

Southern Ocean Iron Fertilization: An Argument Against Commercialization but for Continued Research Amidst Lingering Uncertainty

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Executive Summary: In light of the challenges impeding substantive global action on climate change mitigation, some have begun to look at geoengineering as a possible alternative. Ocean Iron Fertilization (OIF) is one such strategy that seeks to increase oceanic drawdown of carbon dioxide by stimulating marine phytoplankton growth in large iron-limited swaths of the Southern Ocean. Unfortunately, there remains lingering scientific uncertainty regarding the viability of a sustainable, global scale, iron-induced sequestration pathway. While reduced uncertainty could one day reveal a reasonable, measured approach to leverage OIF under unilateral authority and dynamic management, I argue against attempting to commercialize OIF under any emerging market framework. Current standards for globally recognized compliance offset markets require that a recognized activity is permanent, additional, free of leakage, and absent of adverse side effects. At present, there is not adequate scientific evidence that OIF is any. Worse, measurement challenges, unreliable auditing, ambiguous baselines compromised by high-frequency variability, and uncertain externalities could combine to cripple a market-based approach. Fortunately, the UN London Protocol has banned non-scientific iron fertilization, precluding the adoption of OIF into any international, compliance offset markets. However, voluntary offset markets, or those in which offsets are bought and sold without any federally mandated obligation, are not subject to any legitimate regulatory or enforcement mechanisms. I make that case that absent the appropriate oversight OIF activity on voluntary offset markets motivated by a reasonable market opportunity, the relative ease of deployment, and the perception of an ethical imperative, can, and will continue to, emerge. In turn, I argue that continued research is necessary to help constrain the public perception that voluntary markets depend on by further clarifying the risks, elaborating the challenges, and delegitimizing the promise of an iron bullet.

I. Introduction

Although geophysical scientists can say with increasing certainty that anthropogenic climate change poses a serious threat to human life and livelihood (IPPC AR5 2014), decisive political efforts to reduce emissions have proven slow and

insufficient (Clark 2012; Hovi et al. 2009; Shear 2018). Hedging against the potential for a collective action crisis of this scale (Thompson 2006) many have turned to adaptation to confront a future potentially plagued by unchecked fossil fuel consumption. The most dramatic of these adaptation strategies, known

broadly as geoengineering, can be categorized as any deliberate, large-scale, manipulation of natural processes to affect the climate system, ostensibly to curb the effects of global warming.

Geoengineering is an understandably enticing proposition. By targeting the symptoms of a carbon heavy economy (i.e. increased levels of carbon dioxide (CO₂)) for pennies on the dollar, geoengineering evades the daunting economic and cultural sacrifices that serious mitigation might demand. While its proponents preach the need to leverage human ingenuity (Lynas 2011), the temptation of such a convenient *deus ex machina* raises some serious red flags. Critics stress that in the complex, non-linear, earth system the treatment may not work as advertised, allowing the underlying cause to aggravate while unpredictable, side effects fester unchecked (Robock et al. 2008). Despite the controversy, the promise of a silver-bullet techno-fix has proven difficult to ignore, attracting attention from activists (Keith 2013), policymakers (Full Committee Hearing - Geoengineering, Part I 2009; Reichle et al. 1999), and scientists alike (Yoon et al. 2016).

One of the most prominent geoengineering strategies is carbon sequestration. The global carbon cycle, which influences climate via the radiative capacity of atmospheric carbon dioxide, largely operates on two time-scales. The 'slow' carbon cycle, driven by tectonic activity, is balanced by volcanic outgassing and geological weathering (Berner 1990). The 'fast' carbon cycle, driven by biology, is balanced by the reduction of inorganic carbon by photosynthesis and the oxidation of organic carbon by respiration (Riebeek 2011). Although these two cycles are naturally linked by the eventual fossilization of organic matter, the rapid anthropogenic combustion of fossil fuels is pumping CO₂ out of the 'slow' cycle much faster than natural cycles can compensate for (Chisholm et al. 2001). The goal of carbon sequestration then is to geoengineer a carbon sink that is capable of routing carbon back into the 'slow' carbon cycle at a rate commensurate with which we are extracting it.

Ocean Iron Fertilization (OIF) is one of several carbon sequestration strategies. OIF seeks to harness the power of ocean biogeochemistry to amplify atmospheric CO₂ drawdown by augmenting

inefficiencies in phytoplankton productivity. Microscopic marine phytoplankton account for roughly half of the photosynthetic reduction of inorganic carbon into organic carbon on earth (Falkowski et al. 2000) and thanks to the rapid turnover time of their population (~1 week) they are able to influence climate on a much faster timescale (Falkowski 2002) than terrestrial plants. Although most of the carbon reduced by marine photosynthesis is rapidly recycled and released back to the atmosphere, a small fraction (~15%) is exported by sinking deep into the ocean where it might remain sequestered for tens to hundreds of years (Laws et al. 2000); This process is known as the biological pump (de la Rocha 2006). OIF hopes to increase the strength and efficiency of the biological pump thereby stimulating greater net atmospheric CO₂ drawdown into the ocean (see Figure 1).

Variability in the biological pump is widely accepted as an important factor in regulating glacial-interglacial cycles in atmospheric CO₂ (Berner 1991; Sigman and Boyle 2000), however the precise mechanisms that drive changes to the biological pump are less clear (Falkowski 1997). In the late 1980s John Martin proposed that iron was limiting primary production over large swaths of the ocean (Martin and Fitzwater 1988). Iron is a micronutrient essential to phytoplankton growth but only required in small concentrations relative to macronutrients like Nitrogen and Phosphorus. Regions, known as HNLCs (High Nitrate, Low Chlorophyll), that yield low primary productivity despite an abundance of unutilized macronutrients are now thought to iron-limited. Martin went on to hypothesize that variability in the airborne deposition of iron over HNLC regions has triggered variability in primary productivity, the biological pump, and the net drawdown of atmospheric CO₂ over glacial-interglacial cycles (Martin 1990). Following Martin's hypothesis, OIF seeks to fertilize HNLCs with the deliberate addition of iron in order to increase the strength of the biological pump and enhance oceanic drawdown of atmospheric CO₂.

Research over the ensuing decades ranging from shipboard in-vitro incubations (Martin et al. 1991) to mesoscale in-situ fertilization experiments (Yoon et al. 2016) has largely confirmed that iron fertilization can in fact stimulate primary production in HNLCs. It is decidedly less clear, however, whether or not that

increased productivity is routed into localized export (Boyd et al. 2007). When considered at a global scale, there remains even more doubt over the validity of a sustainable iron-induced sequestration pathway (Winckler et al. 2016). Additional concerns over the practical challenges of creating a credible auditing framework and the potential for unpredictable, adverse side effects create further complications.

Nevertheless, the allure of OIF remains theoretically seductive. HNLCs cover roughly a third of the world's oceans (Boyd et al. 2007) and if continuous fertilization was generously assumed to utilize and export all previously unutilized nutrients, models predict an atmospheric drawdown as high as 50-100 ppm CO₂ (Aumont and Bopp 2006) with up to several hundred million tons of sequestered CO₂ per year (Buesseler et al. 2008b), nearly 5% of the anthropogenic CO₂ released annually (IPCC AR4 2007). Despite substantial uncertainty associated with the assumptions requisite of these model estimates, geochemical proxies in ice cores (Winckler et al. 2008) linking elevated iron to depressed atmospheric CO₂ and recent observations of localized export after an artificially induced bloom (Smetacek et al. 2012) have provided additional hope for proponents of OIF. While, OIF could not alone tackle the entirety global emissions, fractional gains could constitute an important piece of a more diversified approach. For instance, in the Stabilization Wedge strategy championed by Pacala and Socolow (Pacala and Socolow 2004), a complete reduction in emissions is the composite result of progress towards several separate reduction strategies, or stabilization wedges. If optimistic estimates for sequestration were met, OIF could potentially account for one of Pacala and Socolow's proposed stabilization wedges (Pacala and Socolow 2004), enough to garner considerable attention (Buesseler et al. 2008a).

Faced with the simultaneous allure and uncertainty surrounding OIF, two predominant questions emerge. First, given the scope of the climate crisis, could the commercialization of OIF under emerging compliance offset markets be a valuable piece of the solution despite lingering scientific, economic and environmental concerns? In light of looming challenges to the safety and efficacy of global-scale market-based OIF, in Section II I present the case against commercialization. Second, if not, is it prudent to dedicate valuable, finite, scientific

resources to continuing incremental research targeted at reducing the uncertainty clouding the feasibility, implementation, and risk of OIF? Even if commercialization under compliance markets is already deemed unacceptable by scientists and policymakers, in Section III I present the case that continued research is vital to delegitimize future developments in voluntary carbon markets that, at present, may be incentivized to proceed contrary to the precautionary principle.

II. The case against commercialization

At present, the commercialization of OIF is not advisable. There is not sufficient evidence that a market-based approach to OIF could satisfactorily comply with existing standards for international offset markets or demonstrate with reasonable confidence that it would be safe from adverse, unintended consequences. The Clean Development Mechanism (Gillenwater and Seres 2011), developed under the Kyoto Protocol, has become the preeminent international offset program and has set basic guidelines for qualifying projects. Eligible projects must be, amongst other stipulations, permanent, additional, free of leakage, and amenable to monitoring (Gillenwater and Seres 2011). Implicit in the consideration of any project of this scale is that it does not inflict harm in excess of its benefit. In the context of OIF this amounts to three basic questions.

First, will it work? That is, will fertilizing iron-limited swaths of the ocean stimulate new ("additional") production that will sequester carbon into the deep ocean for long periods ("permanent") without leading to downstream reductions in productivity ("leakage") triggered by upstream macro-nutrient utilization? Second, can it be measured? That is, can the net additional carbon sequestration from an individual OIF project be quantified accurately enough to ensure fair and consistent compensation? Third, is it safe? That is, could the rapid and dramatic modifications to ocean ecosystems lead to negative impacts on human health or the environment from adverse? The litany of challenges, risks, and lingering uncertainty that beguile each of these questions is detailed respectively in the following subsections (also see Figure 2). In light of these complications, I conclude that safe, predictable, and effective management of OIF in a market framework would likely fail.

i. Will it work?

In order to effectively sequester carbon, OIF would need to stimulate the primary production of new organic biomass that is eventually exported out of the surface ocean to the deep where it must remain for adequate time scales before being transported back to the surface ocean where it can be released back to the atmosphere. Further, this entire process must be induced without triggering disproportionate, competing effects wrought by dramatic ecosystem change or downstream effects. Each of these links is examined in detail below.

Does iron fertilization stimulate new production?

Over the last three decades, a series of iron enrichment experiments have confirmed that artificial iron fertilization, at relatively small scales and carefully selected sites, can in fact stimulate new production. After Martin's Iron Hypothesis was proposed in 1991, early shipboard incubations (Martin et al. 1991) began to provide compelling evidence for iron limitation. Although these incubations were plagued by methodical biases, the results were enough to prompt an era of in-situ, iron enrichment experiments (Chisholm and Morel 1991). Since 1990, 13 mesoscale artificial enrichment experiments have been performed, with 7 located in the Southern Ocean.

These experiments were all carried out in a similar manner. Several hundreds of kilograms of Iron, dissolved into acidified seawater, were dumped into HNLC surface waters of the span of several days (or sometimes weeks), while the concurrent addition of SH_6 , a biologically inert chemical tracer, allowed the water parcel to be tracked and observed in a Lagrangian framework for the following 10-40 days (Boyd et al. 2007). The ensuing biogeochemical response consistently showed an increase in photosynthetic efficiency, chlorophyll concentration, primary production and a corresponding drawdown of CO_2 and macro-nutrients (Yoon et al. 2016). Collectively, combined with observations of naturally enriched waters (de Baar et al. 2005), results have demonstrated fairly convincingly that iron fertilization does stimulate local productivity in certain HNLC regions (Boyd et al. 2007; Yoon et al. 2016).

Note, however, that the timing and location of these relatively small-scale experiments was carefully

chosen. Blooms can still be limited, or co-limited, by light, silicate, macro-nutrients and grazing, leading to variability in the efficiency of iron fertilization. Discrepancies in local environmental, physical and seasonal conditions have been shown to have a pronounced effect on the relative success of any given particular patch fertilization (Boyd et al. 2007). In order to scale up, each site would need to be chosen with care and precision, which could prove challenging in a dynamic ocean.

Is stimulated primary production routed into export production?

Even if mass fertilization is scalable, there is little evidence to suggest that a meaningful amount of new biomass would consistently get exported out of the surface ocean. It is critical to remember that iron limitation is only the first step of the Iron Hypothesis (Buesseler et al. 2008b). Leveraging this insight into a sustainable global carbon sequestration program hinges largely on ambiguity over the long term fate of the new organic matter that is produced. The stimulation of new production is only relevant to the medium-to-long term global carbon cycle if it is subsequently sequestered into the deep ocean. Most new production is, however, is rapidly consumed by bacteria and zooplankton that convert organic matter and oxygen (O_2) into CO_2 and water to produce energy. If the remineralization of organic carbon back into inorganic carbon occurs near the surface ocean, carbon can be released back to the atmosphere as CO_2 . For OIF to be a viable sequestration pathway, a significant fraction of stimulated production must instead be exported out of the surface ocean to depth.

Of the 13 total artificial iron enrichment experiments conducted to date, only EIFEX, a study aboard the RV Polarstern during 2004 in the Atlantic sector of the Southern Ocean (Smetacek et al. 2012), actually observed an increase in export (Yoon et al. 2016). Some naturally fertilized systems have been observed to yield reasonably strong export fluxes relative to nearby iron-depleted water (Blain et al. 2007; Pollard et al. 2009), however, it is problematic to extrapolate natural laboratories to large scale geoengineering efforts, or even patch fertilizations. Localized naturally fertilized regions represent a highly specific response to a particular set of environmental conditions that may not be easy or practical to replicate across the Southern Ocean (Salter et al. 2012). For instance, in natural systems

iron is generally slowly and continuously supplied throughout the year, whereas in artificial fertilizations iron is deposited rapidly in pulsed inputs. This results in a substantial fraction of the deposited iron being lost to abiotic processes such as particle scavenging prior to biological uptake (Bowie et al. 2001).

Does export translate into long term storage?

Regardless of export efficiency out of the surface ocean, only a very small fraction (<~1% of total export (Prentice 2001)) of sinking organic matter will make it to the sediments where it can remain sequestered on geological time scales. The rest is remineralized at depth and eventually transported back to the surface ocean where it can be released into the atmosphere. The timescales over which this occurs vary with the remineralization depth (Gnanadesikan et al. 2003), but generally fall on the order of 10-100s of years. Geoengineering advocates contend that if a large enough export flux is achieved, then this is long enough to buy time until other longer term climate solutions are developed. Questions remain, however, if this relatively mild best case scenario is even attainable.

During EIFEX, the lone artificial OIF experiment that found evidence of increased export, Smetacek et al. (2012) concluded that over half of the stimulated bloom's biomass sank below 1000 meters. These results, however, must be considered in a broader context. The efficiency of the biological pump is highly variable on a regional and seasonal basis. On a seasonal basis, deep winter mixing which can penetrate hundreds of meters below the surface, could quickly return carbon that was remineralized at depth to the surface ocean. Regionally, targeting areas of deep-water formation, where dense surface water is subducted to the deep following the freezing of sea-ice, may increase the remineralization depth as surface waters subduct, but may also introduce operational hazards from working in the coastal, heavily ice covered regions where deep-water typically forms.

Further, some have pointed out that the export flux and variability in the remineralization depth cannot alone describe oceanic carbon storage, pointing instead to preformed nutrient budgets which are additionally controlled by stoichiometry and circulation (Gnanadesikan and Marinov 2008). In this

context, much larger space and time scales must be considered to quantify carbon storage, dramatically complicating the scalability and extrapolation of localized enrichment experiments.

Do secondary effects on ecosystem structure effect the net sequestration of carbon?

Large-scale iron enrichment will dramatically alter the natural ecosystem, potentially leading to several secondary consequences that could undermine the intended sequestration of carbon. For example, Southern Ocean iron enrichment experiments tend to preferentially increase the growth rates of diatoms, shifting community composition from smaller phytoplankton functional types to larger, silicate shelled, chain forming, diatom assemblages (Hoffmann et al. 2006; Hutchins and Bruland 1998). The stimulation of these rapidly sinking, heavy assemblages is key to increasing the efficiency of the biological pump (Hoffmann et al. 2006) but might additionally trigger less desirable secondary consequences.

Additionally, many of the heterotrophic zooplankton, such as copepods, that preferentially graze on diatoms form calcium carbonate (CaCO₃) shells (Tsuda et al. 2007). The precipitation of CaCO₃ triggers a change in the speciation of the equilibrated carbonate system which leads to an increase in dissolved CO₂ (Frankignoulle et al. 1994). Although the dissolution of CaCO₃ is in turn an effective CO₂ sink, if it is first transported to depth calcification can act as a CO₂ source on time scales of 10-100s of years. This process is known as the carbonate pump and has been observed to reduce the carbon sequestration capacity of natural systems by as much as 30% (Salter et al. 2014). If a stimulated diatom population are preferentially consumed by calcifying grazers over non-calcifying grazers, indirect stimulation of the carbonate pump (CO₂ source) must be weighed against stimulation of the biological pump (CO₂ sink).

Finally, and more generally, increased primary production may not dictate a proportionate response in export production. Population size is not only regulated by bottom-up controls on phytoplankton growth rates such as light and nutrient (e.g. iron) limitation, but also by top-down controls on phytoplankton loss rates imposed predominately by grazers (Behrenfeld et al. 2013). If highly stimulated growth rates improve grazing efficiency, a negative

feedback loop could emerge in which increasing grazing rates damp population gains (Rohr et al. 2017). As carbon is transferred up the food chain, and partially respired along the way, increased grazing would decrease the efficiency of carbon export (Boyd and Doney 2003).

Does local macro-nutrient utilization compromise downstream productivity?

Even if long term, local sequestration was successful, in a highly interconnected global ocean it is possible that a local increase in productivity could trigger an ensuing downstream, or non-local, reduction. If successful, OIF would drawdown previously unused macro-nutrients and trap them at depth. While these unutilized macronutrients were previously of little use for carbon sequestration in iron limited surface waters, the depression of the nutrient profile leaves intermediate waters with reduced nutrient concentrations as well. These intermediate waters are eventually advected and upwelled in different parts of the ocean, such as tropical, lower latitudes. To understand the net effect of Southern Ocean OIF we must also understand the price of reducing the supply of downstream macro-nutrients. That is, what is the cost of leakage?

Unfortunately, this question transcends the scope of modern observational capabilities. Several modeling studies, however, have suggested that leakage could be considerable, leading to a significant downstream reduction in primary production, atmospheric CO₂ drawdown and export production in the tropics (Aumont and Bopp 2006; Gnanadesikan et al. 2003; Oschlies et al. 2010; Sarmiento and Orr 1991). Specifically, Oschlies et al. (2010) found that when integrated over 100 years, an increase in CO₂ released at non-local sites compromised the net CO₂ drawdown by 20%. Worse, Gnanadesikan et al. (2003) found that the integrated non-local reduction in export was 30 times greater than locally stimulated export. In turn, after 100 years only 2-44% of the initially stimulated local export remained removed from the atmosphere. While non-local productivity could be damped for hundreds of years, the majority of artificially added iron is likely to be rapidly removed from the water column and buried in the sediments via particle scavenging (Aumont and Bopp 2006), meaning the local stimulus could be short-lived relative to the non-local ramifications. In turn, it is not unlikely that the net effect of time-integrated,

non-local reductions could exceed any local gains felt immediately after fertilization.

Summary: There is not sufficient certainty that OIF will work.

While there is strong evidence that Southern Ocean primary productivity is iron limited, there remains a great deal of uncertainty regarding whether the artificial addition of iron would lead to a net sequestration of carbon at depth for adequate timescale once balanced against the possibility of competing reductions in oceanic carbon storage associated with changes to ecosystem structure or downstream productivity.

ii. Auditing: can it be measured?

Market commercialization is not possible without accurate measurement. If an individual or corporation can not accurately measure what they have done, then they cannot be fairly or consistently compensated for that activity. The ensuing difficulties associated with trading a commodity that is not fairly or consistently valued would inevitably lead to irreparable market instabilities or gaming. In turn, a robust auditing framework, in which all activity can be reliably measured and accordingly compensated, is a pre-requisite for any well-structured offset market. In the context of OIF, this hinges largely on the ability to establish reliable estimates of carbon sequestration, however, tremendous spatial-temporal variability in the stimulated efficiency of the biological pump prevents the simple extrapolation from iron input to carbon sequestration. At best we can attempt to directly measure the induced export flux and infer net sequestration from there. Unfortunately, the dynamic nature of the global ocean not only severely complicates measurements of local export but requires the complete consideration of non-local effects.

Challenges measuring local export

Export production is notoriously difficult to measure. Physical methods such as sediment traps which simply catch particulate "rain" are subject to, amongst other things, grazing by passing zooplankton and hydrodynamic biases over the mouth of the trap (Buesseler et al. 2007). Chemical methods measuring the secular disequilibrium between particle reactive ²³⁴Th and its conservative, long lived parent radioisotope ²³⁸U provide a good proxy for export production (Buesseler 1998) but are

subject to their own problematic biases and assumptions. By providing multiple lines of evidence EIFEX (Smetacek et al. 2012) was able to convincingly conclude that they induced an increase in local export production, but employing a similarly large suite of measurement tools, requiring weeks of ship time, persistent monitoring with expensive equipment, and a host of well-trained technicians, may not be practical at a global scale. Anything less, however, may not be reliable.

Biogeochemical additionality and establishing a baseline

Additionality, the notion that offset credits should not be granted for sequestration that would have happened irrespective of a proposed project, is often only considered in an operational context (Leinen 2008), but for OIF, a process designed to amplify a natural phenomenon, it must also be considered in a biogeochemical context. In order to accurately audit, it is necessary is to establish a baseline by which to quantify how much additional export has been stimulated beyond what would have occurred naturally. Establishing such a baseline would require nearly continuous control measurements over the entire lifetime of the bloom at multiple locations throughout the surrounding unfertilized waters. Even then, separating the OIF induced signal from high frequency spatial-temporal variability, inter-annual variability and long term climate trends would prove nearly impossible (Cullen and Boyd 2008).

EIFEX (Smetacek et al. 2012) cleverly fertilized a water mass trapped in the interior of a large eddy to help control for mixing biases between the fertilized and control patch, but likely introduced new biases as well. Internal eddy dynamics are capable of modifying the in-situ iron flux (McGillicuddy 2016) and accounting for a heightened export flux independent of the stimulus from artificial fertilization. Because the strength and direction of these internal dynamics vary between eddies (Gaube et al. 2014) adequately controlling for them would require the impossible task of measuring the same eddy, at the same time, with and without iron fertilization.

Spatial and temporal dissonance

Finally, overcoming the challenges hindering local export measurement may be irrelevant if the local signal does not dominate the net global signal. Ocean circulation and mixing increase spatial scales and distribute the effects of a local perturbation far from its point source, severely complicating long term verification and assessment (Buesseler et al. 2008b). Non-local effects, largely triggered by the downstream depletion of macro-nutrients, are thought to be of a similar scale and often in an opposing direction to local effects (Aumont and Bopp 2006; Gnanadesikan et al. 2003; Oschlies et al. 2010; Sarmiento and Orr 1991). Accurate auditing, then, would require estimates of both the locally induced export flux and consideration of all non-local effects (Yoon et al. 2016). Unfortunately, large space and time scales prevent direct measurement of these effects (Yoon et al. 2016), while complex nonlinearities prevent reliable model-based estimates for individual deployments.

Summary: It would be extremely difficult to develop a reliable auditing framework for OIF.

Significant challenges associated with the measurement of local export, establishment of a reliable baseline, and estimation of non-local effects, severely hinder the possibility of creating a reliable auditing framework in which individual fertilization events could be consistently compensated for the net sequestration of carbon they induce.

iii. Safety: will OIF induce adverse side effects?

By design, OIF seeks to deliberately manipulate ocean biogeochemistry at the global scale. In a highly complex ocean system, it is unreasonable to expect this will not lead to a bevy of broad ranging, unpredictable and unintended consequences. Given the breadth of the climate crisis, the prospect of marginal gains in carbon sequestration may reasonably justify the risk of collateral damage, however, there is first an obligation to understand the full scope of potentially harmful side effects before we can deem them acceptable (Buesseler et al. 2008b; Cullen and Boyd 2008).

Anoxia and hypoxia

If OIF is successful then increased export production will eventually fuel increased aerobic microbial decomposition and oxygen consumption at depth (Cullen and Boyd 2008), which could lead to the development of hypoxia or anoxia below the euphotic

zone (Yoon et al. 2016). These deoxygenated subsurface waters can eventually be transported to the surface in coastal upwelling systems where they can trigger mass fish die offs (Cullen and Boyd 2008). Similar events have been observed along the Pacific Eastern Boundary current (Chan et al. 2008; Grantham et al. 2004), and are thought to be triggered by non-local anthropogenic nutrient loading.

Simple early box-models predicted that large scale fertilization would create vast subsurface anoxic regions (Sarmiento and Orr 1991). Later models countered that oxygen depletion may not be quite as severe, but only because the magnitude of the predicted sequestration flux also decreased (Denman 2008). Similarly, compensating oxygenation has been predicted to occur at lower latitudes in some models, but only due to a reduction in productivity triggered by upstream nutrient utilization (Oschlies et al. 2010). The net effect is difficult to constrain, but generally appears qualitatively opposed to the desired outcome of OIF; Net improvement in global export is tied to a net deterioration of subsurface oxygen.

Broader ecosystem interactions- productivity, community composition, and fisheries
Despite strong evidence of an immediate, local increase in productivity following fertilization, some predict that on decadal timescales OIF will actually lead to a net reduction in global productivity triggered by a reduction in the downstream nutrient supply, particularly to the tropics (Aumont and Bopp 2006; Gnanadesikan et al. 2003; Zahariev et al. 2008). Over long enough time scales a net reduction in primary productivity could ripple up the food web reducing the availability of harvestable fish stocks. Gnanadesikan et al. (2003) estimated that the cost to fisheries could be as high as \$150 per ton of carbon sequestered via OIF.

The ultimate effect on fisheries is further complicated by the potential for complex, unpredictable changes to ecosystem structure fueled by shifts in species composition at lower trophic levels (Chisholm and Morel 1991). During sustained fertilization, blooms have been observed to shift to diatom dominance (Marchetti et al. 2006), and in turn favor larger species of zooplankton (Tsuda et al. 2006). These changes in community composition have at times lead to an increase in the abundance of

Pseudonitzschia, a diatom genus known to produce the harmful neurotoxin domoic acid (Silver et al. 2010; Trick et al. 2010).

The precise community response, however, remains largely unpredictable. Even at smaller, experimental scales, ecosystems have been observed to respond differently to multiple fertilizations conducted at the same site (Boyd et al. 2007). At a global scale these changes could lead to dramatic and unpredictable regime shifts in community composition and more generally regional biogeochemistry (Boyd and Doney 2003). It is, at best, unclear how major changes in ecosystem structure will affect ocean resources and fisheries.

Non-CO₂ climate active gases

The net radiative effect of OIF may be significantly altered by modified contributions from non-CO₂ climate active gasses, such as nitrous oxide (N₂O), methane (CH₄), and dimethyl- sulfide (DMS).

N₂O is a greenhouse gas roughly 300 times more potent than CO₂ on a per-molecule basis (Ramaswamy et al. 2001). Oceanic N₂O production is associated with both the bacterial oxidation of remineralized ammonium to nitrate, as well as the bacterial remineralization of organic matter at low oxygen levels (Cohen and Gordon 1979). The existence of multiple pathways complicates precise estimates of OIF-induced N₂O fluxes, but N₂O production is generally thought to increase as increasing export is inevitably decomposed. Observations from the SOIREE iron enrichment experiment (Law 2008) in addition to modeling studies (Jin and Gruber 2003; Oschlies et al. 2010) have reported a net increase in N₂O production estimated to compromise the net radiative effect of atmospheric CO₂ removal by 5-10%. EIFEX, one of the largest enrichment experiments to date, however, observed no detectable change in N₂O production (Walter et al. 2005).

CH₄, another greenhouse gas produced during microbial decomposition, is roughly 20 times more potent than CO₂ (Ramaswamy et al. 2001). Oceanic CH₄ is produced predominately by bacteria in completely anoxic microhabitats associated with sinking particulate organic matter (Karl and Tilbrook 1994). While increased export would increase the prevalence of these microhabitats, the net potential

for OIF induced CH₄ production to offset atmospheric CO₂ reductions is not expected to exceed 1% (Oschlies et al. 2010).

DMS, unlike N₂O and CH₄, is not a greenhouse gas. Instead, it leads to the creation of sulfur aerosols which in turn help seed cloud formation, working to cool the atmosphere by increasing earth's albedo. Oceanic DMS is produced as a byproduct by marine phytoplankton and has been proposed as a biological pathway for climate regulation (Charlson et al. 1987). While the nature of this regulatory loop has been found substantially more complex than initially hypothesized (Ayres et al. 1997; Quinn and Bates 2011), it remains a significant link between marine biota and climate. The net effect of OIF on DMS production, however, is unclear. Some enrichment experiments have seen an increase in DMS production immediately after fertilization (Liss et al. 2005; Turner et al. 2004, 1996), with hikes as high as 6.5-fold (Turner et al. 2004). Other experiments, however, have reported no change in DMS production (Nagao et al. 2009; Takeda and Tsuda 2005), or even observed a decrease following an initial spike (Levasseur et al. 2006).

Ultimately, without observations of patch-scale fertilizations longer than 1-2 months, no less for a continuous, basin wide fertilization program, the forcing on non-CO₂ climate active gasses remains largely unknown (Law 2008). Constraining these fluxes is critical to understanding the net radiative effect of OIF and will require a better understanding of changes to community composition, particulate export, and deep bacterial remineralization at time and space scales much larger than a single fertilization.

Ocean acidification

Finally, the desired uptake of CO₂ into ocean will only exacerbate ocean acidification. Ocean acidification is caused as increasing CO₂ shifts the equilibrium of the carbonate system in favor of an increasing concentration of H⁺ ions, thus reducing the pH. Ocean acidification has been widely shown to be detrimental to some marine biota, particularly calcifiers such as corals (Doney et al. 2009). While the majority of anthropogenic CO₂ may inevitably end up in the ocean regardless, if successful, OIF will undoubtedly increase the rate at which it is added, giving organisms less time to adapt (Denman 2008).

Summary: There are several plausible pathways through which OIF could harm environmental or human health.

The intentional manipulation of global biogeochemistry could plausibly lead to unintended consequences ranging from mass fish die-off triggered from anoxia, reductions to global fisheries catch, or an increase in more potent non-CO₂ greenhouse gases. Moreover, the deliberate sequestration of carbon in the ocean ignores the threat of ocean acidification stemming from exactly that.

iv. Concluding case against commercialization

Considering the complications described above, establishing a successful global scale OIF operation would call for careful deliberation into when and where each individual fertilization is implemented (Buesseler et al. 2008b; Yoon et al. 2016). Collectively optimizing a global portfolio of fertilization sites would require intensive monitoring coupled to a comprehensive adaptive management plan. Persistent monitoring would need to account for local and non-local sequestration, a baseline by which to establish additionality, and a suite of complex side effects. Scientific decision making would need to be equipped to understand and react to unpredictable developments on time and space scales well beyond the scope of local fertilization (Gnanadesikan et al. 2003). Implementation would need to be flexible enough to change course on the fly, but also incremental enough to safeguard against significantly time-lagged, downstream consequences. Given the challenges associated with accurate measurement, developing such a demanding management program would be exceedingly difficult, even under unilateral authority; it might not be possible under market control. Institutional inefficiencies would dramatically hinder the ability of myriad independent private corporations to cohesively implement a complex and dynamic plan. At best, any practical approach to establishing a baseline and quantifying additionality would have to be done in a broad mean sense. This sort of generalization creates the exact problem that plagues other offset markets (Gillenwater 2012). Corporations looking to maximize the differential between the baseline and outcome will be incentivized to seek underestimated baselines rather than improved outcomes. Even well intentioned incentives designed to ensure

corporations fertilize the right places at the right times could be corrupted by challenges to enforcement and unreliable auditing. Finally, no project would be truly oceanographically independent, making it impossible to appropriately distribute the costs and benefits across operationally independent projects.

Ultimately, it is difficult to see how market forces could ensure OIF conforms to the best scientific judgment. Consequently, these market failures will compound the already substantial risk of adverse side effects and dampen our ability to react to emerging threats, all while introducing problematic economic and legal ramifications. Economically, without a robust auditing framework to ensure fair and consistent compensation, corporations incentivized to game the system could undermine the entire global offset markets. Legally, if harmful consequences do arise, establishing liability will be nearly impossible across complex, multi-actor, non-local, time-lagged lines of etiology. Taken together, the inability of markets to properly manage the uncertainty and risk associated with OIF on a global scale or resolve the challenges imposed by tremendous spatial-temporal dissonance highlight the case against commercialization.

III. The case for continued research

While the scientific case for commercialization is weak, a more contentious debate has ensued over the prudence of continued research into OIF. Given the concerns over commercialization many argue that further research would only misallocate finite scientific resources and bolster a moral hazard threatening to distract from more legitimate mitigation efforts.

On the other hand, the case for continued research is three-fold. First, from a basic research perspective, unraveling the role of iron in our oceans and its contribution to glacial-interglacial climate variability will help shape our understanding of ocean biogeochemistry and its role in climate change. Second, it is not impossible that some realization of OIF could eventually be safely and thoughtfully implemented under unilateral governmental authority as one of many useful tools to address climate change, particularly if mitigation efforts continue to fail. Third, if there is reason to believe that commercialization could proceed contrary the

scientific consensus, then continued research could help deter reckless behavior by delegitimizing unfounded commercial development. Argument three warrants further consideration; in the following section, I outline the incentives that could drive development on voluntary offset markets and describe the role that continued research can play moving forward.

i. Prospect for commercialization of voluntary offset markets

It is unlikely that any global governance framework would disregard scientific wisdom and begin granting offset credits for OIF under heavily regulated compliance offset markets (COMs), however, there are no such barriers to entry on voluntary offset markets (VOMs). VOMs differ from COMs, such as those implemented by the Kyoto Protocol, in that offsets are bought and sold without any federally mandated obligation. Trading on VOMs is instead motivated by a sense of personal responsibility, corporate branding or an expectation of impending regulations. Lacking significant oversight, VOMs could serve as a vital seed ground for the development of private OIF ventures.

ii. Size of voluntary offset markets

Compared to the \$50-100 billion total value of COMs (Carbon Market Monitor 2016), VOMs pale in size. Still, with 63.4 MtCO_{2e} traded in 2016 for a total of \$191.3 million (Hamrick and Gallant 2017), there is considerable room for a small company to secure lucrative profits. In 2016, the average price for all transactions was \$3.0/tCO_{2e} but ranged wildly from \$0.5/tCO_{2e} to as high as \$50.0/tCO_{2e}. Despite some volatility in market size (demand rose by 10% in 2015 (Hamrick and Goldstein 2016) but dropped off by 24% in 2016 (Hamrick and Gallant 2017)) and the growth of COMs in the wake of COP 21, there is an expectation that VOMs will remain viable with the overall demand for sustainable development and industry interest in carbon neutrality on the rise (Hamrick and Gallant 2017).

iii. Perception of low cost alternative

Relative to other carbon offset projects, there is a perception that OIF is a substantially cheaper, economically viable solution (Keith et al. 2006; Worstall 2012). Given the low cost of iron and the very high stoichiometric ratio with which CO₂ is fixed and iron is utilized (C:Fe = 10⁶ (Anderson and Morel,

1982)), it is easy to understand how OIF can appear, at first glance, seductively affordable. Early projections estimated the cost of OIF as low as \$1-2/tCO₂e (Markels and Barber 2002), leaving substantial room to profit over the average price currently being traded on VOMs.

Of course, the reality may be much less enticing. Early estimates were biased by problematic assumptions regarding export efficiency, downstream macro-nutrient depletion and compensatory climate active gas fluxes, and did not internalize the true cost of research and development, monitoring, or delivery systems at the global scale (Watson et al. 2008). Revised projections generally range from \$8-10/tCO₂e (Boyd 2008), but still typically exclude the price of potentially harmful externalities which have been estimated as high as \$150/tCO₂e to fisheries alone (Gnanadesikan et al. 2003). One, more extreme, estimate argues for an almost certainly prohibitory price of \$457/tCO₂e (Harrison 2013). Perhaps most accurately though, in light of the vast uncertainty in what we can infer from patch scale fertilizations and model integrations, the truth is that we just do not know how expensive long term iron induced sequestration might be at a global scale (Barker and Bashmakov 2007).

What we do know, however, is that it is not very expensive to dump iron into the ocean. Even if the cost of sequestration in a comprehensive, credible OIF scheme is prohibitory, the operational startup cost for small-scale, speculative operators is not. Whether these deployments could ever actually sequester what they claim remains uncertain, but it is precisely this uncertainty that creates the opportunity to discount the risk portfolio and overvalue the chance to win big. More research is needed to constrain the true cost of sequestration and delegitimize the idea that it can be easily extrapolated from one-off, patch-scale, fertilization experiments. Investing in the future and establishing intellectual property

Without a firm grasp of the true cost of sequestration, buttressed by the low price of iron and overhead, there is a reasonable economic argument for small-scale operators to invest in the development of OIF. Even if the odds for success are slim, the stakes are low (economically if not environmentally) and the jackpot is huge. In the most optimistic, albeit unlikely,

scenarios, OIF could generate billions of dollars' worth of offsets (Cullen and Boyd 2008), fundamentally disrupting carbon markets (Neeff 2007). Relative to the low cost of investment, the upside is high enough that even if OIF is not immediately profitable it could be justified as a shrewd investment.

It is exactly these sort of financially low risk, high reward ventures that appear poised for success on VOMs, which are seen as promisingly fertile soil to test emerging carbon sequestration technologies (Hamrick and Gallant 2017; Hamrick and Goldstein 2016). In the hope that one day OIF will be adopted into compliance markets, it is relatively affordable for entrepreneurs to stage preliminary development on VOMs with an eye to test methodologies and preemptively establish intellectual property (see Early Case Studies below). If further research can clarify the biogeochemical impediments to a market-based OIF approach and diminish the perception that it will ever be viable on COMs, it will deter speculative investment on VOMs.

iv. Regulatory and legal framework

Exploratory development on VOMs benefits from a loose regulatory environment with no federally mandated oversight. While a suite of standardization bodies have emerged to administer credibility by verifying that projects are, in fact, permanent, additional, and free of leakage (Hamrick and Gallant 2017), it is unclear how a collection of independent auditors would cohesively overcome immense monitoring challenges to develop a comprehensive OIF validation scheme. It is more likely that commercial operators would shop between diverse auditing options before settling on the most economically favorable framework. Even if more reputable standards bodies refuse to accredit OIF, there is nothing blocking the emergence of new organizations willing to do so, and only the scientific community would be equipped to discredit them. This regulatory flexibility relaxes the burden of proof that should be expected from commercial operators and could encourage reckless development.

In theory, the United Nations Convention on the Law of the Seas and the London Convention, which generally ban dumping on the high seas, should prevent overtly harmful operations. Unfortunately when it comes to OIF, international jurisdiction is

often vague and difficult to enforce (Bertram 2011). In 2008, the London Protocol, with support from the International Maritime Organization (IMO 2008), banned commercial fertilization (LC-LP.1 2008), but ambiguity arose over what constituted a permissible, legitimate scientific activity (Bertram 2011; Goodell 2011a). In 2013, the UN formally recognized OIF as geoengineering and mandated stricter environmental assessments and approval prior to permitting (LC-LP.4 2013), but questions remain over the capacity to enforce international law in the remote Southern Ocean without any centralized legal authority. Poor enforcement and protections under the guise of science have long sheltered the whaling industry (Mangel 2016) and could potentially do the same for OIF. Without legitimate, peer-reviewed research programs for reference, it could be even easier for commercial operations to feign scientific legitimacy.

v. Ethical arguments and public perception

OIF can only leverage a loose regulatory and legal framework if there is a market to support it. The question of whether there is demand for legally and scientifically suspect offset credits, however, might not be a strictly economic one. Absent any formal obligations, buyers on VOMs are often driven by an earnest desire to do what is right. Given the increasing threat of climate change and the deteriorating state of ocean health, it is not difficult to see how OIF could be sold to a less informed public as an ethically viable gamble.

By fixating only on favorable outcomes, OIF can and has been spun as marine forestation (Goodell 2011b); a global gardening project to support ecosystem health, boost global fisheries, create jobs, and help feed the world, all while sequestering billions of tons of carbon. Buyers are increasingly interested in these sort of social and environmental co-benefits and are willing to pay for them (Hamrick and Goldstein 2016). Terrestrial analogs like forestry and land use projects promise similar protection to ecosystem services and successfully captured the second largest market share at the highest average trading price on VOMs in 2016. Together, they were three times more valuable than renewable energy commodities (Hamrick and Goldstein 2016). Current scientific wisdom suggests this comparison is not justified, but without continued research, commercial operators may be able to leverage lingering uncertainty to cast

OIF in a positive light and shape public opinion, and in a buyer's market, where there is no obligation to participate, public perception is tantamount to value.

vi. Early case studies

Several early examples demonstrate commercial interest in developing OIF in the private sector. By the mid-late 2000s, start-ups championing OIF had gained considerable momentum. Planktos, founded at the turn of the century by Russ George with an expressed intent to "save the world and make a little cash on the side", had acquired an oceanographic vessel (Goodell 2011c). GreenSea Ventures, a Virginia based outfit, had begun to establish intellectual property by securing patents for several iron delivery strategies (Bowie et al. 2016). Most notably, Climos, had acquired 3.5 million dollars in series A venture capital funding and the support of Elon Musk ("New Plankton-Seeding Venture Reaps \$3.5 Million" 2008). The reputability of these organizations ranged from a pirate-like disregard for scientific nuance at Planktos (Goodell 2011c), to an active engagement with the scientific community at Climos (Leinen 2008).

By the end of the decade, however, the scientific consensus had begun to crystallize; it was too early to support the commercialization of OIF (Buesseler et al. 2008b). With the increasingly negative perception coupled to legal challenges introduced by the London Protocol (LC-LP.1 2008), the tide began to turn for the first wave of OIF start-ups. In 2008 Planktos was forced to halt operations mid-deployment after investors jumped ship before shutting down all together shortly thereafter. Climos, lasted longer but ultimately could not withstand the legal and scientific scrutiny, eventually shifting their focus towards broader geoengineering technologies (Goodell 2011d) before seeming to disappear completely. In both cases, improved scientific clarity was critical in discrediting these speculative ventures.

Nevertheless, the threat of commercial development has not receded entirely. In 2012 Russ George reemerged to dump some 100 tons of iron sulphate into the Pacific Ocean (Lukacs 2012). More recently, in 2017, the Oceaneos Marine Research Foundation sparked controversy when it began to seek permits to dump 10 tons of iron off the Chilean coast (Tollefson 2017). If long term mitigation efforts continue to fail, it is unlikely that commercial interest in OIF will disappear on its own. Further research is needed to

continue to unravel the complexity, uncertainty, and risk inherent in a global scale OIF platform and highlight the challenges to market based management that should preclude commercialization from consideration.

IV. Conclusions

The prospects for a successful, basin wide, OIF campaign are shrouded in uncertainty and appear dubious at best. Even if iron is able to stimulate productivity at scale in HNLCS it is unclear how much will be exported to depth to be sequestered for adequate time scales and to what degree complex, non-linear, feedbacks into ecosystem structure and downstream macro-nutrient utilization might compromise net atmospheric CO₂ drawdown. Worse, we don't fully understand how deliberately manipulating ocean biogeochemistry at this scale could threaten intricate marine ecosystems, global fisheries, or the flux of non-CO₂ climate active gases.

Nevertheless, the climate crisis is not going to disappear and all potential contributions to a solution warrant thorough consideration. Risk and uncertainty will weigh heavily in all options and must not alone preclude any from consideration. Success, then, will be largely predicated on selecting strategies that can optimize our ability to manage uncertainty and improve our preparation to adapt to unpredictable developments along the way. I have made the argument that a market-based approach to OIF will do neither.

As continual fertilization induces an increasingly non-local and time-lagged response across the ocean it will become impossible to accurately distribute

responsibility across many independent operations. The inability to attribute the true and total consequences of any individual fertilization, compounded by the uncertainty associated with measuring even the net effect of all integrated deployments, would likely derail any hope for reliable auditing. Without a robust auditing framework or serviceable enforcement, misaligned incentives could prevent market forces from aligning with a rapidly evolving fertilization scheme and compromise our ability to react and adapt to unpredictable developments beneath a cloud of uncertainty. If OIF was ever to be implemented, likely as a last ditch effort, I contend that it should be under unilateral authority and with dynamic management. Fortunately, in line with the scientific consensus, the London Convention, has banned non-scientific iron fertilization, effectively precluding the commercialization of OIF on reputable, regulated, markets.

Nevertheless, I argue that continued, incremental, research will not only clarify the viability of a potential emergency deployment, but, perhaps more importantly, could be critical in deterring the unregulated development of OIF on VOMs. Without consumer confidence that offsets are meaningful, there is no financial or ethical imperative to drive demand on VOMs. As it stands, the uncertainty surrounding OIF is large enough to justify a diversity of public opinion, particularly if developers highlight only positive outcomes. Further research is needed to reduce uncertainty and constrain public perception by continuing to clarify the risks, elaborate the challenges, and delegitimize the promise of an iron bullet.

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Supplemental Figures

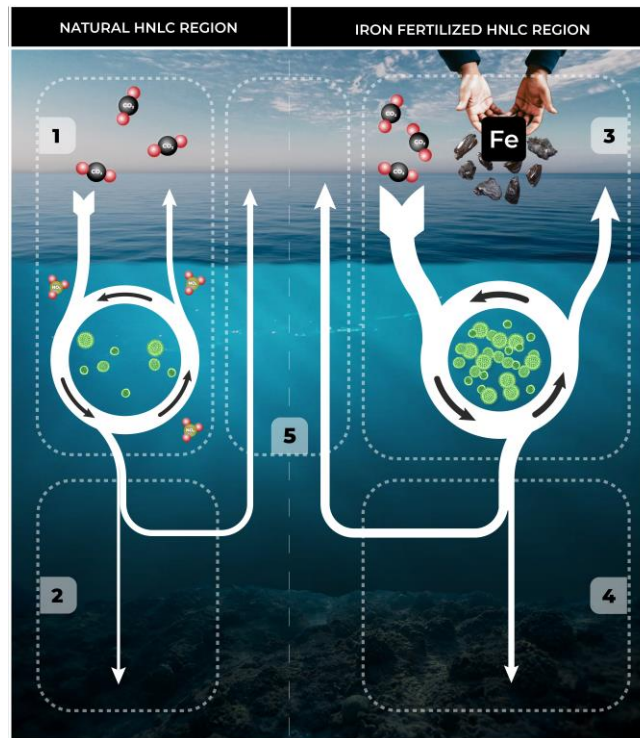
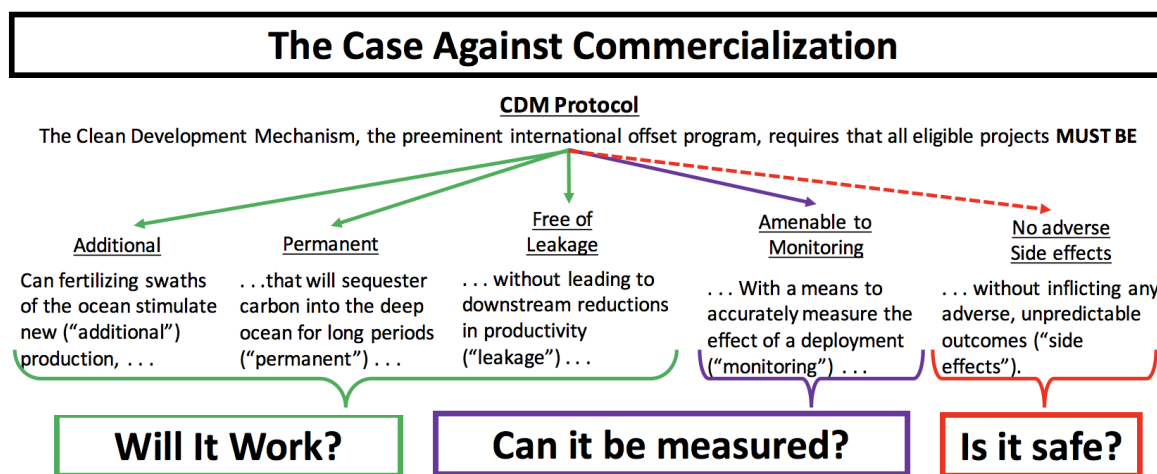


Figure 1. Schematic of the biological pump in natural and iron fertilized high nutrient low chlorophyll (HNLC) regions. On the left is a schematic of the biological pump in a natural HNLC. 1) Carbon Dioxide (CO_2) is absorbed into the surface ocean where it is used by phytoplankton for cell growth and metabolic processes via photosynthesis. Cell growth is, however, limited by iron, meaning that macronutrients like nitrate remain unused, and phytoplankton growth and abundance is low. Of the phytoplankton that do grow, most are quickly consumed by zooplankton or decomposed by bacteria. Zooplankton and bacteria respire organic matter, releasing CO_2 as a by-product. Much of this CO_2 is recycled in the surface ocean or escapes back into the atmosphere via gas exchange. 2) Some phytoplankton escape consumption and/or decomposition in the surface ocean and sink to depth. Most of these phytoplankton are decomposed by bacteria, converting their organic carbon back into CO_2 through respiration. This carbon can remain trapped in the deep ocean for 100s-1000s of years before being upwelled back to the surface. A small fraction of phytoplankton biomass, and its associated carbon, reaches the seafloor, where it can become sequestered in the sediments for much longer geological time scales. Iron fertilization hopes to increase the magnitude of this biological pump. On the right is a schematic of the biological pump in a HNLC region. 3) Iron fertilization allows phytoplankton to use previously unutilized macro-nutrients, like nitrate, increasing growth rates, phytoplankton abundance, and the drawdown of atmospheric CO_2 . Still, though, much of these phytoplankton are rapidly recycled, releasing CO_2 into the surface ocean, where it can be outgassed back into the atmosphere. 4) Some phytoplankton, however, will sink out of the surface ocean, into the deep ocean, or to a lesser extent, the sediments. Iron fertilization should increase the magnitude of these fluxes by increasing the magnitude of phytoplankton above. 5) Eventually, the carbon trapped in the deep ocean via the natural biological pump and the iron fertilized biological pump will return to the surface, elsewhere in the ocean, and likely escape to the atmosphere.

**Figure 2.**

Flow Chart: The case against commercialization. In the context of the Clean Development Mechanism, a viable commercialization strategy must be, additional, permanent, free of leakage, and amenable to monitoring. Logically, any project must also be free of adverse side effects. In the context of SO OIF this amounts to three questions: Will it work (II.i), can it be measured (II.ii) and is it safe (II.iii)? Note that the red line is dashed to indicate that safety is not explicitly part of the CDM protocol.

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