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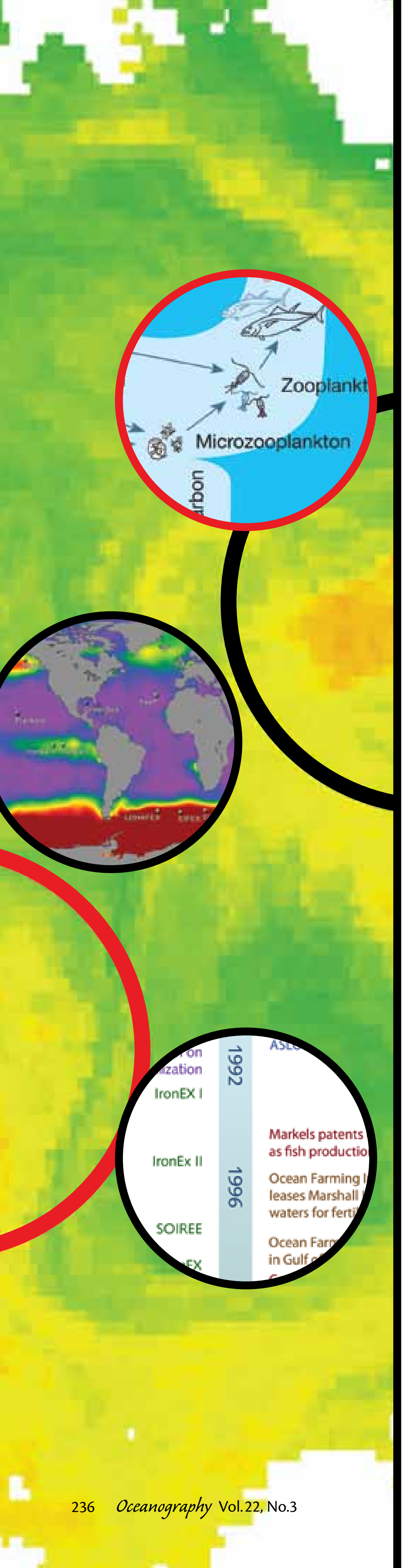

Ocean Fertilization

Science, Policy, and Commerce

BY AARON L. STRONG, JOHN J. CULLEN, AND SALLIE W. CHISHOLM

ABSTRACT. Over the past 20 years there has been growing interest in the concept of fertilizing the ocean with iron to abate global warming. This interest was catalyzed by basic scientific experiments showing that iron limits primary production in certain regions of the ocean. The approach—considered a form of "geoengineering"—is to induce phytoplankton blooms through iron addition, with the goal of producing organic particles that sink to the deep ocean, sequestering carbon from the atmosphere. With the controversy surrounding the most recent scientific iron fertilization experiment in the Southern Ocean (LOHAFEX) and the ongoing discussion about restrictions on large-scale iron fertilization activities by the London Convention, the debate about the potential use of iron fertilization for geoengineering has never been more public or more pronounced. To help inform this debate, we present a synoptic view of the two-decade history of iron fertilization, from scientific experiments to commercial enterprises designed to trade credits for ocean fertilization on a developing carbon market. Throughout these two decades there has been a repeated cycle: Scientific experiments are followed by media and commercial interest and this triggers calls for caution and the need for more experiments. Over the years, some scientists have repeatedly pointed out that the idea is both unproven and potentially ecologically disruptive, and models have consistently shown that at the limit, the approach could not substantially change the trajectory of global warming. Yet, interest and investment in ocean fertilization as a climate mitigation strategy have only grown and intensified, fueling media reports that have misconstrued scientific results, and conflated scientific experimentation with geoengineering. We suggest that it is time to break this two-decade cycle, and argue that we know enough about ocean fertilization to say that it should not be considered further as a means to mitigate climate change. But, ocean fertilization research should not be halted: if used appropriately and applied to testable hypotheses, it is a powerful research tool for understanding the responses of ocean ecosystems in the context of climate change.

INTRODUCTION

Over the 20 years since oceanographer John Martin of Moss Landing Marine Laboratories quipped, "Give me half a tanker of iron, and I'll give you an ice age," fertilization of the ocean with iron has drawn increasing attention as a potential geoengineering strategy for carbon sequestration. As interest in the idea has increased, so has the controversy surrounding it. In January 2009, major news services broadcast the gripping story of the suspension of LOHAFEX[1], an iron fertilization experiment in the Southern Ocean. The research vessel *Polarstern* was midway between South Africa and South America when the German Research Ministry put a halt to the experiment. The story was featured in *Wired* magazine (Keim, 2009) and on Reuters (Szabo, 2009) and the BBC (Morgan, 2009). A blog headline covering the controversy posed the question: "LOHAFEX—If you mean well, are you allowed to screw up the oceans?" (Campbell, 2009). The experiment drew immediate and intense commentary from environmental nongovernmental organizations (NGOs), one of which cast it as a violation of the 2008 United Nations (UN) Convention on Biological Diversity's moratorium on iron fertilization activities (ETC Group News Release, 2009). The international press, including news articles in *Science*, consistently referred to LOHAFEX as a "geoengineering project," an experiment designed to test the potential of ocean iron fertilization to change global climate (Kintisch, 2009).

The LOHAFEX scientists, however, defended their experiment as purely scientific and consistent with relevant UN regulations. And, the Director of the Alfred Wegener Institute (AWI), which sponsored LOHAFEX, defended the scientific validity of the research, stating that they "neither plan to nor want to smooth the way for a commercial use of iron fertilization with our expedition," and that they "oppose iron fertilization with the aim to reduce CO_2 to regulate the climate" (AWI News, 2009). After the German Research Ministry received several independent environmental assessments of LOHAFEX and an impact statement from the Indo-German research crew on *Polarstern*, the green light was given (AWI Press Release, 2009a): scientists commenced fertilizing the Southern Ocean with 10 tonnes of iron sulfate on January 27, 2009.

At the core of the controversy over LOHAFEX was the idea of using iron fertilization to mitigate global climate change by sequestering carbon dioxide in the deep ocean. Over the last two decades, this idea has attracted the interest of several commercial ventures seeking to carry out large-scale ocean fertilization activities to sell carbon-offset credits in a carbon trading market. These ventures have been a cause of concern for some scientists and several environmental NGOs, who have argued that claims of significant carbon sequestration are unsupported by scientific evidence, and that large-scale iron fertilization will, by design, profoundly alter marine ecosystems (Chisholm et al., 2001; Gnanadesikan et al., 2003; Cullen and Boyd, 2008; Denman, 2008; ETC Group News Release, 2009; World Wildlife Fund International, 2009). These concerns have helped spur recent UN resolutions, which were intended to restrict iron fertilization activities to small-scale scientific research (UN CBD, 2008; London Convention Meeting Report, 2008).

> "...THE HISTORIES OF THE SCIENTIFIC AND COMMERCIAL INTERESTS IN OCEAN IRON FERTILIZATION (OIF) ARE INTIMATELY CONNECTED—CO-EVOLVING AND TRANSFORMING OVER TIME."

As we describe below, the histories of the scientific and commercial interests in ocean iron fertilization (OIF) are intimately connected—co-evolving and transforming over time. In studying this history, it becomes apparent that despite the lack of experimental results indicating that OIF would be effective for significant climate mitigation,

[1] "LOHA" is Hindi for "iron," FEX stands for "FErtilization eXperiment."

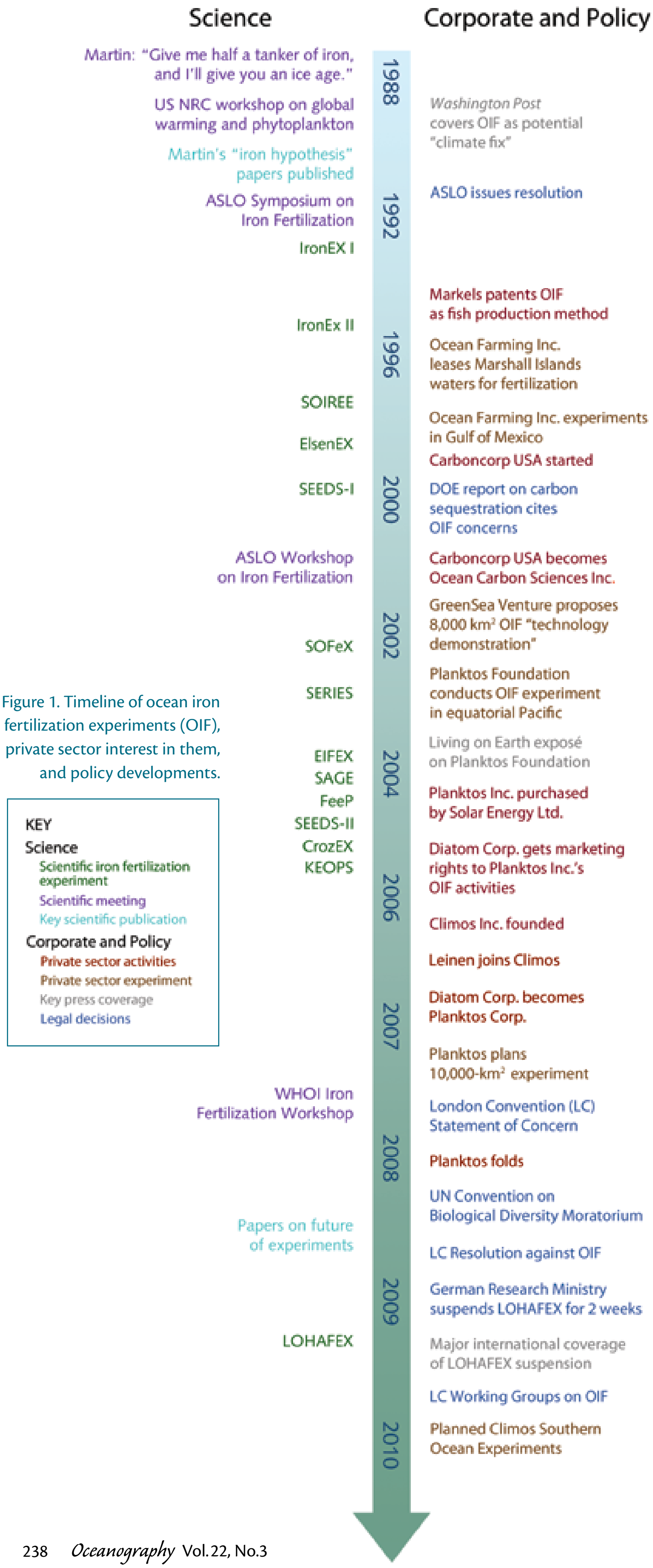

Figure 1. Timeline of ocean iron fertilization experiments (OIF), private sector interest in them, and policy developments.

commercial interests have continued to pursue and advance the idea, fueling a cycle of media interest, followed by calls for caution, and then proposals for more research requiring longer and larger experiments. Here we take a synoptic view of the two-decade history of this cycle (Figure 1) to better understand how the scientific and commercial interests have become intertwined, conflated, and confused. We have much to learn from this history, as proposals for research on other forms of geoengineering are beginning to emerge (Latham et al., 2008; Rasch et al., 2008).

HISTORY OF PUBLIC-SECTOR SCIENTIFIC OCEAN FERTILIZATION EXPERIMENTS

The "Iron Hypothesis"

While the idea that iron limitation might control productivity in certain areas of the ocean has been around since the mid-1920s (Hart, 1934) if not before (de Baar, 1994), the contemporary history of ocean iron fertilization and the "iron hypothesis" is attributed to John Martin. During a 1988 lecture at the Woods Hole Oceanographic Institution,

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Martin famously quipped, "Give me half a tanker of iron, and I'll give you an ice age" (Martin, 1990a). Referring to shipboard experiments on samples of seawater, and ice core data showing a relationship between atmospheric iron dust deposition and atmospheric CO_2 concentrations over the past 160,000 years (Figure 2), Martin developed a two-part hypothesis. First, he argued that the "high nutrient, low chlorophyll" (HNLC) regions of the ocean could be explained by iron limitation (i.e., surface nitrate and phosphate concentrations were not depleted because additional phytoplankton growth was limited by iron). Second, he argued that if iron did indeed control the productivity of HNLC waters, and thus the transport of organic carbon to the deep sea via the so-called biological pump (Figure 3), it could explain the observed relationship between atmospheric iron dust deposition and atmospheric CO_2 during the last glacial maximum (Martin, 1990b). He also commented that this "paleo-iron" hypothesis could be important, because intentional oceanic iron fertilization could prove an effective method of drawing down atmospheric CO_2 "should the need arise" (Martin et al., 1990; see Box 1).

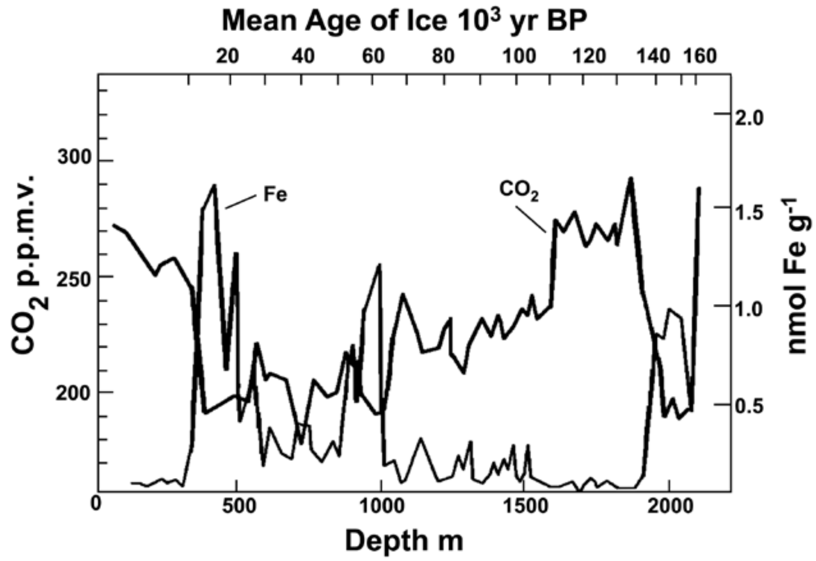

Figure 2. Relationship between Fe and CO_2 concentrations from the Vostok ice cores. *After Martin (1990b)*

Using ultra-clean experimental approaches with seawater incubated on the deck of a ship, Martin's team successfully demonstrated that iron addition could stimulate phytoplankton growth in bottled samples collected from the HNLC Gulf of Alaska (Martin et al., 1989) and the HNLC Southern Ocean (Martin et al., 1990). Wide acceptance of the iron hypothesis would require tests on open waters, however. Though, sadly, Martin did not live to see it, in 1993 his colleagues carried out the first open-ocean mesoscale (i.e., more than several kilometers on a side) iron fertilization experiment, "IronEx I," in equatorial Pacific HNLC waters (Figure 4). The results demonstrated a phytoplankton bloom in response to iron addition, but they were confounded when the fertilized patch was subducted under low-density water (Martin et al., 1994). Thus, several hypotheses remained untested (Cullen, 1995).

Armed with this experience, a second experiment, IronEx II, was organized in May 1995—again in the equatorial Pacific. This time, a 72-km² patch was fertilized serially three times over the course of one week. This experiment demonstrated a strong phytoplankton response to iron addition in these HNLC waters, prompting the authors to conclude that "it is now time to regard the 'iron hypothesis' as the 'iron theory'" (Coale et al., 1996). The authors suggested that the logical next step was to conduct an experiment in the Southern Ocean as this is "where most of the HNLC waters are found and where paleoclimate coherence between iron flux and carbon export has been observed" (Coale et al., 1996).

The Next Round of Experiments: Carbon Sequestration Becomes the Hypothesis

Over the five years from 1999 to 2004, eight more major open-ocean iron fertilization experiments would take place in the Southern Ocean and subarctic Pacific HNLC regions (Figure 4; Table 1). These experiments sought, for the most part, to track the fate of carbon fixed in iron-induced blooms. As such, they became increasingly focused on the question of carbon export from the surface waters, as this is what is necessary to draw CO_2 out of the atmosphere and transport it into the deep sea. At the same time, as interests in OIF for carbon sequestration were taking off (see below), the scientific language began to morph: increasingly, "carbon export" became

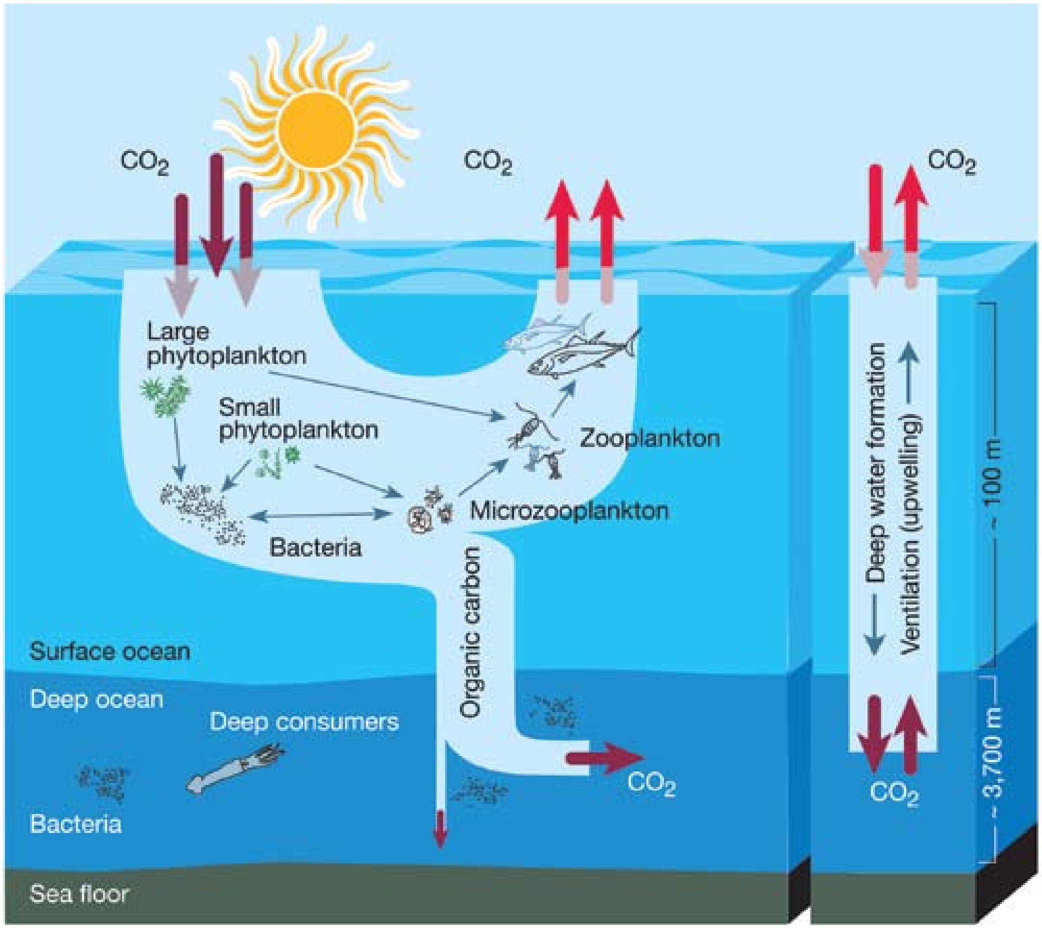

Figure 3. Carbon dioxide that would otherwise be in the atmosphere is stored in the deep sea because the biological pump puts and keeps it there. Phytoplankton in the lighted surface layer take up nutrients (e.g., nitrate and phosphate) and grow, converting CO_2 to organic matter that fuels marine food webs. Some of the organic matter—for example, senescent phytoplankton, fecal pellets, and aggregated debris—sinks to the deep ocean where it decomposes, releasing CO_2 and nutrients while consuming oxygen. When the ocean carbon cycle is roughly in balance, this carbon- and nutrient-rich deep water does not reach the surface for decades to hundreds of years, and when it does, biological productivity consumes the CO_2 and nutrients and sends C, N, and P back to deep waters as sinking organic matter. The amount of CO_2 thus stored in the deep sea largely corresponds to the amount of major nutrients (N and P) consumed in the lighted surface layer of the ocean. When iron limits productivity, N and P persist where they wouldn't otherwise; if iron limitation is alleviated, major nutrients are consumed, more organic matter is produced, and more carbon sinks to the deep sea. This extra carbon associated with added iron (either natural or intentional) could be considered sequestration. But the amount and duration of carbon sequestration depends on how deep the organic matter sinks before it is decomposed and whether or not iron is still available in excess when carbon- and nutrient-enriched waters reach the surface again. *Figure modified from Chisholm (2000)*

"carbon sequestration" (Boyd et al., 2000, 2004; Buesseler et al., 2004), a term used in the US Department of Energy (DOE) climate mitigation vocabulary (Department of Energy, 1999). This shift in language contributed to blurring the lines between the basic and applied science dimensions of OIF.

An analysis of the "post-IronEx" mesoscale experiments illuminates the evolution of hypotheses that motivated them (Table 1; see de Baar et al., 2005, and Boyd et al., 2007, for reviews). The new focus on the Southern Ocean began with the Southern Ocean Iron Release Experiment (SOIREE) and the European Iron Enrichment Experiment (EisenEx; Boyd et al., 2000; Smetacek, 2001), and placed more emphasis on longer-duration experiments tracking particle export, remineralization, and changes in zooplankton communities. Both experiments confirmed the hypothesis of iron limitation of primary production in the HNLC Southern Ocean. Although diatom production increased in response to iron addition in the SOIREE patch, carbon export did not (Boyd et al., 2000). EisenEx also demonstrated a diatom bloom, and measured a larger net atmospheric CO_2 drawdown than SOIREE, but storms interrupted the experiment and the fate of fixed carbon could not be tracked (Assmy et al., 2007). A year later, SEEDS-I (Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study) confirmed that productivity was limited by iron in the HNLC region of the western subarctic Pacific,

Box 1. The Paleo-Climate Portion of the Iron Hypothesis: Still an Open Question

Recently, some paleoceanographers have called into question the causal link between atmospheric dust deposition and lower atmospheric CO_2 (and thus a cooler climate) during the last glacial maximum. Kohfeld et al. (2005) analyzed the role of the biological pump in glacial CO_2 drawdown using sediment records, for example. Their data indicate that in large portions of the Southern Ocean, export productivity was actually lower during the last glacial maximum—exactly during a period of increased dust flux. They thus argued that iron fertilization from dust could not have been solely responsible for CO_2 drawdown (Kohfeld et al., 2005).

Using these productivity data and those of others (Paytan et al., 1996; Anderson et al., 2008) and comparing them to dust flux records from Winckler et al. (2008), Anderson et al. (2007) presented an argument that there is no correlation in the paleoceanographic data between dust flux and increased export productivity in the equatorial Pacific or the Southern Ocean. While their data do show a strong anti-correlation between dust flux and CO_2, they argue that there is no evidence that the dust caused the CO_2 drawdown. The causality inferred from the original ice core data (Figure 2) has been a central thread in the argument for OIF for geoengineering, and, at the very least, these recent arguments questioning that causality deserve more attention and research (Anderson et al., 2007). Alternate hypotheses include strong influences of changing wind patterns on the overturning of carbon-rich southern deep water (Toggweiler et al., 2006).

documenting a floristic shift toward diatom production. Carbon export was not measured (Tsuda et al., 2005).

The next set of experiments were designed to be larger and longer, with the hope that this would allow better tracking of the fate of iron-induced blooms. The Southern Ocean Iron Experiment (SOFeX), a multi-part, multi-ship iron fertilization expedition, set out to address hypotheses about carbon export as influenced by silicate availability in the context of iron-induced blooms (Coale et al., 2004). SOFeX produced the first conclusive measurement of enhanced particulate organic carbon (POC) export resulting from an intentional iron-fertilization-induced bloom (Buesseler et al., 2004). Although POC export from the iron-enriched patch was elevated, the incremental flux was small compared to those observed during a natural iron fertilization event in the same location in 1998 (Buesseler et al., 2001). The authors concluded that the observed carbon flux was small relative to what would be required by proposed geoengineering plans to sequester carbon using iron fertilization, but they stressed that they had not been able to observe the termination of the iron-induced bloom (Buesseler et al., 2004).

The Subarctic Ecosystem Response to Iron Enrichment Study (SERIES) expedition followed. Conducted over a month in the subarctic Pacific, a 77-km^2 iron-enriched patch was created and POC export flux monitored (Boyd et al., 2004). The decline and termination of the iron-induced bloom (caused by silicate limitation) was observed. The majority of the carbon fixed in SERIES was remineralized by bacteria and zooplankton grazing in the surface waters. Only a small fraction (8%) of the fixed carbon sank below the 120-m permanent pycnocline, significantly lower than the deep-export rate observed in natural blooms (Buesseler, 1998). Further, the iron content (Fe:C) of the exported material was a thousandfold higher than that assumed in assessments of the efficiency and cost of OIF for climate mitigation. Noting increased attention to the idea of iron fertilization for geoengineering, Boyd et al. (2004) argued that "inefficient vertical transfer of carbon may limit the effectiveness of iron fertilization as a mitigation strategy."

The European Iron Fertilization Experiment (EIFEX), conducted in 2004 and the longest iron fertilization experiment to date, was also designed to evaluate the carbon export response and community shifts in a Southern Ocean iron-induced bloom (Hoffmann et al., 2006). Biomass export resulting from the sinking of an iron-induced bloom represented the highest ratio of carbon exported to added iron to date (Jacquet et al., 2008). At the same time, SEEDS-II, a second subarctic Pacific experiment, detected no significant bloom response to iron enrichment (Tsuda et al., 2007).

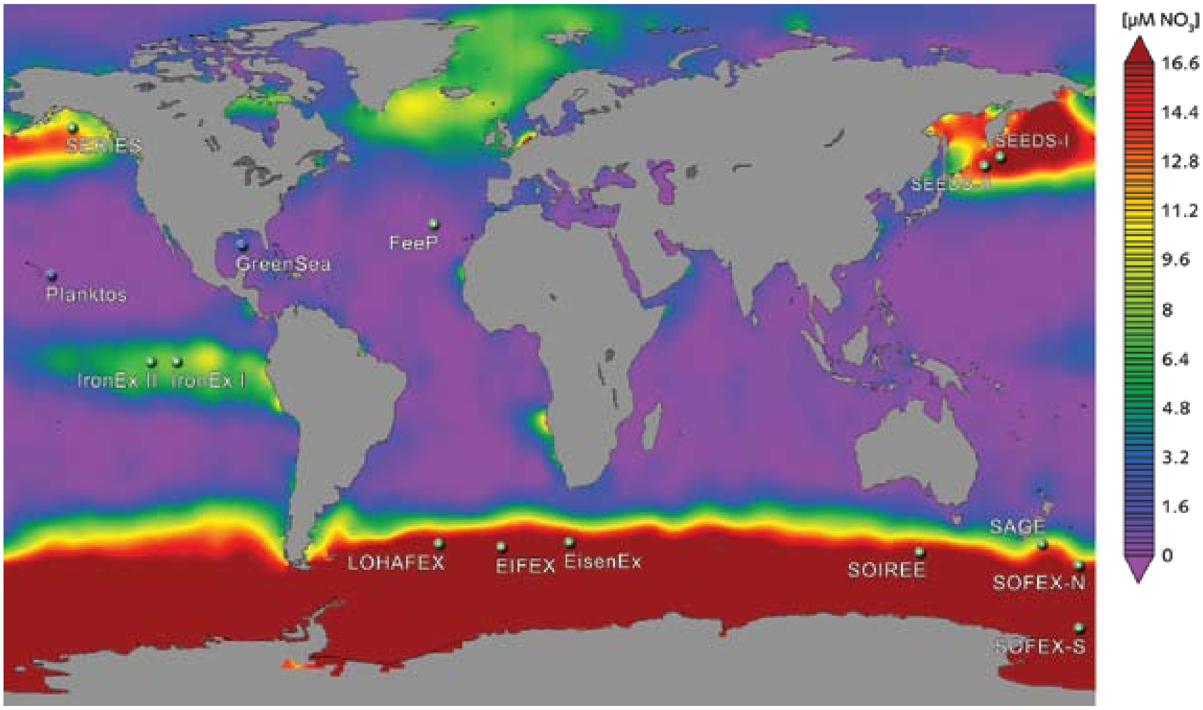

Figure 4. Locations of major artificial iron enrichment experiments, including the pilot demonstrations of GreenSea Venture and Planktos. Color heat map represents surface nitrate concentrations with warmer colors indicating higher concentrations, showing three major HNLC regions in the Southern Ocean, the eastern equatorial Pacific, and the subarctic Pacific. *Data from National Virtual Ocean Data System, http://ferret.pmel.noaa.gov/NVODS/; analyzed nitrate data from the World Ocean Atlas 2005*

Two other experiments were conducted in 2004 to test additional biogeochemical hypotheses using iron enrichment. The Surface-Ocean Lower-Atmosphere Studies Air-Sea Gas Exchange (SAGE) experiment in the sub-Antarctic Pacific off New Zealand sought to understand the effects of iron addition on air-sea gas exchange, particularly dimethylsulfide (DMS). DMS plays a role in cloud formation, and as such is thought to play a role in climate regulation and, potentially, in increasing Earth's albedo (Charlson et al., 1987). In this experiment, scientists fertilized serially with over 5 tonnes of iron sulfate, but found only a modest chlorophyll increase and no increase in either CO_2 drawdown or DMS production, which they believed may have been due to light limitation (Law et al., 2006). Another iron-enrichment experiment, FeeP, performed a combined Fe and phosphate addition to low nutrient, low chlorophyll (LNLC) waters in the Northeast Atlantic to test the hypothesis that iron enrichment of LNLC waters can lead to a net N import (ultimately supporting increased productivity) by stimulating nitrogen fixation. Although rates of nitrogen fixation increased in response to enrichment, productivity did not. Carbon export in response to enrichment was not measured (Rees et al., 2007; Karl and Letelier, 2008).

Collectively, these experiments taught us a good deal about the initial phytoplankton community response to iron enrichment, and confirmed iron limitation of productivity in HNLC regions around the globe. The results, however, were highly variable and inconclusive with regard to carbon sequestration: the major conclusion to be drawn is that physical oceanographic, geographic, and biological variability all influence the long-term fate of blooms induced by iron fertilization, significantly constraining generalizations about iron-induced carbon sequestration (Boyd et al., 2007).

Modeling

Open ocean iron enrichment experiments over the last 16 years have confirmed the hypothesis of iron limitation of productivity in HNLC regions and have provided evidence for highly

Table 1. Summary of ocean iron enrichment experiments conducted between 1993 and 2009. See also reviews by de Baar et al. (2005) and Boyd et al. (2007).

Experiment	Year	Location	Duration	Magnitude	Rationale/Hypothesis Tested	General Conclusions
IronEx I Martin et al., 1994	1993	Eastern equatorial Pacific Ocean	10 days	450 kg Fe 64 km^2	• Iron limitation of productivity in HNLC region	• Iron limits phytoplankton growth rate, but patch subducted; broader implications of OIF unclear
IronEx II Coale et al., 1996	1995	Eastern equatorial Pacific Ocean	17 days	450 kg Fe 72 km^2	• Iron limitation of productivity in HNLC region	• Iron definitively limits productivity in equatorial Pacific. Larger bloom than IronEx I
SOIREE Boyd et al., 2000	1999	Southern Ocean-Australia; South of Antarctic Polar Front (APF)	13 days	1740 kg Fe 50 km^2	• Iron limitation of productivity in Southern Ocean, south of the Antarctic Polar Front (APF) • Fate of carbon fixed in bloom	• Iron limits productivity in Southern Ocean • No downward carbon transport observed
EisenEx Smetacek, 2001; Assmy et al., 2007	2000	Southern Ocean-Africa; in APF zone	21 days	4 tonnes $FeSO_4$ 38.5 km^2	• Iron limitation of productivity in Southern Ocean, along APF • Simulate Fe dust deposition to test whether Fe dust contributed to lower atmospheric CO_2 concentrations during glacial periods	• Iron limits productivity in Southern Ocean • Fate of the bloom uncertain • Iron only affected certain species of phytoplankton
SEEDS-I Tsuda et al., 2005	2001	Subarctic Pacific-Northwest	13 days	350 kg Fe 80 km^2	• Iron limitation of productivity in HNLC of subarctic Pacific • Fate of carbon fixed in bloom	• Iron limits productivity in subarctic Pacific • Floristic shift to diatoms • Downward carbon export minimal
SOFeX-N **SOFeX-S** Coale et al., 2004; Buesseler et al., 2004	2002	Southern Ocean-New Zealand; north and south of APF	30 days	N: 1712 kg Fe 225 km^2 S: 1260 Kg Fe 225 km^2	• Does OIF increase flux of carbon to deep ocean? • Silicate influence and geographic variability of response	• Increase in POC export flux, but magnitude is small relative to natural blooms
SERIES Boyd et al., 2004	2002	Subarctic Pacific-Gulf of Alaska	25 days	490 kg Fe 77 km^2	• Fate of carbon fixed in iron-induced bloom • Efficiency of carbon export to deep ocean	• Majority of carbon remineralized • Inefficient transport of carbon below thermocline
EIFEX Hoffmann et al., 2006; Jacquet et al., 2008	2004	Southern Ocean-Atlantic	35 days	7 tonnes $FeSO_4$ 150 km^2	• Iron addition impacts on phytoplankton community structure • Carbon sequestration efficiency and remineralization rates	• Shift away from picophytoplankton • Majority of carbon fixed was not remineralized • Unpublished "massive carbon export" paper by Smetacek et al.
FeeP Rees et al., 2007; Karl and Letelier, 2008	2004	Sub-tropical Northeast Atlantic-LNLC	21 days	5 tonnes $FeSO_4$ (+20 t PO_4) 25 km^2	• Interaction between iron and phosphorus controls on biological activity in the subtropical North Atlantic	• Increased N-fixation activity was observed • No increase in primary productivity • Carbon export not measured
SAGE Law et al., 2006	2004	Southern Ocean-250 km from New Zealand	15 days	5.4 tonnes $FeSO_4$ 100 km^2	• Iron addition's influence on sea-air gas exchange • CO_2 drawdown and dimethylsulfide (DMS) production	• Doubling of chlorophyll *a* but no significant DMS production and no significant CO_2 drawdown (preliminary results)
SEEDS-II Tsuda et al., 2007	2004	Subarctic Pacific-Northwest	26 days	491 kg Fe 64 km^2	• Monitor ultimate fate of bloom and carbon for longer time period than SEEDS-I	• No diatom bloom response • Increased zooplankton grazing
LOHAFEX NIO Press Release, 2009	2009	Southern Ocean-Atlantic	40 days	10 tonnes $FeSO_4$ 300 km^2	• Ecological shifts and fate of sinking carbon	• Increased zooplankton grazing • Negligible carbon export (preliminary results)

variable, and small, rates of carbon export from these iron-induced blooms. But experiments at this scale cannot resolve key questions about geoengineering scenarios for carbon sequestration on the order of decades to centuries, and on the scale of the entire Southern Ocean and beyond. These questions can be addressed effectively only by using global biogeochemical models.

From the very beginning of research on the iron hypothesis, models were used explicitly to predict what small-scale experiments could not show: the global carbon cycle response to large-scale OIF. In response to the initial interest in iron fertilization as a potential tool for global climate mitigation in 1990, Sarmiento and Orr (1991) modeled what complete depletion of surface-layer macronutrients in the Southern Ocean (by iron-induced phytoplankton blooms) would do to global atmospheric CO_2 and ocean chemistry. Their model, operating on a 100-year time frame, predicted a net global drawdown of around 1–1.5 Gt C yr^{-1} (98–181 Gt C total over 100 yr). At the time, this figure represented offsetting about 20% of anthropogenic emissions over the 100 years, corresponding to a delay in the rising atmospheric CO_2 trajectory of about 18 years. Even so, the projections resulted in a global atmospheric concentration of CO_2 near 700 ppm by 2100. Their model also predicted a huge area of anoxia in the southwestern Indian Ocean, and a high potential for methane production as a result of this anoxia (Sarmiento and Orr, 1991; see also Fuhrman and Capone, 1991). Of essential importance is that these results, by design, represent the extreme (unrealistic) case scenario—fertilizing the entire Southern Ocean with iron for 100 years, and assuming that all of the macronutrients available were completely used up. Thus, these results represent an unachievable (both logistically and ecologically) upper limit.

Since these initial modeling efforts, there have been many published variations on the theme (Table 2)—all concluding, more or less, that large-scale ocean fertilization could, at the limit, sequester only modest amounts of carbon relative to global human emissions. All such scenarios involve spatial scales of the entire Southern Ocean or beyond and time scales of decades to centuries. Most recently, Zahariev et al. (2008) modeled how the "elimination of iron limitation" in the ocean globally would affect atmospheric CO_2. Their results were similar to previous estimates: rates of 0.9 Gt C yr^{-1} reduction in atmospheric carbon, or about 11% of 2004 global emissions, and these sequestration rates could only occur "for a year or two, even under continuous fertilization." They conclude that their idealized model of iron fertilization offers only a "minor impact on atmospheric CO_2 growth" (Zahariev et al., 2008).

The early publications also recognized the downstream effects of OIF, that is, (1) the influence of iron-induced nutrient depletion on surface waters that are subducted and transported, and that ultimately resurface elsewhere with diminished nutrient supplies, and (2) enhanced decomposition of organic matter in subsurface waters, depleting oxygen with ecological and biogeochemical consequences that over time will extend well beyond the fertilized location. As Sarmiento and Orr (1991) put it, the fact that an increase in productivity of such a magnitude would be concentrated in 16% of the world ocean would have "dramatic effects on oceanic ecology which are difficult to predict." Fuhrman and Capone (1991) highlighted expected influences of enhanced nutrient cycling on global production of the potent greenhouse gases methane and nitrous oxide. Including tentative assessments of effects on fisheries, Gnanadesikan et al. (2003) modeled what some of the long-term downstream ecological effects of nutrient depletion might look like, and argued that downstream reduction in productivity could far outweigh the benefit of the initial iron-induced carbon sequestration in terms of a global carbon budget.

In short, marine ecosystems are complex, and any estimate of the net impact of iron fertilization on *global* carbon storage and greenhouse warming requires an analysis of all of the downstream potentially negative effects, including a long-term reduction in ocean productivity, alteration of the structure of marine food webs, and a more rapid increase in ocean acidity (Denman, 2008). As argued by Cullen and Boyd (2008), such long-term and downstream effects must not only be acceptably predictable, but also verifiable, if OIF is to be considered a viable technology for climate mitigation. So far, no proponents of OIF have demonstrated, or even argued, that these effects can be monitored over decades to reveal statistically significant assessments against the backdrop of climate variability.

Integrating the Science and Moving Forward

Between 2005 and 2009, the scientific community reviewed the results from previous artificial fertilization

Table 2. Selected models of large-scale ocean iron fertilization and its impact on atmospheric carbon inventory. Most models show high rates of CO_2 drawdown in surface waters, with only a small fraction exported below the pycnocline, and only a small fraction of that exported carbon sequestered. Models converge at < 1Gt C yr^{-1}, and generally assume near-constant fertilization of vast HNLC areas for decades to centuries.

Model	Approach	Overall estimate of C sequestered	Maximal estimate of C sequestration rate	Summary
Sarmiento and Orr, 1991	Complete macronutrient depletion due to iron fertilization of HNLC regions	98–181 Gt C over 100 yrs	Rates around 1–1.5 Gt yr^{-1} integrated over a century	Assumes complete macronutrient depletion due to OIF of the entire Southern Ocean and results in a 20% reduction in anthropogenic emissions only if this level of fertilization is maintained for 100 years.
Gnanadesikan et al., 2003	Patchy fertilization; includes downstream effects of macronutrient depletion on biological pump	Ultimately, the negative effect on productivity from OIF could be 30x the amount of C exported from OIF	2–20% sequestration of 2 Gt yr^{-1} as an initial estimate of global export production	Sequestration (for 100 yr) is a small percentage of annual export production. Overall downstream impacts of OIF may outweigh the carbon sequestration response.
Aumont and Bopp, 2006	Uses models based on OIF experiments to simulate productivity, export production, and ultimately sequestration	70 Gt C over 100 yrs	Export production: Initial increase 3.8 Gt yr^{-1}, slows to 1.8 Gt yr^{-1} Sequestration: 0.3–1 Gt yr^{-1}	Ultimately, 90% of sequestration comes from the Southern Ocean. Model predicts substantial increases in productivity. Only a fraction of this productivity is ultimately exported, and only a fraction of that is ultimately sequestered. Requires constant summer fertilization.
Jin et al., 2008	Models patch to basin-scale fertilization for one decade; analyzes CO_2 drawdown	3.4 Gt C over 10 yrs	N/A	The model shows high atmospheric CO_2 uptake efficiency, but low total biological pump efficiency: full fertilization of the entire Pacific HNLC for 10 yrs results in 3.4 Gt of CO_2 drawdown.
Zahariev et al., 2008	Complete relief of iron limitation in the global ocean	77 Gt C over 5,300-yr maximum	1 Gt yr^{-1} maximum	Continuous fertilization of the entire Southern Ocean results in about 11% offset of global emissions under the most ideal conditions.

experiments and models (de Baar et al., 2005; Boyd et al., 2007; Powell, 2007–2008) and began a more public discussion about where the field was, and should be, going (Boyd, 2008; Buesseler et al., 2008; Lampitt et al., 2008; Smetacek and Naqvi, 2008). Although mesoscale experiments had shown that iron addition caused phytoplankton blooms in HNLC regions, what happened to the carbon in those blooms, however, was less consistent and did not support key calculations in Martin's "paleo"-iron hypothesis. For example, an analysis of results from experiments in the Southern Ocean (de Baar et al., 2005) revealed that the average net dissolved inorganic carbon (DIC) drawdown from the atmosphere as a result of iron enrichment was approximately 4347 mol C per mol Fe. Assuming a carbon export rate to the deep ocean of 20% of primary production, carbon export efficiency (amount of carbon exported to the deep ocean per unit of iron added) is thus 870 mol C per mol Fe. This figure is 200 times less than required to explain paleo-climate observations (de Baar et al., 2005). Thus, the collective carbon export efficiency results from open-ocean experiments were significantly lower than initially hypothesized.

An important symposium was held at the Woods Hole Oceanographic Institution (WHOI) in September 2007 (http://www.whoi.edu/page.do?pid=14617) that included invited representatives of private companies promoting ocean fertilization for climate mitigation. Experimental results and modeling predictions, as well as the policy implications and economics of OIF, were discussed. In an outgrowth of that workshop, Powell (2007–2008) summarized the state of OIF science as it relates to climate mitigation. He concluded that iron fertilization may work in principle to sequester some carbon, but yields are low and long-term sequestration is difficult to verify, making it less attractive and making the cost per ton of carbon sequestered greater than proponents might hope. Uncertainties about ecosystem disruption and other potential downstream negative side effects were also recognized as a cause for concern.

In an outgrowth of the WHOI workshop and in an effort to move the field forward, Buesseler et al. (2008) focused on the need to reduce uncertainties about OIF as a climate mitigation strategy, arguing that there is "as yet, no scientific evidence for issuing carbon credits from OIF." They urged a move to larger and longer experiments because "ecological impacts and CO_2 mitigation are scale-dependent" (Buesseler et al., 2008). The proposed experiments would seek to test a broad array of ecosystem impacts of iron fertilization, would integrate with modeling efforts to analyze potential downstream effects of OIF, and would attempt more detailed measurements of the fate of fixed carbon from iron-induced blooms.

Around the same time, Smetacek and Naqvi (2008)—arguing that an apparent consensus against OIF was premature—also called for larger and longer experiments to test both the geoengineering potential of OIF and the potential for unintended negative side effects. Collectively, these proposals advocated cautiously moving forward, gradually increasing the size of experiments, and measuring carbon export, net greenhouse gas budgets, food-web disruption, and other parameters, in order to gain more information about the potential of iron fertilization as a climate mitigation strategy. Following up on arguments presented at the WHOI workshop, Cullen and Boyd (2008) pointed out that it will be necessary to predict and verify cumulative and long-term effects of OIF for climate mitigation, and there are good reasons to believe that it may not be possible to detect significant downstream effects of wide-scale OIF, such as increased anoxia and nitrous oxide emissions, against a background of ocean variability. It follows that if negative effects were large but masked by natural variability, they might not be detectable until they were irreversible. But regardless, it was the responsibility of proponents to show that these effects could be assessed (Cullen and Boyd, 2008).

As the cycle of experimentation, media coverage, and calls for more research on unintended side effects continued, the scientific questions being addressed by OIF experiments evolved substantially. One defining aspect has emerged: the experiments that were once focused on controls of ocean productivity and their relationships to climate are now almost exclusively couched—either explicitly or implicitly—in terms of testing iron fertilization as a carbon sequestration strategy for mitigating excess global atmospheric CO_2.

The first experiment after the 2008 calls for geoengineering research, LOHAFEX, was conducted in early 2009 amidst international controversy and after a temporary suspension by the German government. The controversy stemmed from a belief that the experiment, the largest and longest conducted to date, would pave the way for geoengineering projects and, by being an experiment designed to test the idea that iron fertilization could alter CO_2 concentrations, was itself geoengineering.

The initial results of the LOHAFEX experiment, conducted over 40 days using 10 tonnes of iron sulfate distributed over 300 km^2, demonstrated the expected iron-induced bloom (AWI Press Release, 2009b). However, the bloom also induced an increase in copepod grazing and amphipod abundance, channeling carbon into the food web and largely to respiration; in this way, the vast majority of the newly fixed carbon was rapidly remineralized and only a negligible amount was exported. The National Institute of Oceanography (NIO) report indicated that these results "dampened the hopes" of using OIF in the Southern Ocean to mitigate global climate change (NIO Press Release, 2009). The controversy surrounding LOHAFEX brings into focus the dynamics between OIF science, companies hoping to conduct OIF commercially, and international and national regulations on OIF. No publicly funded scientific experiments beyond LOHAFEX have been announced, but future experiments will be conducted under new regulatory regimes and, certainly, under close scrutiny.

OCEAN FERTILIZATION AS A COMMERCIAL VENTURE

The History of Commercial Interest Parallels the Science

As the iron hypothesis—and John Martin's famous quip—became popularized, so did the idea that fertilizing the ocean could be a cheap, fast, and easy solution to the greenhouse gas problem. Not long after the hypothesis was first put forward, *The Washington Post* published an article on iron fertilization as way to "battle the greenhouse effect" (Booth, 1990). This attention would quickly translate into commercial ventures seeking to profit from ocean fertilization's geoengineering potential.

After the first round of press coverage, the American Society of Limnology and Oceanography (ASLO) held a workshop to review the science (ASLO, 1991). After many presentations and long discussion, participants agreed on a resolution, endorsed by the Society, "urging all governments to regard the role of iron in marine productivity as an area for further research and not to consider iron fertilization as a policy option that significantly changes the need to reduce emissions of carbon dioxide" (see preface to Chisholm and Morel, 1991). This resolution's emphasis on the scientific uncertainties surrounding the ecosystem response to iron fertilization stimulated important OIF research as intended, but the carefully worded phrase about OIF as a policy option did not stem the growing interest in ocean fertilization for commercial gain.

Interested in what appeared to be an easy and intriguing solution for global warming, the press followed the IronEx I and II experiments in 1993 and 1995, and interpreted their results in a different context from the intent of the experiments. The addition of iron to equatorial Pacific waters in IronEx I resulted in a phytoplankton bloom, and the scientists involved were justifiably very excited about the results: iron did indeed stimulate the growth of phytoplankton consistent with the first arm of the iron hypothesis—that iron limits productivity in these HNLC waters. The magnitude of the bloom, however, was muted, in part because of the design, and in part because of unexpected physics during the experiment. The press coverage of the experiments, however, focused on the small magnitude of the bloom and its meaning in the climate mitigation context, rather than the exciting fact that there was a bloom at all. (This view is understandable, as they are writing for an audience that is not interested in whether or not iron limits HNLC regions of the ocean; it is interested in climate change.) One headline prompted by the low-magnitude response during the IronEx I experiment read: "Pumping iron: too weak to slow warming" (Monastersky, 1994), and another account reported that "the idea of fertilizing the entire Southern Ocean should probably be considered dead" (Kunzig, 1994). But such skepticism was short-lived. When results from IronEx II were published in 1996, *The Washington Post*'s coverage described them as a confirmation of Martin's hypothesis of CO_2 sequestration and climatic cooling (Suplee, 1996).

"WE SUGGEST THAT IT IS TIME TO BREAK THIS TWO-DECADE CYCLE, AND ARGUE THAT WE KNOW ENOUGH ABOUT OCEAN FERTILIZATION TO SAY THAT IT SHOULD NOT BE CONSIDERED FURTHER AS A MEANS TO MITIGATE CLIMATE CHANGE."

The First Commercial Proposal: Ocean Fertilization for Fish Production

In 1994, before IronEx II had taken place, Michael Markels Jr., former CEO of the engineering firm Versar Inc., filed the first of several patent applications for a method of improved production of seafood by ocean fertilization (Markels, 1995). The method referred to fertilizing with "all nutrients that are found to limit production in the surface ocean." In this patent, Markels cited the results of the IronEx I experiment and suggested that he could constantly fertilize 140,000 km^2 of the Gulf Stream (which is not an HNLC region) with enough iron, phosphate, and micronutrients to remove 1.3 Gt of CO_2 and produce 50 Mt of additional seafood production annually (Markels, 1995).

Markels would go on to found Ocean Farming Inc., a company seeking to capitalize on what it said was ocean fertilization's promise to increase fish biomass production. In early 1998, Ocean Farming Inc. carried out two successive small-scale (9 km^2) ocean iron fertilization "demonstrations" in the Gulf of Mexico. The results were not published, but it was reported that, while the iron fertilization induced an initial increase in phytoplankton production, the bloom failed to expand as much as anticipated, owing to a "second limitation," most likely from phosphorus (Markels and Barber, 2001)—an unsurprising result because the Gulf of Mexico is a low macronutrient region, not favorable to iron-induced bloom development (Markels and Barber, 2001).

Citing its own unpublished activities from the Gulf of Mexico, and the initial results from IronEx I and II experiments, Ocean Farming Inc. then reportedly secured a lease of 800,000 square miles of LNLC tropical ocean in the exclusive economic zone of the Republic of the Marshall Islands in the western Pacific Ocean (Markels, 1998). According to the structure of the lease, once fertilization of this vast area occurred and fish catch had commenced, Ocean Farming Inc. would pay the Marshallese government $3.75 a square mile or 7% of the profit, whichever was more (Markels, 1998).

"BUT, OCEAN FERTILIZATION RESEARCH SHOULD NOT BE HALTED: IF USED APPROPRIATELY AND APPLIED TO TESTABLE HYPOTHESES, IT IS A POWERFUL RESEARCH TOOL FOR UNDERSTANDING THE RESPONSES OF OCEAN ECOSYSTEMS IN THE CONTEXT OF CLIMATE CHANGE."

The Change to Carbon Credits

While the fertilization of the waters near the Marshall Islands never did take place, the idea of commercializing the ecosystem response to ocean fertilization did not disappear. Instead, it morphed. As Markels wrote in 1998, "Ocean fertilization also promises benefits that should be welcomed by those concerned about possible global warming. The growth of phytoplankton in the ocean removes CO_2, a greenhouse gas, from the ocean surface and the atmosphere. About half of the carbon removed in fertilized areas will sink to the bottom of the deep ocean…The continuous fertilization of the same 100,000 square miles of tropical ocean should sequester about 30 percent of the CO_2 produced by the United States from the burning of fossil fuels" (Markels, 1998). This statement was published before any OIF experiment had provided an estimate of carbon export from an iron-induced bloom. A year later in an article in the journal of the Cosmos Club, Markels discussed combining the dual purposes of ocean farming and carbon sequestration from OIF. He also started a new company, GreenSea Venture, which sought to commercialize ocean fertilization to sell carbon offset credits for sequestered CO_2 (Markels, 1999).

A More Crowded Field: GreenSea Venture Gets a Competitor

In the late 1990s, a second corporation seeking to invest in ocean iron fertilization as a way to sequester carbon and sell carbon offset credits, Carboncorp USA, was created. According to an archived copy of the Carboncorp USA Web site (Carboncorp USA, 1999), "Ocean Carbon Sequestration (OCS™) patented nutrient supplements will stimulate an immediate plankton bloom. This bloom of plant biomass removes CO_2 from the atmosphere and stores it safely in rich phytoplankton." At the time, Carboncorp USA proposed to use commercial ships traversing shipping lanes on the high seas to meter small amounts of the company's nutrient supplements into the water. The idea was to offset the emissions of the shipping by sequestering carbon and selling credits (Carboncorp USA, 1999; Adhiya, 2001).

By 2001, Carboncorp USA had disappeared, and many of its ideas were presented by Ocean Carbon Sciences Inc., led by Vancouver-based entrepreneur Robert Falls. Representatives from both Ocean Carbon Sciences Inc. and GreenSea Venture were invited participants in a 2001 ASLO workshop on iron fertilization (ASLO Workshop Statement, 2001), as commercial ocean fertilization for carbon sequestration was attracting attention and investment (Krivit, 2007).

Scaling Up: A Proposal For a Technology Demonstration

Ocean Carbon Sciences Inc. initially committed $325,000 CAD to the Canadian component of the SERIES experiment, but defaulted on the pledge, did not participate in the experiment (Canadian SOLAS Report, 2003), and made little headway toward conducting its own experiment. GreenSea Venture, however, was moving forward. In 2001, Michael Markels teamed up with Richard Barber, a highly respected biological oceanographer at Duke University and one of the scientific team from the original IronEx experiments. At the 2001

National Energy Technology Laboratory Conference on Carbon Sequestration, hosted by the Department of Energy, Markels and Barber announced plans for GreenSea to move ahead with a 5,000-square-mile "technology demonstration" of ocean iron fertilization for carbon sequestration in the HNLC region of the equatorial Pacific (Markels and Barber, 2001). Supporting their proposal, they cited the two IronEx experiments, SOIREE, and Ocean Farming's two Gulf of Mexico demonstrations. Although none of these experiments showed any carbon export from an iron-induced bloom, it was argued that increasing the size of the fertilized patch approximately 100 times from previous experiments would yield better estimates of carbon export potential of OIF (Markels and Barber, 2001). While the proposed technology demonstration never did take place, the commercial potential suggested in their proposal—quoted at a cost of $2 per ton of sequestered carbon dioxide, including the cost of verification, overhead, and profit—served to broaden the discussion about the ways in which ocean fertilization experimentation should move forward.

Despite no direct scientific evidence that ocean fertilization could substantially slow global warming, the simply stated appeal of OIF as a quick climate fix continued to attract media attention. This attention, in turn, further fueled commercial interest in the idea. In an interview with *Wired* magazine in 2000, Markels claimed that "given 200 boats, 8.1 million tons of iron, and, say, 11 percent of the world's ocean," he could "zero out global warming. Next question?" (Graeber, 2000). The vision of commercial ventures interested in using iron fertilization for geoengineering was unquestionably large in scope and was not being dictated by the results of initial scientific OIF experiments.

Scientists Give Mixed Signals

At this point, the activities of GreenSea Venture and Ocean Carbon Sciences elicited a response from oceanographers, who raised concerns about the disconnect between scientific evidence and commercial proposals. Several of us cited the difficulties of verifying the magnitude of carbon sequestration explicitly caused by ocean iron fertilization, and argued that this would make ocean fertilization ineligible for carbon credits (Chisholm et al., 2001). We pointed out further that widespread ecosystem disruption is inherent to the design of ocean fertilization, and the unintended consequences of this disruption would likely be significant and unpredictable. Although we maintained that ocean iron fertilization should not be conducted on a commercial scale, we also made explicitly clear that we were not arguing against small-scale scientific iron enrichment experiments designed to answer specific questions about how marine ecosystems function. Some felt that we had "overstated the current knowledge in reaching [our] opinion that iron fertilization is not a viable option for CO_2 management" (Johnson and Karl, 2002), and countered that verifying carbon credits is not the critical issue, what is key is whether OIF "is a feasible strategy to mitigate increasing CO_2 in the atmosphere" (Johnson and Karl, 2002). Thus, the potential for climate mitigation using OIF was gaining credibility (at least as a testable hypothesis) in the scientific community.

THE RECENT HISTORY OF COMMERCIAL OIF AND OIF REGULATION

Commercial Ventures Continue to Experiment

As scientists were gearing up for the SOFeX experiment in the Southern Ocean, California-based entrepreneur Russ George founded the Planktos Foundation, which billed itself as a not-for-profit organization seeking to use iron fertilization to solve global warming. Planktos offered, for sale by charitable donation on the Internet, $4 "Green Tags" (Planktos Green Tags, 2002), which were in effect like personal, small carbon footprint offsets and would be used to support the foundation's efforts to develop iron fertilization as a technology for carbon sequestration (Plotkin, 2002).

In the summer of 2002, temporally and geographically between SOFeX in the Southern Ocean and SERIES in the Gulf of Alaska, the Planktos Foundation conducted its own iron fertilization "demonstration," dumping iron-containing paint pigment into the North Central Pacific along a 50-km transect east of Hawaii (not HNLC waters) from Neil Young's antique sailing yacht, *Ragland* (Schiermeier, 2003). Journalist Wendy Williams quoted Russ George in a piece for *Living on Earth* as arguing that this fertilization project had induced a large phytoplankton bloom and had sequestered enough carbon to offset the entire carbon footprint of his California hometown of Half Moon Bay. George further described Planktos' activity as "really more of a business experiment" (Williams, 2003). Although the results of the experiment were never made public, a description of the activity was

Box 2A. United Nations Convention on the Law of the Sea (UNCLOS)

WHAT:

- International treaty first passed in 1982 that governs territorial legality of the ocean areas.
- United States has not yet ratified it, but many provisions are regarded as binding international law.
- The Law of the Sea sets limits for exclusive economic zones and laws of conduct on the high seas.
- UN General Assembly passes relevant resolutions. UN's International Maritime Organization and other organizations administer UNCLOS.

HOW IT RELATES TO OIF: Several general provisions of UNCLOS are relevant to OIF. Article 145 stipulates that use of the high seas for marine scientific research must be for peaceful purposes geared toward the increase of knowledge and understanding for all humankind. Various other articles outline requirements of states to protect life of the marine environment. UNCLOS is also relevant to OIF for fish production, as it governs both the delimitation of fishing rights within exclusive economic zones (EEZs) and fishing rights on the high seas.

KEY STATEMENTS AND DECISIONS ON OIF:

Dec 2007: General Assembly resolution calls for more research into the effects of ocean iron fertilization.

Dec 2008: General Assembly resolution welcomes London Convention and Convention on Biological Diversity decisions against large-scale OIF.

FUTURE REGULATIONS: Although the General Assembly has not yet passed specific regulatory resolutions regarding OIF, the centrality of UNCLOS to maritime regulation, and its relevancy to environmental protection, scientific research regulation, and international waters legal issues, could make it a good forum for coordinated regulation of iron fertilization in the future.

published in the news feature section of *Nature* the following year (Schiermeier, 2003), including a photo of George on *Ragland*. The Planktos Foundation, and the entire idea of carbon credit sale from ocean fertilization, was gaining attention and momentum.

Legal Issues Arise

As it became evident that commercial operations were moving forward, concerned scientists and environmental groups continued to raise questions about the efficacy and legality of commercial ocean fertilization. There appeared to be no law preventing ocean fertilization beyond the 200-mile exclusive economic zone of any country (Markels and Barber, 2001; McKie, 2003). Indeed, to our knowledge, the initial, small-scale, scientific OIF experiments were carried out without permits, as there were no clear statutes at the time. Also, it was widely recognized that the small scale of the experiments rendered their impacts miniscule and ephemeral by any measure.

Several international treaties cover activities in international waters, including the United Nations Convention on the Law of the Sea, the 1972 London Convention on Marine Pollution and Ocean Dumping, and the 1959 Antarctic Treaty, which covers portions of the Southern Ocean. The UN Convention on Biological Diversity also regulates activities that will impact ecosystem species diversity (see Boxes 2A, 2B, and 2C). At a 2001 ASLO workshop on ocean fertilization, the former secretary of the Intergovernmental Oceanographic Commission, Geoff Holland, stated that "there are no legal precedents that apply directly to ocean fertilization, though there are parts of existing laws that are relevant" (Holland, 2001). At the time, it was not clear whether ocean fertilization fell under the purview of the London Convention, and the lack of clarity on the legal issue meant that commercial interests could move ahead, for the time being.

Commercial Ventures Advance Plans for Fertilization as Scientists Debate Its Future

After 2004, while scientists were analyzing previous results and planning future experiments, commercial interests continued to advance their plans. The

Box 2B. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972 London Convention and 1996 London Protocol)

WHAT:

- 1972 intergovernmental treaty involving 86 countries.
- Headquarters: International Maritime Organization in London, a UN organization.
- London Convention regulates pollution via dumping at sea (but not coastal runoff).
- Some dumping pollution (such as scrap metal) is regulated, and some (such as mercury) is banned outright.
- 1996 London Protocol expands the London Convention to use the "Precautionary Principle" and reduce pollution.
- United States is party to Convention, but has signed but not ratified the London Protocol.
- US enforcement of London Convention by EPA under Marine Protection, Research, and Sanctuaries Act of 1972.
- Enforcement is by each country in its own waters and to ships sailing under its flag. No international enforcement.

HOW IT RELATES TO OIF: Because iron fertilization activities require the addition of inorganic material in the HNLC regions of the world ocean, and generally take place in international waters, the London Convention is deemed relevant. This relevancy has been the subject of some discussion, however, as the London Convention regulates dumping for disposal of waste. Because OIF for carbon sequestration would sequester carbon in the deep ocean, the discussion of whether OIF is more appropriately the dumping of carbon has also been raised.

KEY STATEMENTS AND DECISIONS ON OIF:

Jun 2007: Scientific Group issue "Statement of Concern" to the London Convention over large-scale ocean fertilization activities.

Nov 2007: London Convention Resolution adopts "Statement of Concern" and agrees that ocean fertilization falls under the resolution's purview.

May 2008: Scientific Group outline what ocean iron fertilization entails and detail some unknown risks.

Oct 2008: London Convention Resolution states that no ocean fertilization activities other than "legitimate scientific research" (to be defined in 2009) should be allowed.

Feb 2009: Technical Working Group drafts ecological risk assessment framework for OIF research stipulating that the research must be hypothesis-driven. This point does not rule out commercial gain or carbon credits from legitimate research.

Feb 2009: Legal Working Group proposes new resolutions and new binding articles on OIF, outlining future regulatory possibilities for consideration of the full Convention.

May 2009: Scientific Group meet in Rome to consider reports from the working groups and to start outlining the acceptable levels of negative environmental impacts from legitimate scientific research (i.e., experiments 200 x 200 km or smaller).

FUTURE REGULATION: The London Convention is clearly grappling with the difficult issue of regulating scientific research at the supranational level. At the same time, there is a clear push toward further restriction of nonscience OIF activities. Specific proposals from the February 2009 working groups range from outright bans of all nonscience OIF activities to "suspensions" of activity until more data can be gathered. The questions of commercialization, ecological assessment, and degree of enforcement/intensity of regulation have all been raised but none of them is resolved. The Scientific Group have started to discuss the questions about how much of an environmental impact from scientific research is too much and will present a report to the governing bodies of the convention when they meet in London in the fall of 2009.

Planktos Foundation became Planktos Inc. in 2005 and was shortly thereafter purchased by Solar Energy Limited (Business Wire, 2005a). Later that year, Diatom Corporation agreed to purchase the marketing rights for carbon credits generated from Planktos Inc.'s iron fertilization activities (Business Wire, 2005b). About 18 months later, publicly traded Diatom Corp. became Planktos Corp. (Business Wire, 2007). During this time, the other commercial entity involved in OIF, GreenSea Venture, had moved from ocean fertilization demonstrations to financial support for

Box 2C. United Nations Convention on Biological Diversity (CBD)

WHAT:

- International treaty established at the Earth Summit in Rio de Janeiro in 1992.
- Dual purposes of biodiversity conservation and sustainable use and equitable distribution of resources.
- All UN nations are party, except the United States, which has signed but not ratified the treaty.
- The Convention is administered by the UN Environment Programme (UNEP).
- Enforcement by individual ministries of member states.

HOW IT RELATES TO OIF: The Convention regulates actions that threaten biodiversity, including marine biodiversity. In this way, the unknown ecological effects of large-scale OIF implementation fall under the purview of the Convention.

KEY STATEMENTS AND DECISIONS ON OIF:

May 2008 CBD Decision: "All large-scale OIF activities should not be allowed."

- Makes exception for "small scale studies in coastal waters." Coastal waters may be an aberration.
- Decision explicitly mentions commercial interests as a reason not to allow OIF.
- Decision passed because of ecological risks of OIF and uproar over Planktos' experimental plans.
- Widely viewed as a "UN moratorium" on commercial OIF activities.

FUTURE REGULATIONS: The CBD suggested that OIF regulation be done in coordination with the International Maritime Organisation (IMO) and London Convention. It calls for a global transparent control and regulatory mechanism to be established, and urges consultation with all parties involved to establish a knowledge base about the associated ecological risks.

NOTE ON CBD ENFORCEMENT: In early 2009, the German research ministry cited the UN CBD COP 9 moratorium on ocean fertilization in its decision to suspend the Indo-German LOHAFEX OIF experiment. It demanded more environmental risk assessments and independent scientific assessments of the project, specifically mentioning the coastal water stipulation and citing the ecological concerns raised by CBD. Although the experiment was eventually given the green light, it was a first test of country-specific enforcement of international treaties on this issue and has informed the London Convention working groups' discussions on how best to regulate the science of OIF.

biogeochemical modeling (Chu et al., 2003; Rice, 2003). Meanwhile, Dan Whaley, a former information technology entrepreneur, founded Climos Inc., a for-profit company setting out to pursue the same goals as Planktos Inc.: selling carbon credits from ocean iron fertilization (Riddell, 2008). Thus, by 2006, two companies operating in the San Francisco Bay area—Climos and Planktos—were developing the business of iron fertilization.

In late 2006, it was reported that Planktos donated carbon credits to two California environmental organizations to make them "carbon neutral" for 2007 (Industrial Environment, 2006), a claim that was based on an upcoming pilot demonstration of ocean fertilization. At this time, Planktos was describing itself as an "ecorestoration" company, seeking to replenish what was described as diminished plankton stocks in the ocean, in addition to sequestering carbon for offset credits. In a 2007 presentation to the US House Committee on Energy Independence and Global Warming, Planktos' Russ George stated that "our ocean plankton restoration pilot projects will generate the first substantial iron seeded blooms aimed at serving our twin purposes of restoring ocean plant ecosystems and sequestering atmospheric CO_2" (George, 2007).

Planktos Folds Before It Can Fertilize

In early 2007, Planktos Inc. announced plans to conduct a large fertilization experiment in the equatorial Pacific near the Galápagos Islands. Like the proposed Markels-Barber demonstration, the experiment was to be on a previously unachieved scale of 10,000 km^2; it would be the first pilot project in a planned "Voyage of Recovery" (see Figure 5 for a sense of the relative size of this experiment). The company purchased a retired research vessel, *Weatherbird II*, from the Bermuda Biological Station to execute the experiment (Environmental Protection Agency, 2007). The scale and seriousness of this proposal, coupled with increasing concerns about risks to marine ecosystems, mobilized environmental NGOs. The Canadian-based ETC Group called on the US Environmental Protection Agency (EPA) to stop the Planktos experiment (ETC Group News Release, 2007). The World Wildlife Fund argued that Planktos was taking too big and too dangerous a leap with the scale and intent of the experiment, especially because it was near the Galápagos Islands (Sullivan, 2007). The Sea Shepherd Society threatened to block Planktos' fertilization ship physically (South Bay, 2007), arguing that it was a violation of international laws on marine dumping (the London Convention; Sea Shepherd News, 2008).

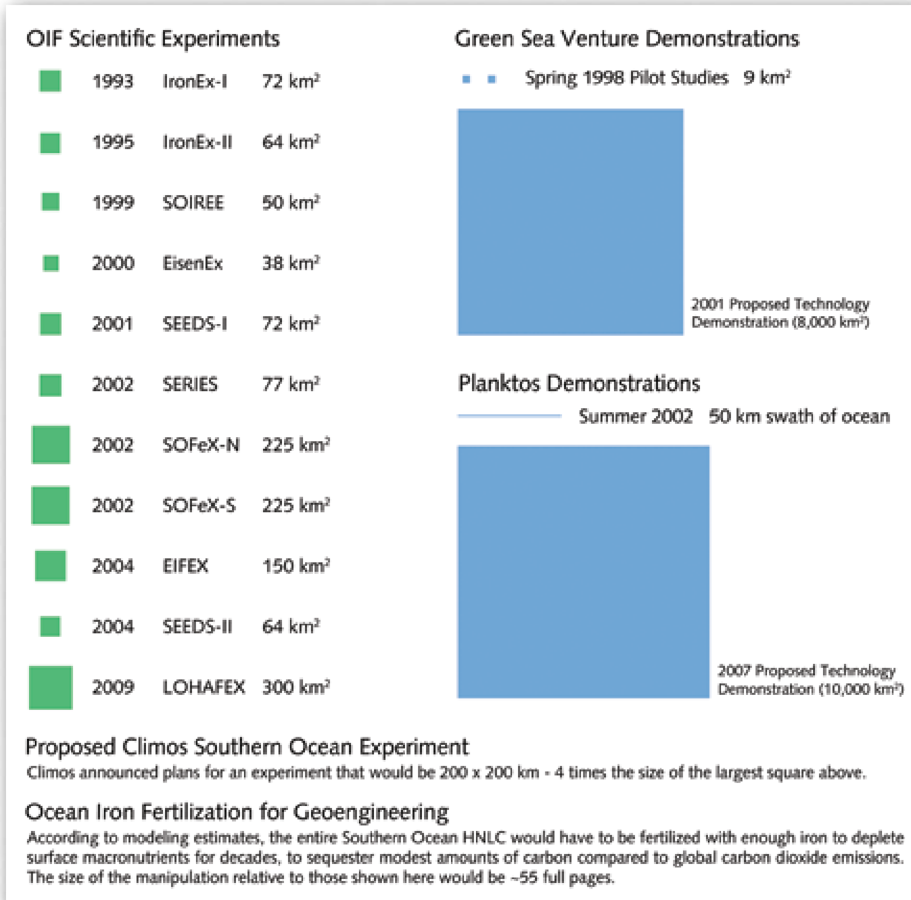

Figure 5. The relative sizes of fertilized patches in ocean fertilization experiments, and in demonstrations carried out, or proposed, by the private sector. At bottom is an estimate (based on the model of Zahariev et al., 2008) of the size of the patch that would result from fertilizing the HNLC regions of the Southern Ocean.

With international law once again in question, the legal arguments began to mount. The Scientific Group of the London Convention issued a June 2007 statement of concern about Planktos' plan (Scientific Group of the London Convention Meeting Report, 2007). In a statement submitted at that London Convention meeting, the US EPA announced that it would not permit the Planktos plan to proceed under the US Marine Protection Research and Sanctuaries Act of 1972 (the US enforcement of the London Convention) if Planktos was flying a US flag from *Weatherbird II* (Parks, 2008; Scientific Group of the London Convention Meeting Report, 2007). Apparently, Planktos assured the EPA that it would not be sailing under a US-flagged ship (International Center for Technology Assessment, 2007), which seemed to contradict that *Weatherbird II* was a US-registered vessel and would set out from a US port for the experiment. Because of the proposed experiment's proximity to the Galápagos, the government of Ecuador also issued statements of alarm (Scientific Group of the London Convention Meeting Report, 2007). In the fall of 2007, as Planktos' vessel prepared to leave the eastern coast of the United States, the full Conference of Parties to the London Convention issued a statement of concern about the legality and wise practice of large-scale ocean iron fertilization activities, taking the first step toward explicit international regulation of iron fertilization (London Convention Meeting Report, 2007).

Planktos' experiment did not take place (Courtland, 2008). Citing concerns over disruption of their activities, *Weatherbird II* left port headed to an undisclosed location in the Atlantic

Ocean. When the ship approached the Spanish-owned Canary Islands, reportedly to pick up supplies, the Spanish government refused it port entry (Consumer Eroski, 2007), a decision that Planktos blamed on environmental organizations (Thompson, 2008). The ship eventually docked in the Portuguese island of Madeira to take on needed supplies (San Francisco Business Times, 2007). Investors pulled out of Planktos, and, in early 2008, Planktos Corp. ended its relationship with Planktos Inc., as did Solar Energy Limited. Planktos Inc. then suspended operations (Business Wire, 2008; Kerry, 2008), citing both a lack of funds and a "highly effective disinformation campaign waged by anti-offset crusaders" (Brown, 2008). Several months later in June 2008, Russ George started a new iron fertilization "ecorestoration" company, named Planktos-Science, though there has been little activity other than Web posts from this company thus far (see http://www.planktos-science.com/).

> "THE POTENT INTELLECTUAL RESOURCES THAT HAVE BEEN TIED UP IN THE OCEAN FERTILIZATION CONTROVERSY YEAR AFTER YEAR SHOULD BE FREED TO PURSUE MORE EFFECTIVE RESPONSES TO THE PERVASIVE THREAT OF CARBON DIOXIDE EMISSIONS AND GLOBAL WARMING."

Climos' Path Forward

These events left Climos as the leading company involved in the nascent commercial iron fertilization business. Since its inception, Climos made clear its intention to conduct research in collaboration with the scientific community, and to this end brought in Margaret Leinen, an accomplished oceanographer, and former Assistant Director for Geosciences at the US National Science Foundation, to be Chief Science Officer (Climos About Us, 2008). Climos' initial plan was to attract substantial business investment and to employ environmental consulting firms to produce codes of conduct for iron fertilization experiments as a first step toward eventual verification for carbon credit sale (Climos Press, 2007). Climos representatives have attended international meetings, UN meetings, and scientific conferences to participate in debating the future of iron fertilization science. At the same time, the company has also made clear its plans to conduct its own technology demonstration (Murray, 2008). In early 2008, Climos issued a press release responding to Greenpeace criticisms of plans for commercial OIF (Allsopp et al., 2007). In particular, Climos challenged what it described as Greenpeace's assumption that OIF for carbon sequestration would require large-scale and continuous fertilization, something that "no commercial entity has suggested should take place before a period of experimentation" (Leinen et al., 2008). On its Web site and in the press, Climos has announced plans for a Southern Ocean demonstration experiment that would be "part of a new phase of research focused on the efficacy and impact of moderately sized experiments (< 200 x 200 km)" that would "emphasize research related to export and sequestration as well as environmental impact" (Climos FAQ, 2008). In a statement to the press, Climos officials indicated that they hope to conduct their first trial by the end of 2009 and to be able to start selling carbon credits shortly thereafter (Murray, 2008). More recently, Leinen has been identified as Chief Executive Officer of the Climate Response Fund, "a nonprofit organization formed to provide funding and support for other activities needed to explore innovative solutions to the effects of climate change" (Climate Response Fund, 2009). At the time of this writing, it is unclear whether the formation of this new nonprofit organization will influence the plans of Climos.

Regulatory Clarity Is On The Horizon

In part due to the activities of Planktos, Climos is operating in a vastly changed regulatory arena than existed in the early years of commercial interest in ocean fertilization. Planktos' proposed experiment, and the vigorous response to it from environmental NGOs and the London Convention regulators, showed the first signs of a negative feedback loop. Up until this point, the trajectory had been continued expansion of commercial interest and proposed demonstrations, despite the absence of direct evidence for commercial claims from the results of scientific experiments. After concerns were expressed at the 2007 London Convention assembly regarding the planned Planktos experiment in fall 2007, representatives met again in May 2008. They reiterated their concerns about unchecked large-scale fertilization activities, and defined how iron fertilization fit under the jurisdiction of the London Convention (Scientific Group of the London Convention Meeting Report, 2008).

That same month, members of the UN Convention on Biological Diversity passed a decision on iron fertilization (UN CBD, 2008), citing the London Convention's statements of concern. They requested all member states to ensure that ocean iron fertilization activities do not take place, with the exception of small-scale scientific studies in coastal waters (see below), until there is adequate scientific basis on which to justify these activities. They emphasized that the excepted small-scale studies could not be used for the generation of carbon offset credits.

While the Convention on Biological Diversity did not explicitly define what was meant by "small scale," a report submitted by the Intergovernmental Oceanographic Commission (IOC), part of UNESCO, to the London Convention Scientific Group at Guayaquil in 2008, proposed that OIF activities greater than a size of 200 x 200 km (40,000 km^2) should be considered "large scale," and anything smaller would remain "small scale" (Scientific Group of the London Convention Meeting Report, 2008). The area 200 x 200 km is two orders of magnitude larger than the largest OIF experiments to date (Figure 5).

The stipulation of "coastal waters" in the CBD statement was largely viewed as an aberration, as most coastal waters are not iron limited, and this is why all previous scientific studies have taken place in the open ocean (Owens, 2009; Alfred Wegener Institute, 2009). Nonetheless, because the stipulation was written into the UN CBD language, members of the LOHAFEX scientific team found themselves having to find a way to describe their open-ocean experiment as "coastal" in order to proceed. Thus, when providing their risk assessment to the German Research Ministry during the experiment's suspension (see introduction above), they argued that iron fertilization in the Southern Ocean would stimulate the growth of "coastal species" of phytoplankton, an argument that was apparently accepted, as the German ministry ultimately allowed the experiment to proceed. If science and policy are to move forward on this issue, lines of communication between sectors should be continually improved.

A few months after the Convention on Biological Diversity decision, the full London Convention took up the issue of ocean iron fertilization once more, and passed a Resolution on the Regulation of Ocean Fertilization, announcing that all iron fertilization activities, with the exception of "legitimate science," were in violation of the London Convention's regulations on marine dumping. The London Convention also decided that technical and legal working groups would meet in February 2009 to determine what constitutes legitimate scientific research, establish an assessment framework, and propose future regulations under the Convention. A multi-step delineated environmental risk assessment framework was proposed for future experiments, including small-scale scientific experiments (Report of the First Meeting of the Intersessional Technical Working Group on Ocean Fertilization, 2009). The hope is to avoid the kind of controversy and uncertainty surrounding LOHAFEX by having a system in place to prevent confusion between scientific experiments and geoengineering projects.

In May 2009, the Scientific Group of the London Convention met to discuss the report of the Technical Working Group and attempt to further define the acceptable ecological impacts of "legitimate scientific research." Specifically on the agenda was a "Draft Action List for Ocean Iron Fertilization," proposed by representatives from Australia and New Zealand, which lists upper and lower limits for nutrient and chemical species concentrations (dissolved oxygen, pH, nitrous oxide, ammonium, and methane, among others) altered in response to a small-scale (less than 200 x 200-km) scientific experiment. Draft Action Lists are used by the London Convention process to regulate substances on the basis of their effects on the marine environment; the 2009 version entitled "Ocean Fertilization: Development of a Draft Action List" is the first step in the process of answering the question, "How much of a negative result from OIF is too much?" In the fall of 2009, the governing body of the London Convention will take up the reports from the meeting of the Scientific Group.

What remains unclear is whether these assessments of future small-scale scientific OIF experiments will be conducted at the international level of the London Convention, or by the science and research entities of the individual countries involved. Future regulation of larger-scale and nonscientific OIF activities also remains unclear. The Legal Working Group of the London Convention proposed a set of possible regulatory frameworks, ranging from a simply structured nonbinding resolution against large-scale OIF, to a full article amendment to the Convention explicitly prohibiting it (Report of the First Meeting of the Intersessional Legal and Related Issues Working Group on Ocean Fertilization, 2009). The working groups also avoided resolving the issue of whether commercialized carbon credits could be sold as a product of "legitimate scientific research," leaving that question to the full Convention. What is now clear is that the London Convention is the central international legal framework for this issue, and that regulation of OIF will be a subject of continued discussion and debate.

WHAT HAVE WE LEARNED?

A Repeated Cycle

Looking back, it is obvious that the first few years of debate about the iron hypothesis were a condensed version of the 20 years to follow. Small-scale ocean fertilization experiments were executed by oceanographers to address specific scientific questions; far-reaching interpretations, conclusions, and ramifications were highlighted by the media and by entrepreneurs, prompting a response from the scientific community urging caution, followed by calls from academics and commercial-sector proponents of OIF for more research. This cycle has played out repeatedly as the field of ocean iron fertilization has moved forward. And, despite the absence of direct scientific evidence for OIF as an effective long-term climate mitigation tool, appeals for research on its efficacy for this purpose have intensified over the 20 years since the first experiments, leading to larger and longer experiments. The dampening feedback from negative results, central to the advancement of scientific research, seems largely absent from this cycle.

The Science Does Not Support OIF For Global Geoengineering

Nearly two decades of scientific OIF experiments have taught us that iron limits productivity in several regions of the ocean. We have learned that the carbon export response to OIF is highly variable—strongly regulated by the availability of light and silicate as influenced by physics, and also sensitive to the interplay of many other factors that have yet to be resolved. And we have learned that on the temporal and spatial scales of the experiments, carbon export is often quite small due to remineralization of the phytoplankton bloom in the surface waters. Models show that at the limit—assuming complete macronutrient depletion and fertilization of the Southern Ocean for 100 years—what could be expected at most is global sequestration of 1.0 Gt C yr^{-1} (Table 2). In all modeled scenarios, the amount of CO_2 sequestered is small relative to the amount predicted to be released by fossil fuel burning, and the estimates of sequestration have only gotten smaller with more experimentation and modeling (Denman, 2008). Furthermore, models show that in order to maintain the carbon sequestration, we would have to continue to fertilize the entire Southern Ocean with enough iron to deplete macronutrients, in perpetuity. This scenario is not realistic.

Uncertainty and Risk

While the uncertainties about the efficacy of carbon sequestration from OIF as a geoengineering proposal are high (Buesseler et al., 2008), the certainty of ecological disruption is also high. OIF for carbon sequestration is *designed* to initiate a floristic shift to the production of larger, bloom-forming phytoplankton—in particular, diatoms that are heavy and can sink rapidly. This fundamental alteration of the base of a food web would change the structure and biogeochemical function of the community that depends upon it. The induced blooms would consume the excess macronutrients at the surface in HNLC regions, which, in combination with enrichment of deep waters (e.g., Fuhrman and Capone, 1991), would over time alter the biogeochemistry of the global ocean ecosystem. Although we cannot predict the precise changes that would occur, the only way in which iron fertilization can work for climate mitigation is to change deep ocean chemistry and the way endemic marine food webs function. There is considerable risk in trusting inherently uncertain predictions of such large-scale and long-term alterations of the ocean.

Long-Term Ocean Carbon Sequestration from Iron Fertilization Is Not Verifiable

Fertilization-induced changes in ecosystem function would not only have profound effects on the ecology of huge marine ecosystems, but they would also affect the potential efficacy of OIF as a carbon sequestration strategy. As Gnanadesikan et al. (2003) point out, in order to accurately model the net global benefit of carbon sequestration, all downstream effects on biological productivity must be counted, including potential disruption of fisheries from the depletion of macronutrients in the source waters of productive ecosystems. These negative effects may outweigh the benefits of carbon export. Besides the potential for changes in net global productivity, OIF could stimulate nitrous oxide production as a result of increased remineralization of carbon and nitrogen (Denman, 2008). This would result in longer-term and far-field changes in nitrous oxide production that could potentially offset significant amounts of predicted green-house gas benefits of OIF (Law, 2008). It can thus be argued that measurements associated with individual experiments cannot be adequate to verify what would ultimately be a long-term, large-scale effect of many applications of iron (Cullen and Boyd, 2008).

These complex downstream responses to ocean fertilization make verification of net greenhouse gas reduction through fertilization next to impossible (Chisholm et al., 2001; Cullen and Boyd, 2008; Gnanadesikan and Marinov, 2008). Furthermore, carbon export measured as a result of a fertilization-induced bloom would have to be referenced to a baseline rate of carbon export. As ocean fertilization and carbon flux research has shown, this natural rate of carbon export is highly variable in space and time; establishing an appropriate baseline to grant carbon credits for individual applications would be exceedingly difficult, and rife with uncertainty (Figure 6).

At present, there is no system under the Kyoto Protocol's Clean Development Mechanism to provide for carbon credits from offsets by marine carbon sequestration (Powell, 2007–2008). Thus, under the current international mechanism, any credits granted would therefore have to be sold on the currently unregulated "voluntary carbon credit market." Although Climos Inc. submitted a carbon sequestration methodology to Det Norske Veritas, an international verification company, in late 2007 (Climos Press, 2007), official approval or verification has not been given to OIF as a carbon sequestration methodology. Nonetheless, in the future, international carbon credit regulatory systems may well include provisions for marine "sequestration" offsets (Powell, 2007–2008). It will then be very important for OIF proponents to show in their plans that the effects of wide-scale, long-term carbon sequestration from OIF are predictable, acceptable, and statistically verifiable across ocean basins over decades. In our opinion, assessments of individual applications are not enough.

Should We Continue to Test OIF for Climate Mitigation?

Arguments have been made for 20 years that OIF should not be pursued as a "quick-fix" for the climate problem. We hope we have shown that the original arguments have not been weakened

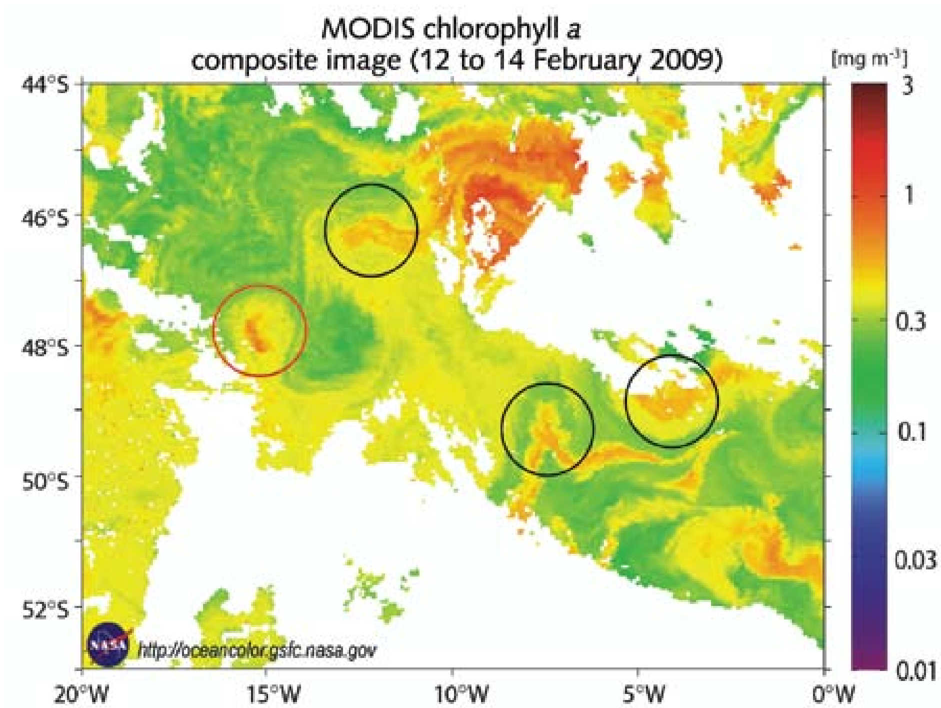

Figure 6. Commercial ocean fertilization, which would involve validated carbon credits, would have to demonstrate that the iron-induced bloom would not have otherwise occurred. This satellite chlorophyll *a* image shows the bloom induced by iron addition during LOHAFEX (red circle). Three other blooms are circled in black. How would one prove that the intentionally fertilized waters, if left alone, would not have bloomed like the neighboring waters? *Image taken from: http://www.awi.de/en/infrastructure/ships/polarstern/weekly_reports/all_expeditions/ant_xxv/ant_xxv3/26_february_2009/*

by new evidence over that interval. Ocean fertilization will not solve the CO_2 problem, and if implemented for profit, regardless of scale, has the potential to change the nature of the ocean through the "tragedy of the commons" (Hardin, 1968). Perhaps it is time to break the two-decade cycle of debate and accept that we know enough about ocean fertilization to say that it should not be considered further as a means of climate mitigation. But our opinions aside—and they are indeed opinions, though science-based—a fundamental issue remains: the ecological and climate mitigation response to OIF is scale-dependent (Buesseler et al., 2008; Cullen and Boyd, 2008), and the biogeochemical changes would be cumulative. The only way to test OIF as a climate mitigation tool (i.e., to see if model projections are right) would be to alter much of the ocean system, perhaps irreversibly, before crucially important negative effects could be evaluated with statistical confidence. We feel that the risk of doing this does not compare well to even the most optimistic predictions of potential climate mitigation.

Moving On

Climate change is already upon us. Society needs to know what the ocean will be like in a high CO_2 world—which ecosystems will be at risk as the ocean warms and acidifies, and how the altered ocean will in turn influence climate. Understanding how ocean biogeochemical cycles are linked, and the processes that drive these cycles, is essential for climate prediction. Transformational developments in genomics along with rapid advances in ocean observations and modeling (Doney et al., 2004) allow us to study the ocean as a system on scales from molecules to ocean basins, and we are poised to fully integrate studies of evolution and biogeochemistry (Woese and Goldenfeld, 2009). These developments open new vistas for understanding the very basis of life processes, and it is these very life processes that, scaled up, regulate the concentration of CO_2 and other greenhouse gases in Earth's atmosphere. In this context, small-scale ocean perturbation experiments are useful tools for probing ecological and biogeochemical relationships, and they should continue to be used as such. The potent intellectual resources that have been tied up in the ocean fertilization controversy year after year should be freed to pursue more effective responses to the pervasive threat of carbon dioxide emissions and global warming.

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