical (BGC) floats (roughly one dozen per deployment), with an equal number of heavily instrumented gliders and/or surface AVs, along a significant number of sediment traps deployed in the upper 1000 m (5 sites, multiple depths, key is carbon flux at the centennial tonne depth and remineralization above). Looking at the essential measurements and AV operations, several contracts to science and engineering teams would be needed over four years (most projects would require support one year prior, two field years and one year after the last of four cruises).

This scenario, combined with supporting data management, field offices, and other costs totals $96M for the four field studies (see costs broken down by year in Table 9.1). That cost is roughly $15M higher for the first cruise, when initial reusable

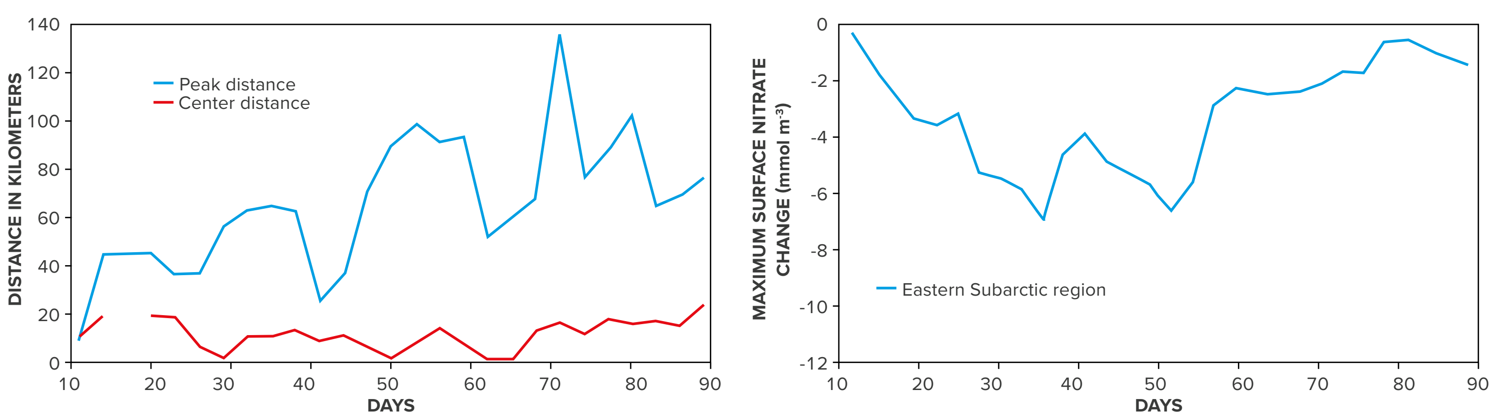

Figure 3.4. Properties predicted from the model used in Fig. 3.2 for NE Pacific projected for 90 days after iron addition. The left panel shows the distance between the Gaussian distributions of the patch center and particulate organic carbon (POC) flux at 200 m (center distance- red line). The distance between patch property maximums and 200 m is also shown (peak distance- blue line). The right panel shows the maximum change in surface nitrate over the same period. Both are from model results supplied by F. Chai et al. (personal communication).

in water assets are purchased (gliders, floats, surface AVs, traps). This notional budget will be refined at an initial field planning workshop in year 1 and rescoping options considered. Costs would obviously decrease if a field program were assembled using pre-existing AVs, traps, and sharing of ship time costs among several partner countries. What ends up being fairly robust, though, in such estimates are the fractional costs, which in this scenario come out to roughly 25% for AVs and their operations, 15% for ship time, 40% for the science teams, and the remaining costs (20%) for data management, addition of iron, and operational support.

The high cost here stems largely from the need for multiple (4) OIF deployments, which would provide a degree of replication lacking in prior experiments, and the ability to alter conditions of iron delivery (e.g., input duration, pulsed vs. continuous, iron form) which will impact the character of planktonic responses and thereby likely the durability of carbon removal. In any scenario, these next generation of OIF experiments, done correctly, are a significant investment of many $10s M each. As a point of reference, the NASEM report suggested that $25M would be needed per OIF field experiment, with a total investment of $290-440M over a 10-year research and development period for a full assessment of OIF for mCDR (1). ExOIS is actively seeking out philanthropic, national agency, individual, and commercial supporters, as long as they support our Code of Conduct and plans to not sell carbon credits as a return on the investment (see Section 1. Introduction).

To put these costs in perspective, the US recently announced investments of over one billion dollars for two direct air capture plants (25) and there is already roughly one billion dollars being invested via the voluntary carbon markets in commercial companies for land- and ocean-based CDR. If markets are established to fund CDR, and with current costs for CO_2 removal benchmarked against $100 per tonne CO_2 and Gt of CO_2 removal needed per year, CDR has the potential to become a $100B per year new market being built out over the course of the next several decades. It is not surprising then that venture capital funds are flowing in. ExOIS' concern is that responsible science provides the urgent guidance needed to ensure that this new industry considers all of its consequences, so that removing CO_2 leads to a net improvement in both human and ecological conditions. Simply put, the investments suggested in this report are small relative to the options of doing nothing, or doing mCDR in the wrong way.

3.5 Synergies and Impact

Field studies are a necessity to advance our understanding of OIF and its potential for mCDR—models are critically important but currently lack essential datasets. Prior OIF experiments are extremely helpful in demonstrating the enhanced phytoplankton growth in HNLC regions in response to iron, and they are strong examples that such shorter-term field experiments do not cause permanent harm, much like natural episodic iron stimulated events (e.g., volcanic eruptions; wildfires). What is new here is the emphasis on replication of larger and longer experiments

CDR has the potential to become a $100B per year new market to more fully capture the potential for durable carbon sequestration and quantify broader-scaled ecological and biogeochemical outcomes.

Advances in new autonomous vehicles (AVs) over the past decades create the ability to support larger and longer observation MRV and eMRV networks that were not possible in the past. By proposing to conduct field studies in a lower energy physical setting, the NE Pacific, we can build upon a considerable body of knowledge from decades-long ocean time series, a prior OIF experiment (SERIES), as well as studies of volcanic ash inputs from Alaska (e.g., 26). In addition to AVs, new advances in using camera-based methodologies for both quantifying carbon fluxes and documenting changes in ecosystems will help replace more time-consuming microscopic and net-based methods (see Section 6. MRV). New advances in omics are also important for looking at ecological responses. Building up ten times larger and longer experiments also has the advantage when looking for secondary nutrient limitations and grazing responses that take longer to develop.

Ultimately whether these next generation of experiments are called "pilot" or "small scale" field studies is not critical, but we should be clear they are far smaller than natural OIF events (26) and no permanent structures need to be built. They would be optimized and quantify the parameters needed to better model and hence design more comprehensive and larger ocean iron observatories by the end of 3-5 years. Showing the public and others that these studies can be done in a responsible way, and risks of undesirable impacts are minimal or manageable is also key (e.g., harmful algal blooms, fisheries collapse, deoxygenated dead zones). The experiments also will provide the necessary database to better inform models that will be needed to evaluate the consequences of OIF deployment on climatically relevant scales.

Field work is thus ultimately of the highest priority for ExOIS but it cannot be done in isolation without consideration of the other four activities described in this report. Nevertheless, each of these activities can begin independently. The combination of rapidly increasing atmospheric CO_2 levels, and the market pressures leading to this situation, means that scientific assessments must begin now if responsible decision making is to stay ahead of poorly-conceived actions to alleviate our climate crisis.

4 MODELING

4.1 Goals for modeling

The efficacy of OIF as a climate change mitigation strategy can be conceptualized along axes of additionality and durability (Figure 4.1). Consider a benchmark of 1 tonne carbon that is sequestered into the deep sea for 100 years, or a "centennial tonne." By virtue of the profile of remineralization of sinking particulate material in the ocean (the so-called Martin curve; 27), that centennial tonne of carbon flux will be part of a continuum of higher fluxes in the water column above, and lower fluxes below—each with correspondingly lower and higher durability, respectively. Whereas additionality will be primarily measurement-based, durability will be primarily model-based. Of course there are uncertainties associated with both additionality and durability. Uncertainty grows with decreasing additionality, as smaller fluxes are more difficult to measure and distinguish with certainty when comparing against a variable background. In contrast, uncertainty grows with increasing durability, as longer timescales are less well constrained in ocean biogeochemical models. Herein we describe the tools required to define the additionality/durability relationship and how it varies regionally with the various sites of OIF being considered. These require models of iron cycling in the ocean, OIF simulations, Observing System Simulation Experiments (OSSEs) to design Ocean Iron Observatories (OIOs), and durability models. Sections 4.3-4.5 below provide estimated timelines, costs, and scientific outcomes.

4.2 Key areas of effort

4.2.1 MODELS OF IRON CYCLING IN THE OCEAN

Accurate representation of iron cycling processes is essential to model the effects of OIF on marine ecosystems and carbon sequestration, and to lay the foundation for OSSEs and MRV. The cycle of iron is distinct from that of other nutrients due to its extremely low concentration in dissolved form and the complex interaction of biotic and abiotic processes (28; 29). One main target for models is to capture the correct residence time of dissolved iron in the ocean (30). A rapid, tight balance between sources and sinks of iron leads to one of the shortest residence times among the nutrients that phytoplankton require. Two timescales are arguably important for OIF simulations: the first one is the iron residence time in the euphotic zone, which would control the ability of OIF to stimulate primary production, carbon export, and CO_2 drawdown at the scale of iron fertilized patches (31). The second one is the iron residence time in the deep ocean, which controls the long-term efficacy of carbon sequestration over centennial periods (32).

A diversity of iron sources and sinks complicates modeling efforts. Among the sources, atmospheric deposition (33), release from sediment (34), and river runoff (35) are the main pathways delivering iron to surface waters. At high latitudes, inputs from icebergs and glaciers (36) can become important, and there is evidence to suggest that submarine groundwater discharges may be a source of dissolved iron (37). At depths of hundreds to thousands of meters, hydrothermal vents release stabilized dissolved iron into the water column (38); this iron can reach the surface in regions of deep upwelling, e.g., in the Southern Ocean (39). To further complicate the picture, iron introduced by different sources is characterized by a range of solubilities and, ultimately, bioavailability (40). The uncertainty is large enough that current models differ significantly in the total input of iron to the ocean, ranging from as low as 1.4 to as high as 195.4 Gmol per year (30).

In parallel, multiple processes remove bioavailable iron from seawater. The oxidized form Fe(III) dominates in the ocean, but is characterized by sub-nanomolar solubilities, and thus quickly aggregates and precipitates (41). Dissolved iron is rapidly incorporated into marine particles by biological uptake and scavenging (29). Iron can be protected by forming complexes with organic ligands, to the point that ligand-bound iron represents the majority of bioavailable iron in the ocean (42). Furthermore, iron incorporation into phytoplankton and zooplankton spans a wide range of cellular quotas (43, 44, 45), and consumption and recycling by bacteria, viruses, and zooplankton complicate the picture (46).

These diverse and intertwined processes pose a significant challenge for models, and limit our confidence in model predictions of OIF responses. Early global models, informed by the first syntheses of iron observations in the late 1990s (47),

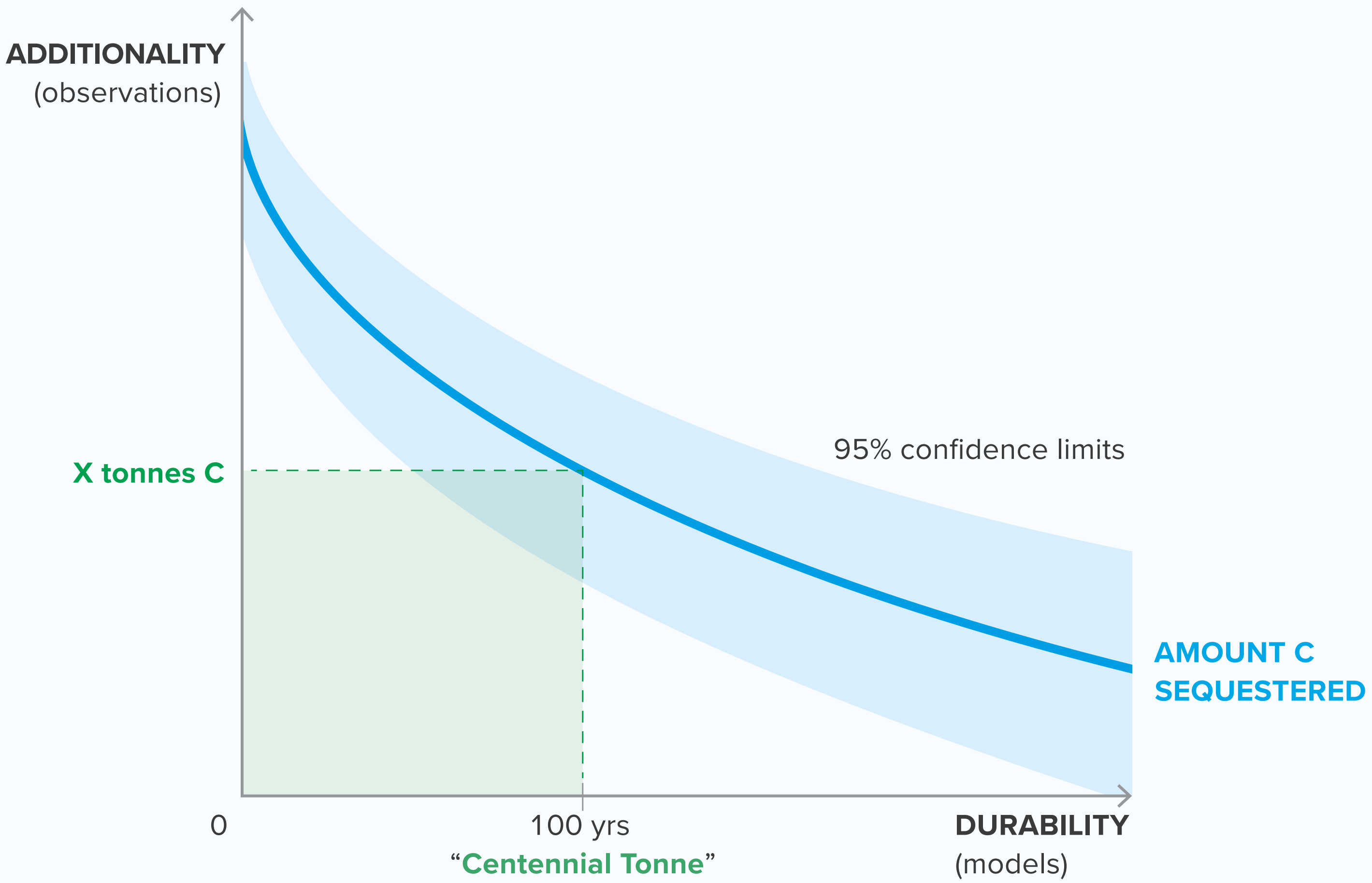

Figure 4.1. Conceptual diagram related to the durability and uncertainty around measuring the "centennial tonne" of carbon. This concept requires observations of carbon flux to depth (y-axis) and model determinations of durability (x-axis). Uncertainties around this predicted centennial tonne metric are possible as shown by the shading. Units would be tonnes (1000 kg) of carbon that are isolated from atmospheric recontact for 100 years or more, on average. Note this curve would vary with time and location in response to OIF and it is the integral of these measurements over the deployment area that is required to determine net additional and durable carbon storage. Also, adjustments for surface CO_2 exchange would be needed (e.g., 24) to determine net impacts of OIF on atmospheric CO_2.

only considered dust inputs, constant phytoplankton iron quotas, and uniform concentrations of organic ligands (48, 49). This conceptual view still informs ocean biogeochemical models today (29). An expansion of iron observations from GEOTRACES and other programs has driven an increase in model complexity, with inclusion of iron sources from continental margins (50) and hydrothermal vents (38). A great deal of effort has been devoted to improving representation of iron-binding ligands and their dynamics. Earlier parameterizations with implicit, constant ligands (50, 51) have given way to models with variable ligand classes, either parameterized as a function of other tracers such as dissolved organic matter or oxygen utilization (52, 53), or represented as time-evolving tracers with their own sources and sinks (54, 55). More sophisticated representations of interactions with sinking particles have also been developed (50). Recently, Tagliabue et al. (56) proposed a revised model in which dissolved iron escapes equilibration with ligands by abiotic aggregation and sinking ("colloidal pumping"). This process is necessary to capture the seasonal cycle and iron speciation at the Bermuda Atlantic Time-series Study (BATS) site, with implications for the residence time of iron at the surface and for biological responses to iron inputs.

The new generation of iron models performs better than earlier ones when compared against iron observations along multiple oceanic transects (30); however, uncertainties remain. With a proliferation of external sources and internal removal processes, dissolved iron residence times are still poorly constrained with modeling results giving a range from a few years to centuries (30). Most models focus on capturing basin-scale patterns in the iron distribution and thus lack an adequate representation of fine-scale circulations (e.g., eddies and jets) that provide a direct route for iron delivery from continental margins to the open ocean (30). Chemical feedbacks and food-web interactions are also uncertain, with implications for OIF responses. For example, if ligand production is tied to organic matter synthesis and remineralization, as assumed by several models (52, 53), purposeful OIF may stimulate ligand release, enhancing iron retention (a positive feedback). On the other hand, if ligand production by phytoplankton is higher under iron-limited conditions (55), it may be reduced by OIF, limiting its effectiveness (a negative feedback). Likewise, increased iron precipitation and scavenging at higher iron concentrations—including by the colloidal pump (56)—could provide negative feedbacks on OIF. Other interactions with seawater chemistry, such as enhanced benthic iron release and high solubility at low O_2 (57), or cascading effects on zooplankton, fish, and food webs (45, 58) remain similarly understudied.

4.2.2 OIF SIMULATIONS

Despite the aforementioned limitations with models of iron cycling in the ocean, there is a long history of model-based OIF studies for carbon sequestration; however, predictions vary significantly. The conceptual view for the ocean iron cycle proposed by Johnson et al. (47) attributed as much as half of the 80 ppm glacial decrease in atmospheric CO_2 to natural OIF by glacial dust inputs (48, 49). However, the carbon sequestration effectiveness of natural dust inputs depends critically on the modeled sources and sinks and the oceanic iron residence time (30). For example, models including hydrothermal iron inputs (resulting in lower residence times) showed weaker carbon sequestration than models that did not consider them (39). Studies focused on purposeful OIF suggest a similar uncertainty. Using a global model, Aumont and Bopp (51) found that global-scale purposeful OIF sustained over 100 years could reduce atmospheric CO_2 by approximately 33 ppm. Other studies, focusing on realistic patch-scale OIF in iron-limited waters (e.g., North Pacific and Southern Oceans), indicate limited impacts on CO_2 drawdown (59, 60). The depth at which additional carbon is exported following OIF is central to long-term carbon sequestration efficacy, as newly sequestered carbon can quickly resurface (59, 60). The retention timescale of iron further affects the long-term efficiency of CO_2 drawdown, with longer iron retention leading to greater CO_2 reduction (31).

Models have also highlighted the potential for undesirable consequences of purposeful OIF, including subsurface oxygen loss (31) and acidification (61); increased emission of climate-relevant gases such as N_2O (59) and dimethyl sulfide (62); and cascading effects on food webs and fisheries (58). Purposeful OIF can also lead to a "nutrient robbing" effect, where increased nutrient uptake in fertilized waters weakens downstream nutrient delivery to the rest of the ocean (63), potentially leading to long-term (century-scale) decreases in primary production (31).

Recent work has focused on OIF simulations inspired by proposed field trials described elsewhere in this report (see Section 3. Field Studies). The following examples are based on a modified version of the CoSiNE-Fe model that was developed in the northwestern Pacific (64), which includes dynamical interactions of biological processes and iron cycling. The model simulates two phytoplankton groups, small phytoplankton and diatoms. As nitrogen fixation is another important component related to carbon cycling in the North Pacific subtropical gyre (65), three nitrogen-fixing phytoplankton groups (*Trichodesmium*, unicellular diazotrophs, diatom-diazotroph-associations) were incorporated in the CoSiNE-Fe model. The 1/8º 60-level physical model was spun-up for 30-years and then the biogeochemical model was coupled and integrated from 2010 to 2017. The model results (3-day averages) in 2017 were analyzed and used as the control run. OIF simulations were conducted in the final year (2017) in three locations of the HNLC region of the Pacific Ocean, the eastern Equatorial Pacific, the western subarctic region, and the eastern subarctic region to mimic the previous field experiments of IronEx (1 and 2), SEEDS (1 and 2), and SERIES, respectively. An experiment was also conducted in the subtropical Pacific Ocean where iron may enhance nitrogen fixation and stimulate phytoplankton growth and carbon export.

Two approaches to iron release were used in the experiments. For the eastern equatorial Pacific, iron was released at a fixed line along 100ºW between 1ºN and 1ºS. Two OIF experiments were conducted during one-year simulations starting from May 1 and July 1, respectively, with each fertilization lasting 10 days. Soluble iron concentrations were continuously maintained at 1.0 nM in the upper 10 meters, which was in the lower range of previous OIF field observations (66). The fixed line release of iron is to take advantage of local well-organized currents from east to west, and relatively low eddy activity. The fixed location iron releases were also tested in the North Equatorial and Kuroshio Currents (Figure 4.2). The second method is to create square patches with different sizes. These are located in the subarctic regions where mean currents are weak. One area for the eastern subarctic (near OSP) was chosen to be about 200 km south of Ocean Station P so the latter could be used as a control site. Three sizes of fertilization patch (30 x 30 km, 100 x 100 km, 200 x 200 km) were considered in different runs. Each patch was fertilized twice starting from May 1 and July 1, respectively, and each fertilization lasted 10 days. These two fertilizations were conducted in separate runs and each run continued through to the end of the year. During the fertilization, the concentration of dissolved iron (soluble iron, weak ligand iron, and strong ligand iron) in the upper 5 m was set to a specified level, such that the total amount of added iron would be 25 t, 300 t, and 1000 t of $FeSO_4$ for the 30 km, 100 km, and 200 km patches, respectively. With this approach, the daily average concentrations of added dissolved iron were about 3.7 nM, 3.9 nM, and 3.3 nM for the 30 km, 100 km, and 200 km patches, respectively, which was in the general range of previous OIF field experiments (e.g., 18, 66).

In this report we show only one example from the NE Pacific of the biogeochemical responses to the OIF experiments that were tracked continuously with the high-resolution coupled model. The difference between control and OIF runs is used to quantify the fertilization effect. For example, Figure 4.3 shows the average difference (over a 60-day period) of surface soluble iron concentration

(Figure 4.3a), small phytoplankton (Figure 4.3b), diatoms (Figure 4.3c), and particulate organic carbon export at 100 m (Figure 4.3d).

4.2.3 USE OF OIF MODELS FOR OSSES TO DESIGN OCEAN IRON OBSERVATORIES

The OSSE concept has its origins in dynamic meteorology and is recognized as an important tool for the development of oceanographic sampling systems (e.g., 67, 68, 69). The effectiveness of any sampling strategy is ultimately determined by the accuracy with which the observations can be used to reconstruct reality—the state of the natural system being measured. In this context, reality is an elusive metric, for property distributions in the ocean rarely (if ever) have been oversampled. **Given the dearth of opportunity for testing sampling strategies against objective criteria with purely observational means, OSSEs offer an attractive framework for investigation of these issues.** The approach begins with the construction of a simulation that is characteristic of the natural system. The model run serves as a space and time continuous representation of reality, which is then subsampled in a specified fashion to produce a simulated dataset. The simulated data are then fed into an analysis scheme in which they are synthesized into a reconstruction of reality. Comparison of the reconstructed field with the "truth" as defined by the original simulation thus provides a quantitative evaluation of that sampling strategy and the associated analysis scheme. Of course there is an important caveat: the OSSEs are based on simulations that are an imperfect representation of the real world.

OIF simulations such as those described above provide the means for OSSEs to determine the observing system requirements for field trials. For example, consider

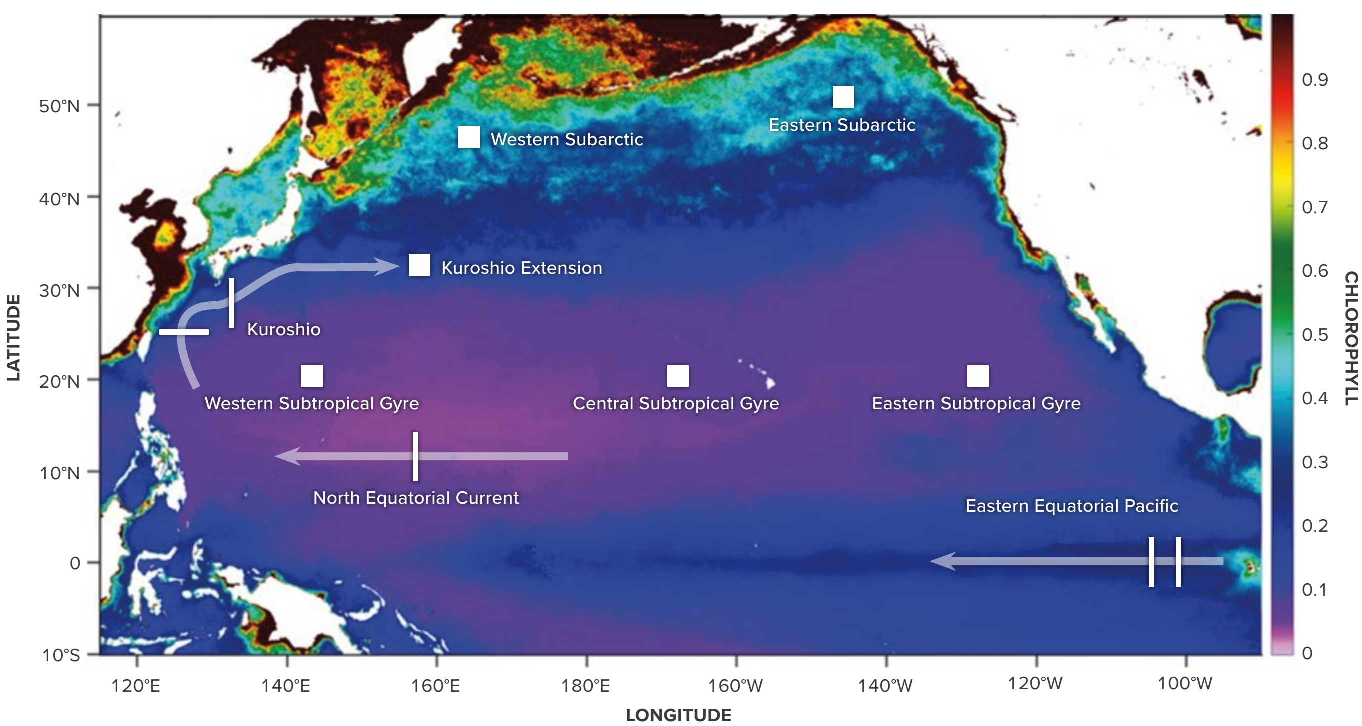

Figure 4.2. Map of north Pacific Ocean showing locations of biogeochemical models of OIF additions. Taken from modeling work by F. Chai et al. as discussed in the text. Map background is chlorophyll.

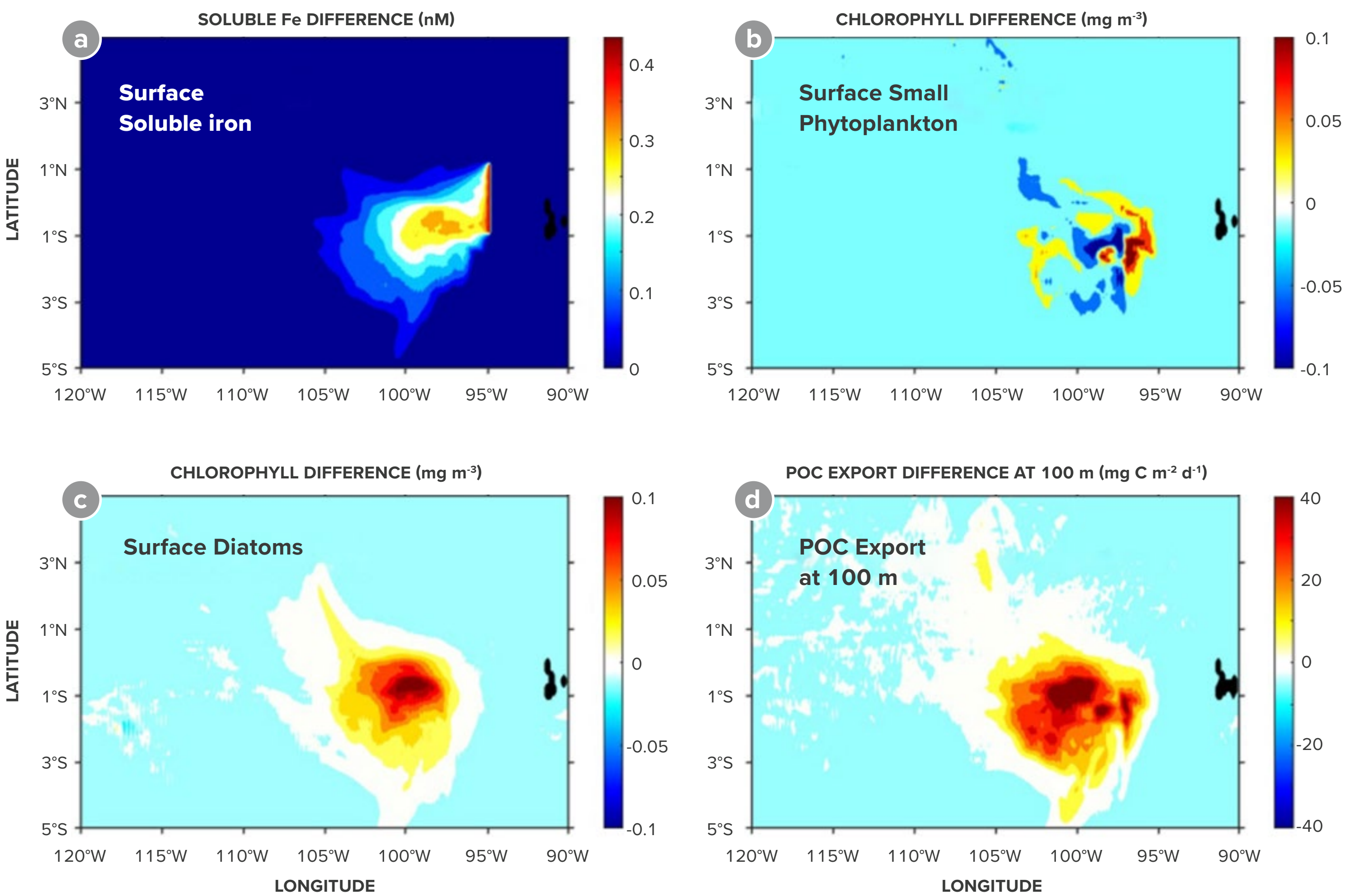

Figure 4.3. Model-derived OIF experimental results from Eastern Equatorial Pacific (see location in Fig. 4.2.). Average results 60 days after iron release are shown for the differences from initial conditions for a) surface dissolved iron; b) surface small phytoplankton abundance; c) surface diatom abundance; and d) particulate organic carbon flux associated with sinking particles at 100 m. More detailed analysis for OIF experiments in the Pacific Ocean are in progress by Xiu, Chai, and colleagues.

a highly idealized observing network for a continuous release of iron at a fixed point (yet another experimental design in addition to those depicted in Figure 4.2). The backbone of the array could consist of moored sediment traps spanning the dimensions of the biogeochemical response plume downstream of the iron source and anchored at the depth of the centennial tonne (Figure 4.4, top panel). OIF simulations yield estimates of the downstream and cross-stream dimensions of the plume, L_x and L_y, respectively. Given the need to constrain the enhancement of carbon export in the plume downstream of the iron source at a specified level of accuracy, specific questions can be posed with OSSEs:

1. What is the required resolution in the downstream and cross-stream directions, Δx and Δy, respectively?
2. Should the moorings be spaced linearly or logarithmically in the downstream and cross-stream directions?
3. How far should the moorings extend beyond the plume in the downstream and cross-stream directions (λx and λy, respectively) to ensure that unperturbed background conditions are sufficiently monitored?

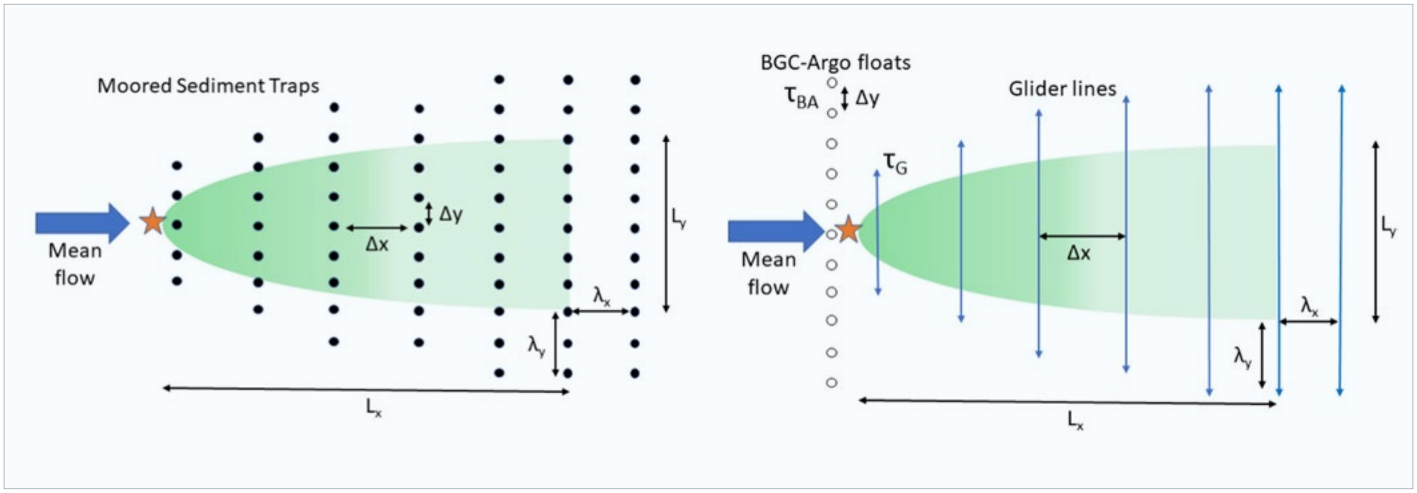

Figure 4.4. Idealized representations of spatial scales of sampling need for OIF field experiments considering a continuous source of iron (red star) and mean flow to the right. Panel on left shows a hypothetical sediment trap array moored at fixed location at the depth of the centennial tonne; panel on right shows a sampling pattern suitable for autonomous platforms such as BGC-Argo profiling floats (released at multiple time points and then drifting with flow) and active vertical and horizontal sampling with gliders along multiple fixed transects. Sampling density, times, and distances would be optimized via OSSE modeling.

4. What is the vertical resolution of the sediment traps deployed on each mooring to achieve sufficiently accurate partitioning of the vertical flux into strata of varying sequestration timescales, vis a vis Siegel et al. (8)?

What we expect to see in the simulations at one depth in one of the meridional lines of sediment traps is illustrated in Figure 4.5. Iron fertilization will stimulate an enhancement of export flux in the downstream plume. Both the control and the experiment will contain variability ranging from mesoscale to submesoscale processes that modulate the "statistical funnel" (70) over which the traps collect sinking material, as well as seasonal to interannual fluctuations in oceanic and atmospheric conditions. The OSSEs provide a means to estimate the statistical robustness of the enhancement in export flux as a function of the spatial and temporal resolution of the sediment trap array. We also expect the signal to be attenuated with depth by virtue of the parameterizations of remineralization used in the models—and this attenuation is a key factor in determining the timescale over which the exported carbon will be sequestered (see below).

Of course, moored sediment traps constitute only one aspect of the observing system, and there are many other platforms and sensors that must be considered. For example, a subset of the moorings could be equipped with Imaging Flow CytoBots (71) to measure phytoplankton community composition, and Environmental Sample Processors (72) to monitor for toxins such as domoic acid that are sometimes produced by diatoms of the genus *Pseudo-nitzschia*.

Autonomous platforms offer important opportunities for augmenting the observing network. For example, a cross-stream array of BGC-Argo floats could be deployed upstream of the fertilization site (Figure 4.4, bottom panel). These profiling systems can monitor the upper ocean biological response bio-optically, as well as nitrate, oxygen, and the carbon system by proxy through pH (73)—thus providing a means to quantify remineralization of sinking organic material. Of course, the float trajectories will be subject to the fronts, meanders, eddies, and active submesoscale dynamics characteristic of this region. Thus, the following questions arise:

1. What is the required resolution of the BGC-Argo array in the cross-stream direction (Δy)?
2. How often must the BGC-Argo arrays be deployed (period τBA) to provide sufficient resolution in the downstream direction?

Numerical analogues of the profiling floats will be inserted into the model to gather simulated data that will then be mapped with objective analysis and compared to the "truth" as defined by the model.

Another complementary approach would be to field a fleet of gliders with similar instrumentation as BGC-Argo floats along cross-stream tracks spanning the plume (Figure 4.4, bottom panel). Relevant questions for this observing platform are:

1. What is the required resolution of the glider array in the along-stream direction (Δx)?
2. How often must the gliders be reset to maintain spatial coverage of the plume?

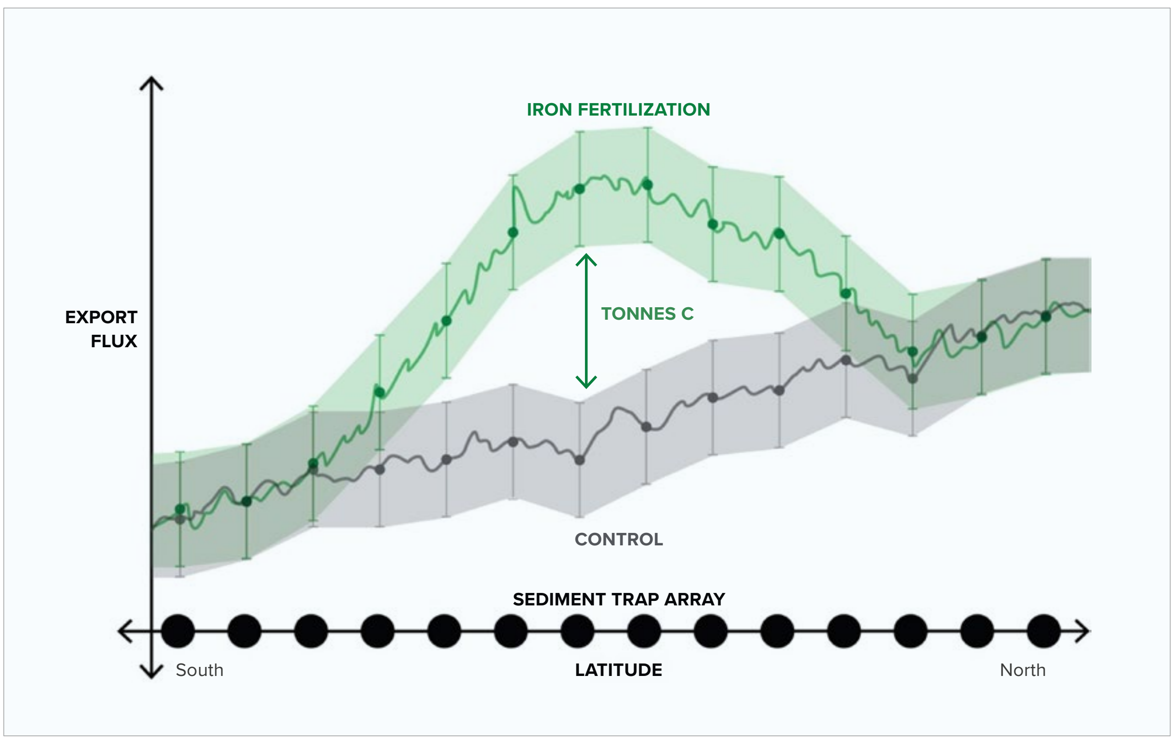

Figure 4.5. Expectations for observations of carbon export flux (y-axis) along one of the sediment trap sampling lines in Fig. 4.4. (x-axis) here conceptualized for conditions where sampling transect crosses both impacted and non affected waters (green points and shaded uncertainties) and a control prior to iron additions (gray points and shading). The key parameter to be quantified in this example would be the additional tonnes of C that result from the OIF experiment that reach the depth of the centennial tonne. In this example, multiple observations along several transects would be integrated to determine the additional net carbon that reaches durable depths.

Although gliders are capable of significant headway, their speed will be no match for the fronts and eddies they will undoubtedly encounter. Tracks oriented in the cross-stream direction will help minimize their downstream displacement, but it is only a matter of time (τ_G) before the upstream glider will need to be replaced.

In this report, we are calling OSSE designed observing systems "Ocean Iron Observatories" (OIOs). The OIO concept fits the phase I and II research plan (see Section 9. Decadal Plan), whereby the end of phase I, we will have determined the most efficient and bioavailable forms of iron and delivery systems, and expanded the use of AVs for iron delivery, MRV, and eMRV to enable establishing OIOs in multiple settings. It is important to recognize that such OIOs must be put in place in advance of the iron fertilization field trial and persist for some time afterward. Specifically, the precursor is essential to measure the background conditions and their variability. Again, the OSSEs will provide guidance on a key question: how long must the OIO be in place to sufficiently characterize the unperturbed state? Similarly, how long must the OIO be kept in place to document whether or not the ocean returns to its unperturbed state after completion of the field trial? Answers to these questions are not straightforward given the tremendous range in the scales of variability, from seasonal to interannual.

4.2.4 ASSESSMENT OF THE DURABILITY OF OIF CDR ACTION

Carbon accounting of an OIF CDR action requires an assessment of both the amount of atmospheric carbon sequestered as well as the timescale that the carbon remains within the ocean. This we refer to here as durability (Figure 4.1). For a passive tracer injected within the ocean, there will be a distribution of contact times with the surface ocean ranging from months to millennia (8). This is because there are an infinite number of paths connecting a given location in the ocean interior to anywhere at the sea surface. This requires metrics to be defined to describe the distribution of OIF CDR durability. Figure 4.6 shows the spatial distribution of the retained fraction of biologically fixed dissolved inorganic carbon mimicking typical remineralization profiles for the ocean biological pump. Global mean

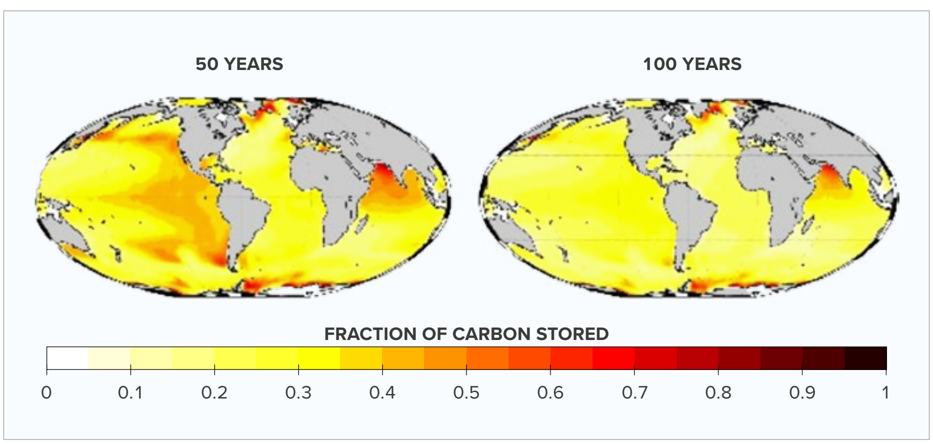

Figure 4.6. Map of the fraction of carbon stored as a consequence of OIF for periods of 50 years (left) and 100 years (right) assuming an average remineralization rate vs. depth as characterized by using the parameterizations b=0.8 as in Martin et al. (27). Based on modeling work in Siegel et al. (8).

retained fractions after 50 years are ≈32% and are ≈25% after 100 years. Substantial geographical variations are also found with higher retention fraction values in the eastern Pacific and northern Indian Oceans and lower values in the subtropical North Atlantic Ocean. We expect that these geographic differences will be important for assessing OIF CDR durability.

The assessment of retention as a function of time can also be used to quantify the durability distribution of a given OIF event (Figure 4.7). Here, OIF CDR durability vs. time profiles are modeled for three potential sites for large-scale OIF CDR experiments using the inverse model solutions provided in Siegel et al. (8). The three sites are the Subarctic North Pacific, the central Equatorial Pacific, and the Southern Ocean near the SOIREE field site. Remineralization profiles are based upon a Martin flux vs. depth relationship but with b values ranging from 0.8 (typical global value) to 0.3 (which should be more representative of export after an intense phytoplankton bloom). For all three sites, the timescale where OIF CDR will be retained in the ocean decreases rapidly in the first 10 years. After that, it decreases much more slowly, with 100-year retention fractions ranging from 20 to 50% depending on the site and the assumed b value. Retention fractions are larger for the Equatorial Pacific than for the Southern Ocean. It should be noted that the durability distributions presented here assume instantaneous air-sea gas exchange. Inclusion of equilibration of CO_2 with the atmosphere would cause the initial values of these curves (time = 0-years) to be zero and not one. Similarly, finite-time equilibration of CO_2 between the ocean and atmosphere could limit the outgassing of sequestered atmospheric CO_2, increasing durability. Further research on these issues is clearly needed.

The assessment of OIF CDR durability requires global circulation models to determine the long-term fates of the sequestered carbon. Durability assessments can be based upon steady-state assumptions of present-day ocean circulation processes (8, 74, 75) or they can use time-dependent circulation reflecting climate change (76). As described above, the Siegel et al. (8) durability figures presented here also assume that air-sea gas exchange occurs instantaneously. However, in much of the ocean, the carbonate system equilibration time can be many months, and circulation and mixing process can limit the time that the upper ocean is in contact with the atmosphere (24). Both of these processes will reduce initial in-gassing of atmospheric CO_2, especially in high latitude regions where deep seasonal mixing and slow CO_2 system equilibration rates are found (77).

4.2.5 DEVELOPMENT OF MRV MODELING SYSTEMS FOR OIF CDR

If OIF is to be conducted at scale as a CDR solution, the monitoring, reporting, and verification (MRV) of any OIF action almost assuredly will be provided using data-assimilating models that integrate available data sources. Models are required as it is not possible to fully observe additionality, leakage, durability, and desired and undesired environmental effects over the required spatial areas and time periods, which range from regional to global and months to centuries, respectively. This necessity is common to almost all mCDR methods and has been discussed extensively in the literature (e.g., 24, 78, 79). These models must provide not only information for carbon accounting of the OIF action (MRV), but also an assessment of the ecological and biogeochemical impacts of the OIF action (eMRV) if OIF is to gain social license to be conducted at scale.

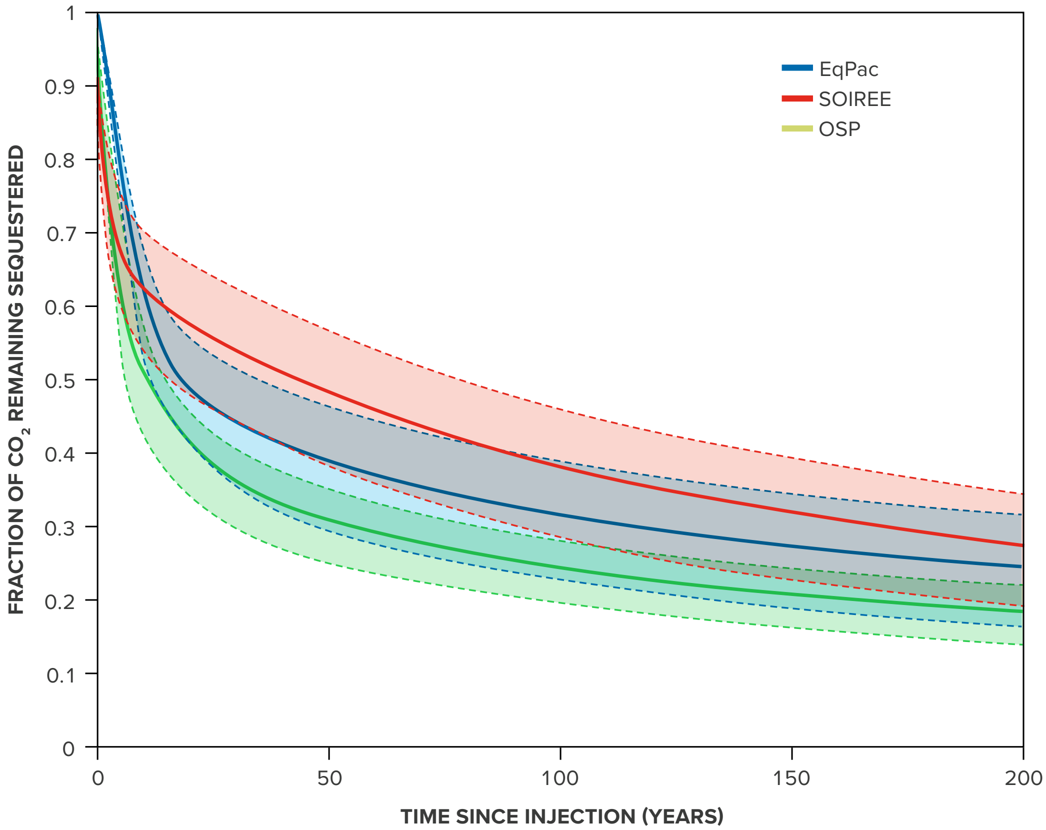

Figure 4.7. Fractions of carbon that remain sequestered (y-axis) vs time (x-axis) projected via models for the Equatorial Pacific (blue); Southern Ocean SOIREE site (red); and Ocean station P (OSP- green). The data fall within the envelope of shading (dashed lines) derived using variable remineralization rates, with a lower bound for lower carbon flux attenuation (b=0.3; characteristic of some diatom blooms) and upper bound for higher/faster remineralization vs depth (b=0.8; more typical of global ocean with average remineralization).

Local (km) to basin (1000s of km) scale MRV assessments will require data-assimilative model systems, based upon the OIF models and OIOs designed with OSSEs at a much larger scale. **These modeling systems need to assimilate regional-scale data as well as appropriate local-scale observations to assess both the critical carbon flows for MRV, but also the ecological and biogeochemical impacts needed for eMRV** (see Section 6. MRV). The field studies as outlined in this report will provide the intensive data needed to develop and validate these coupled MRV/eMRV modeling systems for OIF. Most importantly, these initial field studies will help identify the most important data observations needed to accurately and most economically assess the efficacy and impacts of OIF CDR when or if conducted at scale. This process of iterative model tuning to observed data from OIF pilot studies will also provide bounds for model prediction uncertainty needed to help value carbon credits or other instruments in financial markets.

CDR durability requires global circulation models to determine the long-term fates of the sequestered carbon

There are many advantages of using coupled MRV/eMRV modeling systems. First, model simulations can be run with and without the OIF perturbation, providing the counterfactual or control simulation to assess additionality. This may be particularly useful for regions where the background state is changing rapidly in time or is highly variable spatially. Second, these modeling systems should be shared as open-source codes, enabling all institutional stakeholders (OIF CDR providers, governmental regulators, private industry) to assess the results. Third, these models should be made publicly available so that the OIF CDR community can work collaboratively with all stakeholders to develop products that directly serve their needs in decision support systems. This will help CDR actions to be more equitable and transparent for all stakeholder groups (79).

The development of a coupled MRV/eMRV modeling system will be required if and when OIF CDR is deployed at scale. They will be based upon the OIF models described in Section 4.2.2 that must be developed now and will require the results of multiple field studies from potentially multiple regions to best develop and validate their predictions and the uncertainties. However, the rapid development of the OIF OSSE models proposed here needs to consider their eventual MRV application.

4.3 Timeline

To accomplish these objectives, it will be necessary to convene a consortium of expert groups to (1) assess the efficacy of various iron fertilization approaches in the candidate locations using model simulations, (2) carry out OSSEs to define the required OIOs, and (3) engage with a systems engineering team to create an implementation plan. This multi-model consortium approach is required due to the variations in iron cycling and ecosystem response of state-of-the-art models. A rough timeline for the work to be carried out is:

- **Year 1** – Definition of experimental protocols and initial round of simulations
- **Years 2 to 3** – Analysis, engineering assessment, revision of protocols and second round of simulations
- **Years 3 to 5** – Analysis, engineering assessment, phase II implementation plan, and publications

4.4 Priorities and costs

The total cost of these activities over five years is estimated to be \$16M (see Table 9.1 in Section 9. Decadal Plan). This consists of a leadership and project management team funded at \$300K per year; an OSSE modeling effort to plan NE Pacific and subsequent field planning at \$500K per year; approximately four OIF modeling groups funded at \$500K per year; and a systems engineering team stood up in the second year and funded at \$500K per year.

4.5 Synergies and impact

Execution of this work plan will lead to the definition of observing requirements for OIF field trials. It will also prepare the way for real-time modeling during execution of the pilot studies. Moreover, progress on OIF modeling, OSSEs, and durability estimation will also provide vital information on how OIF could be scaled up for climate mitigation if the field trials prove to be successful.

5 STUDIES OF IRON FORMS AND DELIVERY MECHANISMS

5.1 Overall needs and goals related to iron uptake and delivery

Adding iron (Fe) to high-nutrient, low-chlorophyll (HNLC) regions of the ocean stimulates the growth of phytoplankton and the fixation of carbon dioxide, whether that iron is added from natural sources such as aerosol dust, seafloor sediments, wildfire and volcanic ash, or as acidic $FeSO_4$ as in previous large-scale artificial ocean iron fertilization (OIF) experiments. However, the efficiency of iron addition in terms of CDR per atom of added iron can vary dramatically based upon: 1) the tendency of different forms of iron to dissolve in seawater, 2) the bioavailability of different dissolved iron species to phytoplankton, and 3) the propensity of phytoplankton fertilized in different ways to sink into the deep ocean. **When developing methods for ocean CDR by OIF, the cost, carbon footprint, and scalability of different forms of iron delivery must also be considered**. A crucial near-term goal of OIF research is therefore to rigorously test and compare different forms of iron and delivery methods, with the goal of maximizing the efficiency and minimizing the financial and carbon cost of OIF.

The efficiency of carbon export for previous mesoscale OIF experiments has generally been low, with estimates suggesting that only ≈1% of added iron was required to stimulate additional sinking biomass, while ≈99% of added iron was lost to precipitation or other abiotic fates (6, 80). The low carbon export efficiency was caused by a variety of reasons. Much of the added iron is quickly converted to particulate forms and is lost to sinking before it can be used by phytoplankton. Some of the added iron is bound to weak or non-bioavailable ligands causing it to precipitate before biological uptake can occur. Phytoplankton may take up more iron than needed (so called 'luxury uptake'; 81), further reducing biomass accumulation per iron atom added . Even when iron is taken up biologically, leading to increased phytoplankton growth, those phytoplankton may be consumed by grazers, leading to release of their iron and carbon before the phytoplankton have time to sink into the deep ocean.

Evidence from natural iron fertilizations suggests that much higher efficiencies of artificial OIF carbon export should be possible. Sustained releases of iron into the Southern Ocean from islands, wildfire ash, and volcanic ash have all led to increases in productivity and/or export (26, 82, 83, 84). The biological Fe:C ratio for uptake into Southern Ocean phytoplankton is greater than 1:20,000 on a per weight basis (81), yet the typical Fe:C ratios of sinking phytoplankton are higher (85), suggesting that much iron can sink without bringing carbon with it (86). In warmer regions, the opposite seems to be true, with phytoplankton showing the capacity to recycle iron for growth in the surface ocean even while driving the downwards export of macronutrients and carbon (87, 88). A key factor in the efficiency of natural OIF seems to be the gradual addition of iron over extended time periods, which allows phytoplankton blooms to sustain high rates of growth until the phytoplankton reach a high density and aggregate, which promotes sinking into the deep ocean.

A remarkable diversity of methods have been proposed for OIF (Tables 5.1 and 5.2). These include a wide variety of iron-bearing materials including everything from purified chemical iron, to various nanomaterials, to inexpensive natural and waste materials containing iron. A range of delivery methods have been proposed as well, from the traditional approach of pumping dissolved iron from a vessel, to sprays of aerosolized liquid or powder, to electrochemical dissolution of metal plates. Methods and materials will each be suited to different craft, from autonomous gliders to boats to airplanes. Below we suggest a framework for effectively determining which solutions are most appropriate for climate change mitigation by OIF.

5.2 Key areas of effort

We propose a strategy for testing the chemical and biological activity of different iron addition methods in an organized and standardized fashion or, in simple terms, a 'bake-off'. Below we lay out a strategy for this process, including the key metrics that should be assessed for each method, and a planned infrastructure for testing different methods in a bake-off.

5.2.1 KEY MATERIAL METRICS

Iron solubility – The expected solubility of free iron in seawater is below ≈10 pM, but additional dissolved iron can be maintained via binding of iron to organic ligands and formation of stable colloidal phases. Indeed, the reason why OIF may succeed in HNLC regions is because of the low concentrations of natural iron in the oceans. Iron readily precipitates out of seawater, leaving little behind for phytoplankton. Initial tests should seek to determine the ability of different forms of iron to dissolve in seawater. Each material may have different solubility limits, with some materials precipitating when added at too-high concentrations and others able to maintain their solubility over longer periods of time, which will be important to allow for dispersal in the oceans. Crucially, the apparent solubility is expected to be quite different in the absence or presence of biology, both because of the potential for microbial solubilization (e.g. production of organic ligands and siderophores), and because microbial production of particles may seed aggregation of inorganic iron colloids. Thus, incubations of each material with natural ocean microbial communities will be important. Solubility is necessary to maintain iron in seawater without precipitation and sinking, and is a necessary, though not the sole requirement for bioavailability. Iron solubility is the easiest metric to test, simply by filtering seawater samples and measuring iron concentrations.

Iron bioavailability – Oceanographers view the solubility of metals as crucial to their chemical and biological reactivity, yet the term 'dissolved' is operationally defined and refers to any iron that can pass through a 0.2 μm filter. Thus, 'dissolved' iron can include anything from individual Fe^{3+} ions, to iron atoms bound to complex organic molecules, to small colloidal minerals. While iron solubility is easier to test simply by filtering samples, biological assays must be used to test for iron bioavailability, such as the ability of waters to relieve iron limitation in cultured and natural phytoplankton communities

Iron persistence – The efficiency with which iron stimulates aggregation and sinking of phytoplankton when supplied slowly, compared to a larger single input of iron, means that the persistence of iron in the surface ocean may have a large impact on the eventual CDR potential. Some materials are designed to release iron slowly over time, providing a continual source of new dissolved iron to the oceans, while other materials provide a one-time iron release. The persistence of iron is certain to depend on both the chemical and biological activity of seawater, and thus while early experiments can be performed on sterile water, later experiments will necessarily involve experiments with living phytoplankton and eventually with complete microbial communities.

Ecological compatibility – In addition to delivering iron effectively, it is important that the source of iron have minimal side effects and achieve social license. Both real and perceived possibilities for side effects may make 'natural' materials that mimic pre-existing pathways of iron supply more amenable to deployment. Some of the iron fertilization materials being considered include organic components that may stimulate heterotrophic growth or contribute to light shading. These aspects will also need to be evaluated.

TABLE 5.1. POSSIBLE FORMS AND METHODS OF IRON ADDITION

CHEMICAL FORMS OF IRON
$FeSO_4$ mixed with HCl has been used in all previous in situ OIF experiments. This provides a benchmark for comparison with other methods. The $FeSO_4$ material is relatively inexpensive and has been shown to promote phytoplankton growth, but it is not very efficient at promoting carbon transfer to the deep ocean and thus might require more ship time for deployment.
Natural materials of various sorts have been proposed such as glacial till, silt, natural Fe oxyhydroxides, and volcanic ash. In general such materials are expected to be minimally soluble in seawater, and they must be provided with an extraordinarily small grain size in order to prevent sinking.
Engineered nanomaterials can be produced with a variety of characteristics which are tuned to deliver Fe effectively. Their small size will keep them suspended in solution, at least prior to precipitation. The particles could possibly be tuned to deliver Fe over the most impactful timescales (e.g. weeks), and they could potentially be doped with other elements of value including micronutrients (e.g. Zn, Mn) or anti-fouling materials (e.g. Cu).
Buoyant rice husks coated with Fe have the potential to release Fe over impactful timescales (e.g. weeks), and to ensure that Fe is continually delivered to the upper ocean where light is available. The use of rice husk water reduces manufacturing cost.
Biogenic iron hydroxides might be produced with ideal chemical and physical attributes such as small size so that they remain suspended and slow dissolution to release Fe over appropriate timescales. Experiments to develop this technology are still in early stages.
Other novel forms such as electrochemically released Fe ions from float platforms may be developed.
DELIVERY MECHANISMS
Ship-based dissolved The only method employed so far for Fe delivery to the oceans has been to release dissolved Fe from a ship. In this case, vessels typically spend a few days at the start of each experiment transecting the future patch area back and forth, sometimes referred to as 'mowing the lawn' or 'sowing the lawn'.
Ship-based aerosol The spatial reach of a single ship might be increased by 'spraying' aerosolized Fe into the air. This method has been previously employed to spray seawater into the air for pilot-scale cloud brightening work. The chemical form of Fe coupled to this delivery mechanism is not yet certain, and a wide variety of dissolved and particulate Fe substrates could be coupled with this spraying method.
Land-based aerosol Yet larger regions of the oceans could be fertilized with land-based spraying. Such methods might put Fe higher into the atmosphere so that it 'rains down' over a large geographic area. In this case the atmospheric processing of the Fe aerosols might be expected to have a large impact on their chemistry and Fe availability. Aerosols also impact on Earth's radiative balance, and so the optical properties of such aerosols should be considered, and darkly colored aerosols will likely need to be avoided.
Electrochemical The electrochemical reduction of Fe metal provides a very different means to release Fe into the oceans. The oxidation of Fe in seawater is thermodynamically favorable, so that the energy requirements of this method are relatively modest. The ability to deliver Fe to the oceans directly from a solid phase opens up several novel pathways for release, for example from small autonomous floating platforms run by photovoltaic panels, or long wires covering large distances.
OTHER CONSIDERATIONS
Isotope spiking might be used to trace added Fe through the food web, and eventually into the deep ocean with sinking carbon. Geochemical techniques which have been developed to analyze earth materials are extraordinarily sensitive, being able to measure stable isotopes at parts-per-million deviations from natural abundance ratios. Thus, even a small amount of stable isotope might be traced in the natural environment.

5.2.2 KEY DELIVERY METRICS

Optimum amount of iron to add – Previous OIF experiments have typically aimed for surface ocean iron concentrations of 1-2 nM, roughly 10-fold higher than typical background HNLC iron concentrations, and more similar to concentrations in the dust-rich North Atlantic. However, the impact of varying iron concentrations on phytoplankton growth and carbon sequestration has not been tested from the perspective of maximizing carbon export. To optimize iron additions for OIF, additional experiments are needed to evaluate the efficiency of iron for stimulating carbon uptake at varying iron concentrations, with effective iron forms, in various HNLC regimes.

Optimum addition timescale – Evidence from previous natural and artificial OIF events suggests that adding iron slowly over a long period of time leads to both the greatest increases in phytoplankton biomass and the greatest export of carbon during bloom termination. However, there is a lack of experiments designed explicitly to test the impacts of the iron addition timescale on the bloom dynamics and carbon export. Additionally, it is possible that some iron delivery methods may release iron too slowly such that fertilized waters will sink or be subducted prior to stimulating growth, or that only a minor stimulation of growth is realized, and is not enough to cause a bloom followed by increased export.

Location dependence of response – Finally, we note that all of the metrics discussed above are likely to be differentially expressed in different biological regimes. Thus it will be important to test materials and methods in a variety of laboratory and natural settings.

5.2.3 A PROPOSAL FOR A TIERED IRON “BAKE-OFF”

Like a bake-off among pastry chefs, we envision a series of experiments of increasing difficulty and complexity, with only the highest-performing ‘contestants’ taken forward to the final, most complex experiments.

Challenge 1 – Simple laboratory experiments will be used to test as many different materials as possible, allowing a wide diversity of approaches to be compared. These experiments will focus on the solubility of different iron forms in artificial seawater with no added organics, in artificial seawater with known ligands, and in filtered seawater with natural organic ligands. Both initial solubility and the persistence of dissolved iron over time will be tested. Next, this seawater will be used in simple bioassays to determine the bioavailability of dissolved iron from each source to supply iron to phytoplankton in culture. Various types of representative phytoplankton, with varying iron uptake capabilities, will be used in these bioassays. Standardized experimental protocols will allow for each substrate to be tested in the same way.

Challenge 2 – Large-scale natural water incubations will be the core activity of the bake-off, moving experiments towards more naturalistic conditions. Recently developed 110 L PERIcosms (Pelagic Ecosystem Research Incubators) are designed to incubate complex, diverse, natural ocean microbial communities for timescales of weeks to months in trace-metal clean conditions. PERIcosms are designed with side ports for sampling the dissolved phase and a sediment trap to collect sinking material. They are inexpensive enough that as many PERIcosms can be built as needed to test all of the best-performing iron materials. We envision a series of PERIcosm experiments taking place using natural ocean water from various HNLC regions and other locations. At each location a large tent will be set up for the experiments, several tonnes of seawater will be collected for incubations, and the most promising iron-addition schemes will be tested in naturalistic ocean conditions. Key metrics will include the solubility of iron as mediated by natural biological processes, the ability of each substrate to relieve iron limitation and stimulate biomass accumulation, and the impact on export of carbon to the sediment trap.

Challenge 3 – Integration with ExOIS fieldwork will follow the main bake-off activities. During this phase the technical feasibility of deployment for large scale *in situ* OIF will be a primary consideration. Extensive knowledge about factors that most effectively promote growth and sinking of phytoplankton will inform the strategies for iron addition.

5.3 Timeline

It is crucial for these early-stage experiments to be completed as quickly as possible, so that information can be used when developing the large-scale *in situ* ExOIS OIF activities. During year 1 we would recruit new team members, as well as international partners, and start small-scale laboratory testing. Laboratory testing would conclude in year 2, with conclusions being drawn regarding the most promising materials. Focus and effort would then move to planning for the main bake-off and implementation in the large-scale PERIcosms at multiple distributed sites in years 2-4. Year 5 will culminate in a report of key findings to the ExOIS team, followed by manuscript publication and presentation at scientific meetings.

5.4 Priorities and Costs

Management – A dedicated management team should be funded to coordinate bake-off activities. A management team can take responsibility for coordinating the international community in developing standardized metrics for testing various forms of iron for delivery. This team can also coordinate large-scale collaborative experiments, ranging in scale from receiving materials and performing simple initial tests, up to coordinating large-scale collaborative experiments in various locations worldwide in which all project participants are invited to send personnel to participate. Costs on the order of $150K per year split among a small management team would be needed to fulfill these responsibilities ($750K over 5 years).

Method-specific grants – Many individual methods require a more dedicated effort to test and develop their substrates and methods. Ideally there would be a centralized coordination of funding for these efforts, though in some cases scientists may pursue independent funding in coordination with the support and coordination of the management team. Several Individual grants on the order of $300-400K each would total $2.0M in the first 2 years of this effort.

International Bake Off activities – Developing social license for OIF will require the involvement and engagement of scientists from across the globe, and testing the various forms of iron provides a key opportunity to develop international collaborations early. In addition to testing many of the materials in Table 5.1, testing

Testing the various forms of iron provides a key opportunity to develop international collaborations

TABLE 5.2. KEY FEATURES AND ATTRIBUTES OF DIFFERENT IRON FORMS.

Color coded by our current knowledge on their relative strengths and weaknesses.

KEY: WORST TO BEST

1	2	3	4	5

IRON MATERIALS		SOLUBILITY/ BIOAVAILABILITY	AGGREGATION /SINKING	TESTED?	COST	COMMERCIAL AVAILABILITY	CARBON FOOTPRINT	CO-BENEFITS	POTENTIAL CHALLENGES
$FeSO_4$		Bioavailable	Rapid precipitation and sinking	In situ	Low	Yes	Likely moderate	Unknown	Acidified form
Fe colloids	Engineered nanomaterials	Unknown	Unknown	Available for testing	High	Not yet	Unknown	Controlled Fe release / aggregation	Negative social perception
	Biogenic FeOX	Bioavailable	Low sinking rates	Not yet	High	Not yet	Low	Unknown	Unknow physico-chemicalcharacteristics
Fe-organic mixtures	Buoyant Fe rice husk	Unknown	High buoyancy	Meso-cosm	Low	Not yet	Low	High Si/ patch detectable	Unknown uniform distribution/ stimulate heterotrophic activity
	Organic chelates of Fe	Readily available	Unknown	Available for testing	High	Available Fe fertilizers	Unknown	Patch detectable	Stimulate heterotrophic activity
Electrochemical Fe		Possible control	Possible control	Small-scale	unknown	Not yet	Solar power	low biofouling	Devices/tuning Fe delivery rate
Fe clay minerals	Volcanic ash	Likely low	Potentially high	Natural	Low	Not yet	Low	Delivery of other nutrients	Environmental impacts of supply?

of soils as substrates for iron addition is a pathway to engage scientists from numerous countries. Scientists from each country can help to characterize those soils (and other materials) according to simple metrics, and to participate in bake-off activities evaluating their suitability for OIF. While such soils may not be as effective at promoting carbon sequestration as other methods on a per-atom basis, the social license of adding iron in a 'natural' fashion may be beneficial if suitably effective soils can be found. Additionally, experiments with a range of natural phytoplankton communities will be key to developing social license and covering a range of possible environments and ecosystem responses. This is really the key activity needed in the first 3 years, and if 3-5 groups were operating PERIcosms and evaluating impacts (see Section 3.2.3), each group would require on order \$1M, hence the single largest cost here would be up to \$5-6M for coordinated bake-offs under different environmental conditions. As with all support costs mentioned, some will likely come from individual and ongoing efforts with national resources while others will take assistance from the ExOIS program office to secure new funding.

Delivery mechanisms – In years 3-5, as we move beyond pilot studies and narrow down choices, larger scale engineering of how iron (liquid or solid) could be most efficiently delivered would be needed. The costs to fully implement such delivery will depend upon the scale of the field studies, but certainly testing and engineering of systems to deliver hundreds of tonnes of iron will be needed. We should anticipate that such efforts will cost several million dollars as we move towards consideration of alternatives, including autonomous vehicles or moored platforms. Systems engineering to design these (not to deploy) would require dedicated engineering teams working with OIF iron specialists and have high priority in years 3-5 of this effort.

5.5 Synergies and Impact

The aim of this work is to quickly determine the small handful of methods that are most promising for OIF. These methods should all be relatively inexpensive, have a low carbon footprint and low propensity for other negative environmental side effects, and be highly efficient in terms of shuttling carbon into the deep ocean. These selected methods will then be integrated into the larger ExOIS project, with *in situ* deployment and field testing during the cruise experiments and eventually deployment at the Ocean Iron Observatories.

6 MONITORING, REPORTING, AND VERIFICATION

6.1 Goals for MRV

This section describes the needs and priorities for monitoring, reporting, and verification (MRV) of the effects of potential ocean iron fertilization activities described elsewhere in the report. As defined in the introduction to this report, MRV activities assess the additionality, leakage, and durability of carbon uptake, while eMRV activities assess the ecological and environmental impacts. For MRV, additionality refers to the amount of carbon uptake that can be specifically attributed to the OIF intervention, relative to a baseline or control scenario with no intervention. *Leakage* here refers to the loss of sequestered CO_2 back to the atmosphere – for instance, because of an unexpected ecosystem feedback that leads to shallower

MRV activities assess the additionality, leakage, and durability of carbon uptake, while eMRV activities assess the ecological and environmental impacts

carbon remineralization, and thus less carbon storage than normal. *Durability* refers to the timescale that the atmospheric CO_2 taken up by the OIF action remains within the ocean. Here we specify that MRV activities must quantify the CO_2 that is removed for a timescale of at least 100 years as determined from modeled ventilation horizons (see durability discussion in Section 4. Modeling).

MRV and eMRV for OIF at scale must be provided primarily through data-assimilating models, because it is not possible to observe additionality, leakage, durability, and environmental effects over the required spatial areas and time periods, which range from regional to global and months to centuries, respectively. This necessity is common to almost all mCDR methods and has been discussed extensively in the literature, particularly with respect to ocean alkalinity enhancement (e.g., 24, 78). The goals of this section are to briefly summarize the MRV and eMRV requirements of pilot-scale OIF studies, and to identify priority areas for observational technologies that are needed to support the development, validation, and maintenance of models that will ultimately be required for any large-scale OIF deployment.

Ocean iron fertilization MRV and eMRV models will also need to include the detailed biological taxa and processes responsible for carbon uptake, and be capable of predicting biological and biogeochemical impacts under sustained OIF at scale. Machine learning algorithms, databases, and standardization practices must continue to be developed. Incorporating trait-based modeling into zooplankton and higher trophic level modules could improve model simulations.

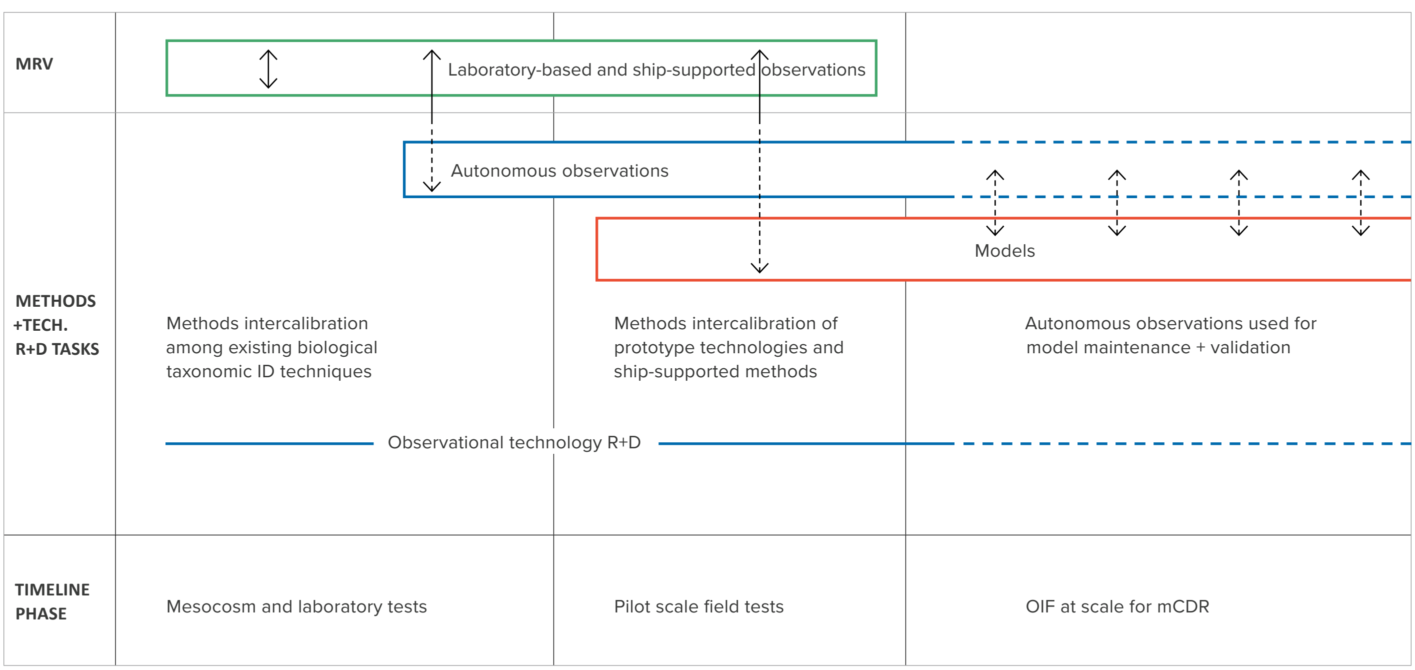

Figure 6.1. Conceptual schematic of MRV approaches and timeline

Short term (next 3-5 years) objectives include the development of observational technologies, and testing and intercalibration activities that leverage simultaneous laboratory, mesocosm, and pilot-scale ocean experiments as described elsewhere in this report. Some critical method intercalibration work (particularly of existing biological tools based on imaging, genetic sequencing, and phytoplankton pigments) can proceed immediately with existing field datasets, but for other nascent methods (e.g., novel chemical and particle flux sensors; see below), a period of intensive ship-supported observations will be required to validate new autonomous technologies prior to their long-term use in MRV and eMRV model development and maintenance. Figure 6.1 illustrates the temporal relationships among these activities. Furthermore, it is important to establish a set of standard operating procedures and best practices for use by ExOIS collaborators, and for others in the wider scientific community that wish to conduct OIF experiments.

6.2 Key areas of effort

Below, the key measurements for MRV and eMRV are summarized, and examples illustrated in Figure 6.2. These are comprehensive and all will be needed during initial mesocosm (as practical) and field studies to allow full assessment of the efficacy and impacts of OIF. With a medium-to-long term goal of transitioning to a model-based and cost-effective MRV system, there is a general need for the development of technologies in all areas that can support autonomous

Figure 6.2. Examples of potential autonomous platforms that could be used for monitoring OIF Field Studies: (top left, clockwise) 1. deep ocean time-series sediment trap, *Daniel Hentz, WHOI*; 2. Saildrone surface vehicle, Saildrone; 3. biogeochemical profiling float (BGC-Argo), *Isabella Rosso, Scripps Institution of Oceanography*; 4. Twilight Zone EXplorer (TZEX), *Kaitlyn Tradd, WHOI*; 5. MINiature IsOpycNal floats (MINIONS), *Melissa Omand, University of Rhode Island*; 6. remote sensing satellite PACE (Plankton, Aerosol, Cloud, ocean Ecosystem), *NASA*; 7. long range glider with particle and plankton camera, *Heidi Sosik, WHOI*; 8. Seaglider equipped with an Underwater Vision Profiler, *Yves Ponçon, BIOGLIDER Program*.

data collection for model validation over large spatiotemporal scales. Table 6.1 summarizes these observational technology needs.

6.2.1 MRV

MRV will require measurements or well-constrained model estimates of carbon fluxes and key biological properties that influence additionality (how much carbon export is caused by OIF), leakage (negative ecosystem feedbacks), and durability (the interaction between circulation and the remineralization depth of the exported carbon). During the next generation field experiments, these measurements may be constrained through intensive observations rather than models (with the data used for both method and model development and validation). To determine the additionality, all parameters need to be constrained both at the treated site and at unamended control sites with similar characteristics. Here, we neglect direct leakage (e.g. emissions due to iron delivery itself) that would need to be considered in a full life cycle analysis, but early estimates indicate it will be small due to the small amount of iron needed relative to carbon sequestered.

Carbon fluxes – The following carbon fluxes must be measured or modeled:

- Net organic carbon flux (both particulate and dissolved) out of the surface layer via all mechanisms of the biological pump (gravitational/migration/advection/mixing; see 89).
- Net air-sea CO_2 flux into the surface layer before it subducts
- The carbon remineralization rate profile below the surface layer, to determine the durability of carbon export.

Organic carbon fluxes and carbon remineralization rates can be observed via a number of methods, some ship-supported and others autonomous. There are no standards for these measurements and careful intercalibration, especially for emerging autonomous techniques that could be used for large-scale MRV model validation, will be a critical task during the initial field experiments. Net air-sea CO_2 fluxes may be difficult to constrain observationally due to variability and long equilibration times, and a modeling approach will be required (78). In general, observations from distributed observational and time series programs outside the OIF implementation can also be used to validate large-scale MRV models. The export and regeneration profiles of macronutrients are included as requirements for eMRV outlined below.

Biological properties impacting carbon – For the next generation field experiments (Section 2. Field studies), information about community compositions of phytoplankton, zooplankton, and vertical migration more generally (also required for eMRV, below) will be needed to attribute the additional carbon fluxes to OIF intervention. The taxonomic resolution required will be site- and trophic level-specific. For example, use of functional groups for phytoplankton (e.g., diatom, dinoflagellate, diazotroph) is unlikely to be nuanced enough, and identification to genus or species level will be required for key taxa responding to iron addition. Emerging and higher-resolution taxonomic techniques should be intercalibrated with remote sensing and traditional community composition tools (pigments, microscopy) to increase efficiency and for scaling up. Diel and seasonal vertically migrating zooplankton taxa will need to be considered because of their role in carbon transfer across ventilation horizons.

Remineralization profiles would optimally incorporate bacterial and zooplankton metabolic carbon demand measurements, in order to better constrain potential nonlinear relationships between the biological response to OIF and the depth of CO_2 remineralization. Remote sensing will allow for temporal and spatial sampling of many of these biological properties and physical conditions in the surface (90).

6.2.2 eMRV

Non-carbon biogeochemical impacts – Biogeochemical shifts inside and outside of the iron-amended region will require measurements that can resolve decreases in subsurface O_2, increases in subsurface CO_2 (which can lead to hypercapnia and acidification), increases in non-CO_2 greenhouse gases (N_2O, CH_4, dimethyl sulfide), and consumption of limiting nutrients other than iron, including macronutrients and other key trace metals (some of which may be co-limiting with iron). In particular, upon alleviation of iron stress, the consumption of secondary limiting or co-limiting nutrients may have impacts on downstream productivity elsewhere in the ocean (e.g. 10), which over most timescales will need to be addressed with a modeling approach. The depth dependencies of nutrient consumption and remineralization, and the carbon-to-nutrient stoichiometries of exported organic matter, are thus key observational requirements.

Ecological and species impacts – The assessment of unpredictable ecological impacts will require broader, less-targeted measurements of community composition and biomass distributions, both in the water column and on the seafloor. These should include any commercially or socially valuable species in addition to lower trophic levels. This set of measurements is less targeted than those required for MRV (see 6.2.1) because of the need to identify unexpected changes (see 6.3.2).

Proxies for modeling adverse impacts – With a long-term goal of conducting MRV and eMRV with a data-assimilative modeling approach, the identification of "indicator" species and biogeochemical tracers whose inclusion in models could help predict linked adverse environmental effects will be a key goal (for example, harmful algal bloom species and domoic acid expression).

6.2.3 GENERAL MRV NEEDS

In addition to the specific observational requirements for MRV and eMRV, there are general needs that apply to both. Distributed measurements at scale for assimilation into models will require suitable autonomous sampling platforms. Decreases in platform cost, renewable power sources, recoverability, and ability to log more complex data streams and perform on-board data reduction would be helpful. Another early opportunity for method refinement would be the intercalibration of existing methods for assessment of biological community composition. This will include resolving measurement uncertainties relative to the size of the anticipated signal, for example limitations of optical imaging proxies for plankton in estimating carbon. Existing datasets from large oceanographic field programs are already available for this. Finally, to establish additionality of carbon uptake vs. a baseline or control scenario, techniques are required for tracking the fertilized patch extent that do not rely on parameters modified by OIF (e.g. chlorophyll or chlorophyll fluorescence) or the introduction of greenhouse gases into the ocean (e.g. the inert tracer SF_6). Knowing a priori the plankton community structure at the initiation of OIF (e.g., via remote sensing, BGC-Argo, eDNA for higher trophic levels) will also be key.

6.3 Timeline

6.3.1 MILESTONES AND DELIVERABLES

MRV observations must accompany all OIF field activities (Figure 6.1). For some parameters there are no automated, scalable observational methods, and so traditional ship-supported observations will be required. These will serve a dual purpose—first, to support decision making about the efficacy and wisdom of OIF, and second, to provide intercalibration opportunities for emerging, scalable technologies under development that can support the validation and maintenance of data-assimilative models over larger spatiotemporal scales. **Another key deliverable on the five-year time horizon is tested, intercalibrated prototypes for sensors that will be able to support long-term MRV and eMRV modeling needs.** Initial, lower-cost testing of some sensors and techniques could happen in concert with mesocosm incubation experiments envisioned for iron delivery testing experiments; others will need to be included in the next generation of field studies.

6.3.2 RISKS AND CHALLENGES

Resource challenges – The research and development, intercalibration, and establishment of a set of best practices required for observational technology development will be significant. Many of the observational requirements above are unique to OIF as opposed to other types of marine CDR activities and broadly focused MRV and eMRV technology investments (e.g. ARPA-E) may not cover all needs. The initial, five-year horizon, goals and milestones will require significant at-sea work, in many cases supported by ships. Staffing this effort will be challenging given the size and competing time priorities of the existing oceanographic research community. A significant investment in training will probably be required. Some savings could be gained by leveraging mesocosm-based activities for some aspects of in-water MRV (but probably not eMRV) technology testing, and site-specific data mining activities, prior to new field experiments.

Scientific risks and challenges – In some cases the sensitivity of available observational methods may be insufficient to constrain the carbon and ecological effects of pilot-scale activities because of strong background variability or effects that take a long time to emerge. Decisions about scaling up may have to be made on the basis of model-based MRV and eMRV alone. The development of untargeted ecological monitoring methods has the potential to provide early warning of unintended impacts on critical species or ecosystems, but the complexity and size of such datasets introduces a risk that key effects will be missed during initial studies. This could be ameliorated, in part, by investing in sufficient scientific effort to interpret the data in near-real time. Finally, the observational data and modeling outputs from all OIF CDR activities must be made public in a findable, standardized format as soon as they have been quality-controlled, and certainly prior to publication through traditional scientific channels. Establishing and implementing the necessary policies will require significant effort due to the complexity and sensitivity of the datasets.

TABLE 6.1. KEY AREAS FOR TECHNOLOGY DEVELOPMENT FOR MRV

MRV NEED	OBSERVATION	R&D PRIORITIES FOR OBSERVATIONAL TECHNOLOGIES
Carbon	Net organic carbon flux out of surface layer	Sinking POC flux
		DOC concentration
		Vertical migrant biomass distributions
	Net air-sea CO_2 flux	None – see Bach et al., 2023 (24)
	Remineralization rate profile	Sinking POC flux
		Carbonate system parameters
		Taxonomic identification tools
		Modeling of higher-trophic level processes
	Biological processes impacting C uptake	Taxonomic identification tools (eDNA, imaging)
		Modeling of higher trophic level processes
Environmental	Non-carbon biogeochemical impacts	Carbonate system parameters
		Non-CO_2 greenhouse gases
		Macronutrients and co-limiting trace metals
	Ecological and species impacts	Taxonomic identification tools (eDNA, imaging)
		Remote sensing and in situ optical proxies for phytoplankton types
	Proxies for modeling adverse impacts	Taxonomic identification tools (eDNA, imaging)
		Tracers of adverse biogeochemical processes (e.g. domoic acid)
General	Autonomous platform development	Renewable/rechargeable power sources
		Recoverability
		On-board data processing for taxonomic identification tools
	Intercalibration of existing methods	Intercalibration and constraining signal:noise of taxonomic identification tools from existing datasets
	Techniques for tracking patch	Development of water mass tracers other than Chl, SF_6

6.4 Priorities and costs

Costs for MRV and eMRV observational method development generally fall into four categories:

1. Intercalibration of community composition measurements
2. Sensor and platform development, testing, and intercalibration
3. Patch-tracking techniques
4. Data-assimilative MRV model development

Of these, category 3 is likely to be supported as part of the design of the next generation field studies (see Section 3. Field Studies), and requirements and costs for category 4, which could also be supported using observations from time series programs and distributed observational networks, are discussed in the Modeling Section 4 of this report. The intercalibration of existing methods for characterizing biological community composition (category 1) is an activity that could be undertaken immediately using large field datasets that are already in hand (e.g. from the NASA-funded EXPORTS program). Two to three standalone projects, each at $500-600K over the first 3 years, focusing respectively on phytoplankton, zooplankton, and microbial consortia, could provide validation and analytical tools for use in field studies. The development, testing, and intercalibration of sensor targeting measurements listed in Table 6.1 and platforms that can sustainably carry them, is a more complex cost exercise. Field testing would ideally be able to leverage the investments in pilot studies that are envisioned (see Section 3. Field Studies).

Federal agencies and private investors whose primary focus is on CDR may support development of some, but not all, of the necessary sensors, particularly those that are specifically required for eMRV but not MRV (e.g. non-CO_2 greenhouse gases, eDNA). On the other hand, sensor and platform development is of interest across the mCDR landscape and oceanography in general, and may have a broader potential base of support. A ballpark budget of $1-5M per development team might be appropriate if field costs are leveraged, but this would depend strongly on the complexity and initial technological readiness levels of various sensors and platforms. Total support on the level of $16M over 5 years specific to OIF MRV and eMRV technologies would thus be warranted on top of other ongoing programs, such as ARPA-E for carbon sensors and agency and foundation technology grants (summarized in Table 9.1).

7 SOCIAL SCIENCE AND GOVERNANCE CONSIDERATIONS

7.1 The need for social science and governance research in early phases of OIF studies

Attention to social dimensions, governance considerations, and public perceptions of OIF will be essential to include in the next generation of OIF field trials. **A central goal of this work is to develop the knowledge needed to make decisions about where, when, under what conditions, and at what scale OIF might be responsibly implemented.** Research on these topics must be fully integrated with the scientific and engineering work associated with field trials.

OIF field trials will necessarily involve activities both onshore and in the ocean—a global common—and thus could raise social and governance issues at both the domestic and international levels. Understanding the international and domestic legal frameworks within which OIF field trials, and any subsequent OIF deployments, is an essential starting point for engaging on these issues. It will be important to identify both strengths and weaknesses in existing frameworks and explore possible alternatives that may be better suited to achieving environmental and social objectives. The intersections between legal and social considerations (e.g., whether and how the legal framework impacts public perceptions of OIF) should also be considered.

In the context of an approach with a legacy of historical controversies (91, 92), it will be particularly important that field trial research explores OIF's social license to operate. Research is needed that examines if, and under what conditions and configurations, OIF might be socially acceptable, or not (93). Research is also urgently needed to understand the potential impacts of different possible OIF approaches to human communities and the resources that they depend on (e.g., fisheries, food security, incomes, livelihoods), as well as the intangible ways (e.g., aesthetic, spiritual, cultural) that OIF might affect the spaces that they live in.

Field trials should be viewed as an opportunity for broader engagement with governments and others about OIF

The research proposed here must work in synergy with social science and governance research on OIF, and be integrated into the broader OIF research agenda in alignment with societal needs, values, and priorities. To ensure research is done responsibly and is attentive to these societal considerations, social and governance research should accompany early-stage field trials and inform decision-making about scaling up trials (94).

7.2 Key areas of effort

We propose six key areas of work that will be important to accompany and integrate with the other OIF research activities described in this report. These work areas would be done simultaneously, and in many ways would inform each other; these sub-components should be understood as intertwined and overlapping.

7.2.1 ENGAGEMENT WITH DECISION-MAKERS

Active engagement with government decision-makers, including regulators, will be needed prior to beginning any OIF field trial. Depending on where a field trial takes place and the precise activities involved, it may be subject to various environmental reviews, permitting, and other legal requirements. Compliance with those requirements is, of course, essential but should not be approached as merely a "box-checking" exercise. Rather, the field trials should be viewed as an opportunity for broader engagement with governments and others about OIF. Such engagement will ensure that the field trials are designed in a way that yields useful information to enable governments to make decisions about whether and/or how to move forward with OIF and the associated governance needs.

The research team will work to promote open dialogue with government decision-makers and other key stakeholders. We will conduct briefings with government officials and other stakeholders, sharing information about the current state of the science regarding OIF, key knowledge gaps and research needs, and the proposed field trials. The briefings should not be "one-way", however. An important part of the briefings will be soliciting feedback about, among other things, the information decision-makers need to develop effective governance frameworks for OIF. This will help to ensure the field trials are designed and conducted in ways that provide decision-useful information.

7.2.2 RESEARCH ON GOVERNANCE FRAMEWORKS

In addition to the engagement described above, there is also a need for complementary legal research to assess strengths and weaknesses in existing governance frameworks for OIF, and reforms that may be needed to ensure that any future deployments minimize risks, maximize benefits, and advance just outcomes.

The U.S. National Academies of Sciences recently called for additional research into OIF governance. In particular, the Academies recommended "normative research, exploring what a model international legal framework [for OIF and other ocean CDR techniques] would look like" (1). Prior research on this topic has primarily focused on ways of adapting the existing global ocean governance regime to regulate OIF. For example, there has been significant prior work discussing the regulation of OIF under international ocean agreements, such as the London Convention and Protocol. Comparatively little attention has been given to the position of OIF in the global climate regime and whether or how that regime could be used to effectively regulate OIF. That will be a core focus of the governance research. **We will also explore the potential for developing a new international compact governing OIF or perhaps mCDR more broadly**, and identify key elements that would need to be included in such a compact. Finally, domestic laws relevant to the OIF field trials, and any subsequent longer-term deployments, will also be assessed.

7.2.3 COMMUNITY ENGAGEMENT

One of the key challenges and urgent needs for OIF is developing a complete understanding of the range of stakeholders relevant to OIF. This delineation of 'possibly affected groups' will need to be developed in conversation with other aspects of OIF research, such as initial understanding of downstream locations via oceanographic modeling. It will also be important to give particular attention to groups that have been historically excluded from decision-making on ocean spaces, such as communities in the Global South and Indigenous groups. It is important, in particular, that Indigenous knowledge holders are included in the research process and that OIF research respects principles of meaningful consent, following the United Nations Declaration on Rights of Indigenous Peoples.

Work to engage communities on OIF will begin with efforts to identify possible affected groups and possible marine activities that might be affected by OIF research deployments. This will be conducted via an expansive literature review of current and past human uses of marine spaces in these locations (e.g., historical, ethnographic, economic, marine spatial planning research and data). It will also be conducted via engagement with NGOs, governments, and civil society groups who may have knowledge of locally relevant groups at different possible OIF sites. Attention will be given to the people that might be affected by OIF deployments at the key sites under consideration for field trials. In particular, early field studies in the NE Pacific need to engage bordering Alaskan and Canadian communities, including First Nations and Alaska Natives.

Community engagement activities, in the form of deliberative small group work (95, 96), will explore not only views of support or opposition to ongoing research on OIF, but more broadly, what groups' central priorities are, and whether OIF may or may not align with these priorities. Engagement work will explore conditions of support and opposition, as well as potential alternative approaches that might be considered preferable to OIF. Given that coastal communities have localized knowledge about how they use marine spaces critical to assessing risks and co-benefits of technologies like OIF, these insights will also be explored and will provide inputs to the work (discussed below) on assessing socio-ecological impacts. Crucially, community engagement on OIF, like other forms of carbon removal and other technologies more generally, should involve, to the extent possible, the active co-creation of research priorities with these groups. This might involve, for example, understanding what are the key concerns and priorities of these groups (e.g.,

It will also be important to give particular attention to groups that have been historically excluded from decision-making on ocean spaces

regarding fisheries, economic livelihoods), and explore how research to address these might be integrated into, and advanced by, the broader OIF research agenda.

7.2.4 PUBLIC PERCEPTIONS RESEARCH

The work on community engagement will develop an understanding of how communities most directly impacted by future OIF research and deployments might think of OIF. However, work is also needed to explore how the broader public views OIF, as this research is at present very limited (97, 98). This includes both whether they might support it or approve of it generally, and also how they might view different possible applications of OIF (e.g., across locations, materials, dispersal methods, and governance arrangements like funding, ownership, and monitoring approaches). Even less research is available on how Indigenous and Global South groups might view OIF (99). Understanding these aspects of public perceptions of OIF is essential for responsible research (93). One way to approach this is via quantitative survey research methods to evaluate larger societal views on OIF, with a particular focus on factors such as site selection, materials used, dispersal mechanisms, and political-economic considerations. Other methods, such as deliberative polling, citizens' assemblies (96), or world-wide views, may also be useful in developing generalizable data on public perceptions of OIF that might inform future OIF research.

7.2.5 ASSESS SOCIO-ECOLOGICAL IMPACTS OF OIF

Building upon ecological impact studies conducted within this broader OIF research project, this research component will investigate the socio-ecological and socio-economic impacts that might arise as a result of different OIF sites and technical approaches. Methods for this assessment will integrate the perspectives of experts, civil society, and community groups, via approaches such as ecosystem service mapping, deliberative mapping, participatory mapping, or participatory GIS (and many others; 100, 101). These approaches will all seek to translate the ecological impacts studied in phase 1 (e.g., those related to harmful algal blooms and fisheries) to understand socio-ecological and socio-economic impacts associated with particular sites. For example, fisheries-related impacts might link to impacts on livelihoods or food security. In addition to tangible instrumental uses of marine resources, this work will also give attention to impacts on intangible resources (e.g., cultural, aesthetic, spiritual; 102) that might be affected by OIF research and/or deployments. Key outcomes of this work will be a deeper understanding of possible risks, co-benefits, and trade-offs associated with different OIF locations and technical approaches.

7.2.6 DECISION RESEARCH ON OIF TRADEOFFS

A last feature of a social science and governance research agenda will involve developing a decision framework for evaluating how to select the next steps for OIF research. **Trade-offs are certain to arise between different sites, implementation methods, and research timelines—and many of these trade-offs may have implications for local communities and disadvantaged groups**, including those who do not often have a voice or access to participate in research decision making.

Structured, multi-criteria assessment approaches, such as structured decision-making (e.g., 103), offer methods for integrating research and information across multiple disciplines in ways that can help to evaluate and make decisions in the context of multiple complex and value-laden tradeoffs (104, 105), including those with important justice implications. Applying a decision research approach will enable an OIF research team to rigorously make decisions about the trade-offs associated with different locations and technical approaches. Such methods would (1) articulate these trade-offs in explicit ways, and (2) seek to ensure that representation by different groups is present in this decision making. Such an approach will help to ensure that social and justice-related considerations are given attention in decision-making about scaling OIF research in phase II of this effort.

7.3 Timeline

TABLE 7.1. TIMELINE FOR SOCIAL AND GOVERNANCE RELATED ACTIVITIES

	YEARLY ACTIVITIES					**DELIVERABLES**
RESEARCH ACTIVITIES	**YEAR 1**	**YEAR 2**	**YEAR 3**	**YEAR 4**	**YEAR 5**	
1. Engagement with decision makers	Initial mapping of groups to be engaged	Conduct initial briefings and outreach	Ongoing briefings			
2. Research on governance frameworks	Conduct research into the treatment of OIF under the global climate change regime and options for utilizing that regime to govern OIF deployments		Investigate options for developing a new international compact on OIF, including research and stakeholder outreach to identify key elements of such a compact.			2-4 peer reviewed studies on OIF governance
3. Community engagement	Conduct literature review to map potentially affected groups; liaise with broader team to understand key locations of interest for field trials	Design and conduct deliberative workshops with key potentially affected groups; make use of tutorials from public perceptions research developed in Year 1		Analyze findings and publish		2-4 peer-reviewed studies on community views on OIF
4. Public perceptions research	Initial literature review to inform survey/polling/assembly design; design instrument; collaborate with broader team to develop tutorials for what OIF deployment might look like	Coordinate cross-national survey/polling/assembly implementation (e.g., translation, recruitment); implement instrument	Analyze and publish findings			2-4 peer-reviewed studies on public perceptions of OIF across multiple jurisdictions
5. Assess socio-ecological impacts of OIF		Work with broader team to understand potential ecological impacts of OIF and translate those to socio-ecological impacts		Analyze and write-up findings		1-2 peer-reviewed studies mapping potential socio-ecological impacts of OIF across different sites and technological configurations
6. Decision research on OIF tradeoffs			Begin integrating findings across work packages; Design protocol to guide decision making across OIF tradeoffs with attention to justice considerations	Conduct decision research method to guide decision making on OIF tradeoffs to inform next steps	Analyze and publish results of study	1-2 peer-reviewed studies on scaling up OIF trials with attention to justice considerations

7.4 Priorities and costs

The activities described above will most likely involve small groups of a lead investigator with one or two postdocs. Broken down by the activities and timeline suggested above, this would require support for 1) Engagement with decision makers on order of $625K over 5 years for one group with a PI and postdoc; 2) research and governance frameworks, $675 over 4 years bringing in one team with a couple of postdocs; 3) Community engagement at about $1.2M over 5 years working in 3 locations/communities; 4) Public perceptions surveys/polls supported at a level of $1.2M over the 5 years; 5) Assessment of socio-ecological impacts $475K, which is of key importance in first 4 years; and 6) Decisions research on OIF tradeoffs, $425K during years 3-5. These costs are summarized in Table 9.1.

7.5 Synergies and impact

After five years at the end of Phase I, we will have developed a robust set of knowledge on the following:

- Feedback from key decision-makers on OIF field trials and an understanding, based on this feedback, of how to generate more 'decision-useful' information from the field trials;
- An assessment of how OIF deployments are likely to be treated under the current global climate regime;
- An understanding of the domestic laws relevant to OIF field trials and longer term deployments;
- An understanding of the options for, and political feasibility of, a new international compact on OIF;
- An understanding of which communities might be affected by potential OIF deployments, and an understanding of the types of socio-ecological and socio-economic impacts that might arise;
- An understanding of how potentially affected communities view OIF, under a diverse set of technical and political economic contexts or conditions;
- An understanding of how the general public, in both the Global North and Global South locations, view OIF and its continued research and/or deployment;
- A recommendation on how (and where, and under what conditions) OIF research might be scaled. This recommendation will be generated via a structured research process that is attentive to multiple trade-offs and their potential to generate justice-related implications.

8 MANAGEMENT PLAN

The activities of ExOIS, including those described in this report, require an organizational structure referred to here as a Program Office (PO). The Program Office would serve to represent the collective ideas of ExOIS members, and manage the resources required to accomplish the goals of ExOIS. A core organizational structure is envisioned as shown in Figure 8.1 and described below, though the structure will need to be flexible and pivot as ExOIS builds out as a research program.

The Program Office would serve to represent the collective ideas of ExOIS members, and manage the resources required to accomplish the goals of ExOIS

Some of the activities within the PO would include: seeking and management of funds and distribution of contracts and awards; the formation of steering committees and working groups specific to the activities of ExOIS, such as those outlined in this report; maintaining close communication within the ExOIS team as well as with non-ExOIS groups conducting mCDR and OIF studies; the setup and management of specific tasks such as data management; creation of web and social media content; attendance and representation of ExOIS at appropriate national and international conferences and smaller meetings; organization of ExOIS awards for activities such as postdoctoral and student support. The basic structure and guidelines provided here will adhere to the ExOIS Guiding Principles (https://oceaniron.org/our-plan/guiding-principles/), which are to prioritize efforts that benefit humans and the environment, include clear lines of responsibility, follow international laws and protocols, commit to open and transparent research, value independent assessments, and engage the public and other stakeholders.

The PO would be run by an Executive Director (ED) who would oversee operations and manage the supporting staff, who will include a project manager and others needed to facilitate day-to-day activities. Currently, ExOIS has a scientific steering committee (SC; five members plus the ED) that assist in strategic decision making. Starting in 2024, the SC members will be rotated to ensure broad scientific and multi-institutional participation, with an international balance and a range of expertise. The SC would help to establish multiple ExOIS working groups that will lead task-specific activities, such as organizing the five activities described in this report.

ExOIS is considering establishing a high-level Advisory Board tasked to provide guidance external to our group. They would meet once or twice per year to review ExOIS, and offer advice regarding ExOIS activities, including strategic planning, funding, social and legal engagements, and PO management. Through their individual stature in their own fields, and high profiles in various science, finance, social, and environmental communities, they would also become ambassadors for responsible mCDR studies in general, and for OIF in particular.

It is anticipated that financial support for ExOIS activities will be multifaceted, and will likely come from a combination of philanthropic organizations, government agencies, and commercial sources. In addition to individuals and groups that are self-supported by grants from their own national funding agencies, a major responsibility of the ExOIS PO will be to raise funds directly from potential donors. As funding is likely to come from a combination of private, federal, international, and commercial sources, management requirements will differ, such that the distribution of funds will need to include directed contracts (approved by non-conflicted SC members), competitive awards (for example postdoctoral fellowships), and competitive funding Announcements of Opportunity (AOs).

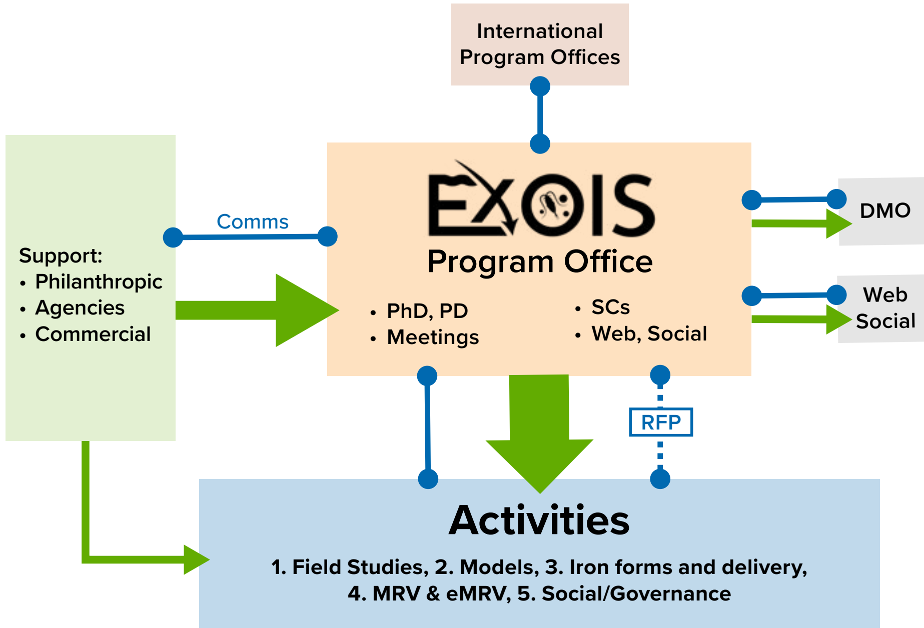

Figure 8.1. Conceptual drawing of the ExOIS Program Office (PO) and management structure. As envisioned, the ExOIS PO would be central to fund raising and managing the resources needed for the five main activities outlined in this report and as indicated in the lower box. Funding (green arrows) coming in from multiple sources could support mCDR activities directly (lower left green arrow) or pass through the PO, which may use a request for proposal (RFP) process for selecting and managing a particular activity. The PO may also fund activities directly, including but not limited to, the support needed for steering committees (SCs), for organizing meetings, engaging a data management office (DMO), organizing web and social media activities, and managing PhD and post doctoral (PD) fellowships, etc.. See text for details.

When used, AOs would be made widely known and open to all within the ocean sciences and mCDR communities. By using a RFP (request for proposal) process, with clear and transparent deadlines, and detailed guidelines, short expression-of-interest statements would be selected prior to inviting full proposals. Every attempt will be made for a streamlined review process and timely award decisions. Each AO will initially be proposed, prioritized, and scheduled by the PO and SC, given funding in hand, and activities such as set out in this report. To minimize conflict-of-interests (COI), a final AO and review process could be administered by entities standing up for specific or multiple AOs, possibly using existing groups such as Ocean Visions (https://oceanvisions.org/) or other ad hoc groups of specialists. The administration of the AOs would follow COI guidelines leading to an open, fair, and ethical review and selection process. Once awarded, the ExOIS office would be responsible for setting up contracts and tracking progress, and awardees would be responsible for reporting on deliverables, sharing data, and interacting with the larger ExOIS team.

The PO would be organized as an entity at the Woods Hole Oceanographic Institution (WHOI), an independent not-for-profit 501(c)(3) research and educational Institution in Woods Hole, MA, USA. The objectives of ExOIS are well aligned with WHOI's mission of emphasis on scientific excellence, independence of its staff, and an organizational structure that allows for entrepreneurial achievements in a supportive and inclusive environment. There are several advantages of setting up an independent PO within WHOI, given the in-house experience in ship operations and large engineering projects, and pre-existing support structure for the services needed to manage grants and contracts, facilitate communications and web services, and assist in fundraising.

9 THE EXOIS DECADAL PLAN

This report outlines a path forward for OIF studies that prioritizes activities during an initial five-year, Phase I period. Depending upon the outcome of these activities, a second five-year Phase II would be launched that would include larger and longer assessments of OIF using an Ocean Iron Observatories (OIO) framework designed to target additional sites using optimized iron formulations and delivery methods, as well as improved models and advances in MRV and eMRV. Both phases are needed to develop the knowledge base to guide decisions about if, when, where, and under what conditions OIF might be responsibly implemented for mCDR.

While a decade may seem like a long time, climate models suggest that this window is critical for seeking effective CDR protocols to approach net zero by mid-century, and thus avert the worst consequences of climate change. **Rapid commercialization of mCDR before we have evidence of carbon efficiencies, biogeochemical, and ecological changes, and societal implications almost certainly will hurt, or even shut off, marine climate intervention efforts**. Quite simply, using OIF for marketable carbon credits, or for governments to meet purported climate goals, is premature until a thorough scientific assessment can be made. That is the fundamental purpose of ExOIS: explore the consequences of OIF, positive and negative, so that society can decide whether to implement the strategy. Our mission is to be a leading force in building the governance structures and agreements needed to regulate mCDR, in particular for this proposed use of the High Seas and the oceans beyond national borders.

The acceleration of climate-induced changes in the earth and ocean systems led to a clear consensus at the Moss Landing Marine Laboratories workshop that now is the time for actionable studies to begin. Delaying field-scale assessments of OIF should not wait for the ideal model, new technology developments, or establishment of the essential governance structures for full scale (operational) CDR. The priority paths forward include: 1) field studies in the NE Pacific; 2) regional, global and field study modeling; 3) testing various forms of iron and delivery; 4) advancing MRV and eMRV; and 5) advancing social science and governance issues. Progress should begin in parallel on these critical research paths, though the timing and progress along these five paths may move independently as a function of available human and financial resources. The next decade of climate losses and interplay between public, economic, and political forces, will require the flexibility to accelerate and/or rescope these plans.

Using OIF for marketable carbon credits …… is premature until a thorough scientific assessment can be made

TABLE 9.1. FULLY SCOPED PHASE I BUDGET ($K) BY YEAR AND ACTIVITY

ACTIVITY	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	SUBTOTALS	COMMENTS
1. Field studies annual est. ($K)	$15,300	$37,800	$35,050	$4,050	$4,050	$96,250	Yr 1 mostly AV costs; yr 2 & 3 field deployments; full costs assuming no in kind contributions from partners
2. Modeling annual est.	$2,800	$3,300	$3,300	$3,300	$3,300	$16,000	Models for field planning; several groups comparing ocean biogeochemical Fe and C models; MRV modeling
3. Iron forms and delivery annual est.	$2,000	$4,000	$3,000	$1,000	$1,000	$11,000	Start with individual groups testing Fe forms; followed by "bake off"; next delivery systems design and engineering
4. Technologies for MRV annual est.	$3,500	$3,500	$3,500	$4,500	$4,500	$19,500	Several ongoing programs such as ARPA-E for MRV are underway; additional MRV specific to OIF needed
5. Social and governance annual est.	$600	$850	$1,050	$1,125	$975	$4,600	Multiple PI teams with PDs and students; separate groups for field study permits and long term mCDR governance
6. Program office annual est.	$1,275	$1,850	$1,850	$2,475	$2,475	$9,925	Program office requirements include seeking funding; organization; meetings; outreach; data management, etc
Sum per year	**$25,475**	**$51,300**	**$47,750**	**$16,450**	**$16,300**	**$157,275**	Highest costs in field years; new funding in Years 4 & 5 to build out larger Ocean Iron Observatories not included

As envisioned, the projected costs and budget targets per year for Phase I are summarized in Table 9.1, with budgets developed from the priorities and timing outlined in the activity sections earlier in this report. The overall support needed increases quickly in the first three years from $25M per year to approximately $50M per year during the second and third years when we are conducting field experiments. In fact, conducting four field experiments as discussed in Section 3 (Field Studies) accounts for about 60% of the $157M total budget in Phase I. Actual field-deployment costs might decrease if existing assets (e.g., expertise, vessels, autonomous vehicles, etc.) become available through partnerships and collaborations. What is presented here are the estimated support levels for a self-contained set of next-generation field experiments that include the key measurements and the 10x larger and longer scales than previous studies needed to assess carbon sequestration, and intended and unintended ecological and environmental impacts. Costs ramp down in this five-year view as field experiments are completed, but the Phase I budget does not consider the additional funding support needed for the Ocean Iron Observatories (OIOs) that are central to Phase II of the decadal plan outlined here.

During Phase I, support for modeling totals $16M, while that for studies optimizing iron formulations and delivery for OIF is $11M (ramping down after the "bake off"). Support for MRV technologies in Phase I is estimated here at approximately $20M, but is harder to scale given the expectation, but not certainty, that outside funding sources also will be supporting MRV developments over the next 5 years. For example, ARPA-E already has targeted an additional $45M investment in MRV for carbon, and other sources are likely to support this type of activity during the years ahead. The essential components of the social and governance activities are less expensive, given the lower equipment and facility needs, but remain essential to the success of this effort. The budget proposed here for these activities builds up over time, and totals $5M in Phase I. The program office budget would increase from about $1M to $2.5M per year over the 5 year timeline in conjunction with the increasing complexities of managing multiple converging studies. To reach these levels of support we are seeking financial assistance from government agencies and philanthropic groups to move these activities forward. Commercial supporters who are willing to participate openly without direct financial benefits, such as gaining carbon credits or proprietary rights, also will be considered.

Table 9.2 summarizes the combined decadal plans for Phase I and II, assuming support can be raised quickly and that the results of Phase I are encouraging. The first year would be dominated by field planning, improving and intercomparing our models, initiating the iron "bake off" activities, encouraging developments in new technologies for MRV and eMRV, and initiating social science studies and governance activities, the later beginning with pursuing field permits. The following two years would continue that work but expand to implement several next-generation field experiments in the NE Pacific. Taken together, we would be ready at the end of Phase I to decide whether to make operational the larger OIOs for replicated studies at multiple sites in Phase II. By then, we would be have determined the most efficient and bioavailable forms of iron and delivery systems, and expanded the use of AVs for iron delivery, MRV, and eMRV to enable establishing OIOs in more challenging settings such as the Southern Ocean, where the high nutrient concentrations increase the potential for OIF to impact atmospheric CO_2 removal. As discussed in this report, both high- and low-nutrient sites would be explored in Phase II for possible use of OIF for mCDR.

Importantly, and embedded within the strategies here, will be the **requirement to compare OIF mCDR costs and consequences against the accelerating rate of climate-driven ecological changes, socioeconomic losses and human suffering** without implementation of climate intervention policies (emissions reductions plus CDR). As the program proceeds, more emphasis will be directed to life-cycle analyses and costs to better inform on the options of OIF vs. other land- and ocean-based CDR approaches. Attention to social dimensions, governance considerations, and public perceptions of OIF are needed from the beginning, and would need to increase as we move ahead in this decadal plan.

Members of the Moss Landing Marine Laboratories workshop recognized that there is a potential for the emerging biogeochemical or ecological consequences of OIF during the next generation of experiments, or during OIO phases, to become problematic. Project planning thus will have to establish sentinels of critical

TABLE 9.2. ExOIS DECADAL PLAN

YEAR	ACTIVITIES
2024-2025	Field planning; model improvements; initiate bake off; invest in new MRV technologies; start social science activities and field permitting; organize ExOIS planning office
2025-2027	Conduct next-generation field studies NE Pacific; continue other paths forward
2028-2029	Continue research paths and sharing of field data; adding systems engineering for Fe delivery; full life cycle cost and C assessments; use OSSE models to design Ocean Iron Observatories
2029-2033	Operational OIOs in multiple HNLC and LNLC settings; Wide sharing of findings; working on larger global governance issues for mCDR
2034	Pass on protocols and technologies

response (biological and chemical) parameters, along with decision-based thresholds for halting iron release or further experimentation. To be clear, determining how or whether these scenarios develop is one of the key goals of the project: establish the potential limitations of OIF before operational-scale mCDR can be allowed to occur. Based on previous OIF experiments, the ocean systems quickly return to ambient conditions once iron infusions stop—a natural brake on such perturbations—so the experimentation proposed here, in progressive steps with checks, will not lead to lasting impacts on the ocean systems.

Beyond the scientific and experimental challenges inherent with proposing an ambitious project like ExOIS, the successful completion of Phase I is also contingent on mitigating certain other risks to the project's success. These include risks such as a shortfall in funding, failure to acquire the necessary permits, and pushback from stakeholders. The ExOIS consortium is aware of these risks and is developing strategies to ensure the risks are analyzed, understood, and mitigated to acceptable levels. Certain steps to risk mitigation include ensuring the ExOIS consortium has the necessary expertise and talent, and identifying and actively engaging with stakeholders.

None of what is presented in this report is meant to lock in a fixed set of activities, as we need to be flexible to adjust as international partnerships evolve and the world's attention to resolving the climate crisis increases. We also need, within each activity, to expand our reach, for example **training the next generation of young professionals to engage in all aspects of mCDR and OIF research, which demands expanding the diversity of groups engaged in mCDR across the Global North and South.** We will build partnerships with the public and associated stakeholders at domestic and international levels from the very start of this decade of activity.

The consensus of our workshop and this report is that now is the time for actionable studies to begin. Research strategies will need to incorporate steps to address historical controversies surrounding geoengineering and OIF in ways that ensure research is done responsibly, openly, and is attentive to societal considerations and governance structures. Tough decisions ahead will rely on those societal values and international laws, as well as a need to consider those groups who are disproportionately impacted by climate change rather than just those who participate in the science, engineering, or commercial markets. The guiding principles laid out by ExOIS (2) need to be considered to determine whether moving forward with OIF for mCDR has the likelihood of improving conditions for the collective benefit of humans and our environment, and at what monetary and social cost. The inclusion of "Exploring" in ExOIS is deliberate as we currently do not have enough data to answer these questions.

Now is the time for actionable studies to begin

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CARBON ACCOUNTING

1 tonne (1,000 kg) of carbon (C) is not the same as 1 tonne of carbon dioxide (CO_2) gas. The atomic weight of carbon is 12 atomic mass units, while carbon dioxide is 44 atomic mass units (CO_2 includes two oxygen atoms that each weigh 16 atomic mass units). 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 tonne of C equates to 3.7 tonnes of CO_2. For context, humans release about 10 billion tonnes of C each year, which is the equivalent to the release of 37 billion tonnes of CO_2.

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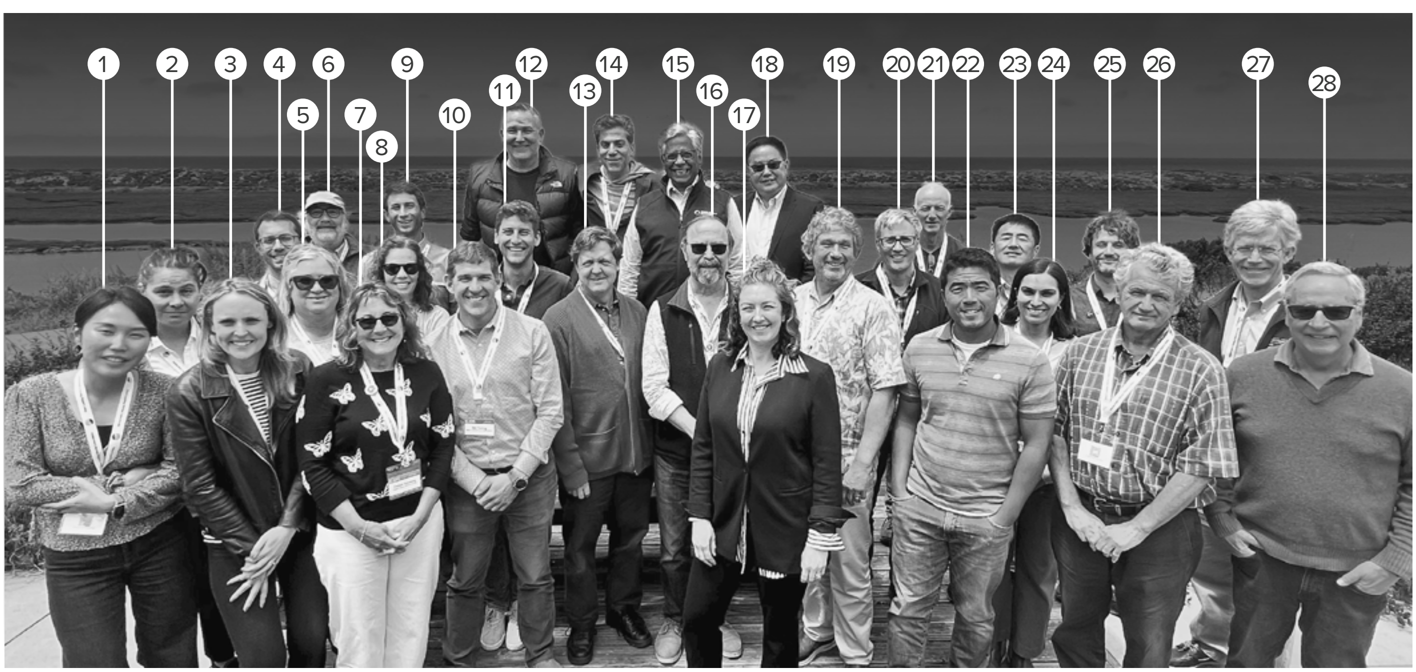

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