POLICY FORUM: OCEANS

Dis-Crediting Ocean Fertilization

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The oceans play a key role in the global carbon cycle and climate regulation. Central to this function are phytoplankton, single-celled photosynthetic organisms that convert CO_2 to organic carbon in the surface oceans. Although accounting for <1% of photosynthetic biomass, phytoplankton are responsible for roughly half of the carbon fixation on Earth (*1*). The organic carbon they produce is mostly eaten by other organisms in the surface waters, and regenerated to CO_2 as these organisms respire. But some organic carbon sinks to the deep ocean, thus reducing CO_2 in the surface layer and elevating it in the deep sea.

The CO_2 concentration gradient maintained by this "biological pump" removes CO_2 from the atmosphere by storing it in the ocean interior. Increased interest in carbon sequestration strategies for mitigating climate change (*2*, *3*)—such as reforestation, CO_2 storage in geological formations, and direct injection of CO_2 into the deep ocean (*4*)—has drawn attention to the biological pump. Some entrepreneurs speculate that if the oceans were fertilized, the rate of carbon flux to the deep sea could be increased, and the incremental carbon could be sold as credits in the developing global carbon marketplace (*5*).

If implemented on a large scale, ocean fertilization would, by design, change the ecology of the oceans. The potential long-term consequences of this purposeful eutrophication strategy are cause for great concern, yet the idea is gaining momentum. Here, we examine the validity of the concept, and propose a policy option that could protect Earth's largest ecosystem from this dangerous course.

The biological pump has been the focus of major research programs for decades. For a long time, nitrogen (N) and phosphorus (P) were believed to limit the primary productivity that drives the pump. Yet in large areas in the subarctic northeast Pacific, the equatorial Pacific, and the Southern Ocean, N and P are never exhausted in surface waters, and phytoplankton biomass is less than expected. Martin (*6*, *7*) suggested that it is the scarcity of biologically available iron in these high-nutrient, low-chlorophyll (HNLC) regions that makes it impossible for the phytoplankton to use the excess N and P. He also recognized that atmospheric dust from land is an important source of iron for the sea and that HNLC regions receive a relatively small dust flux. Furthermore, he noted that ice core records of atmospheric CO_2 and dust concentrations over the past 180,000 years are anticorrelated: when dust was high, CO_2 was low. This is consistent with the notion that during the arid glacial periods, dust transport was greater, more iron was available, and the biological pump delivered more CO_2 to the deep sea. This "iron hypothesis," initially met with skepticism, has slowly garnered support from geochemists as one of several possible mechanisms that can account for changes in atmospheric CO_2 during glacial–interglacial transitions (*8*). The iron hypothesis was extended by Martin to imply that the deliberate addition of iron to the surface oceans could increase carbon storage in the deep sea. Only partly in jest he quipped: "Give me half a tanker of iron, and I will give you the next ice age" (*9*).

True color satellite image of a 200-km phytoplankton bloom in the Bering Sea. Such blooms are part of the natural cycles of production and regeneration in ocean ecosystems. Ocean fertilization for the purpose of carbon sequestration would disrupt these cycles and significantly alter oceanic food webs.

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Although at the time there was no direct evidence that iron limited primary production in HNLC regions, by the late 1980s the possibility of fertilizing the oceans with iron to mitigate the rise in atmospheric CO_2 was beginning to be taken seriously. This prompted the American Society of Limnology and Oceanography (ASLO) to issue a resolution discouraging iron fertilization as a policy option (*9*).

Around the same time (sadly, just after Martin died), oceanographers began to pursue small-scale (ca. 100 km^2), iron addition experiments in the open ocean. These experiments were designed to determine whether iron was indeed the limiting nutrient in HNLC regions, as Martin had hypothesized. They were not intended to demonstrate the feasibility of fertilization for purposes of carbon sequestration. Over the past 10 years, four such small-scale experiments have been conducted in the equatorial Pacific and the Southern Ocean (*10*–*13*). They have shown that adding small amounts of iron to these waters increases phytoplankton productivity and biomass over periods of a few days to weeks. In one experiment, phytoplankton biomass increased 20- to 30-fold (*11*).

These scientific experiments, which were conducted on very small scales, did not document a net transfer of CO_2 from the atmosphere to the deep sea. Press coverage, however, left the impression that phytoplankton hold the cure for global warming. Corporations and private entrepreneurs took note, and numerous patents were filed on ocean fertilization processes (*14*), anticipating a global market in which credits for carbon sequestered through fertilization might be traded.

One such enterprise, GreenSea Venture, Inc. (*15*), has recruited leading oceanographers to join their mission, which includes a proposed 8000 km^2 demonstration experiment (*16*) in the equatorial Pacific. Carboncorp USA (*17*) has also promoted ocean carbon sequestration through fertilization. They have described a process in which commercial ships that routinely traverse the high seas release small amounts of a proprietary fertilizer mix.

The Ocean Technology Group of the University of Sydney has patented an "ocean nourishment" process in which ammonia is produced from atmospheric N_2 and piped to coastal waters to stimulate phytoplankton blooms (*18*). In partnership with a Japanese firm, they have approached the Chilean government and the World Bank about installing such a facility in Chilean waters (*19*).

Despite the concerns of many oceanographers and environmental groups, the concept of industrial ocean fertilization is winning advocates. Proponents claim that ocean fertilization is an easily controlled, verifiable process that mimics nature; and that it is an environmentally benign, long-term solution to atmospheric CO_2 accumulation (*14*). These claims are, quite simply, not true.

It is not easily controlled. A fertilized patch in turbulent ocean currents is not like a plot of land. The oceans are a fluid medium, beyond our control.

It does not mimic nature. The proponents argue that ocean fertilization is similar to the natural iron deposition from atmospheric dust, and to the natural upwelling of

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nutrients from the deep sea. These analogies are flawed. Phytoplankton species that bloom in response to upwelling are adapted to a turbulent regime, and a complex mixture of upwelled nutrients that are part of the natural nutrient regeneration cycle of the oceans. Furthermore, proposed designs employ an artificial chelator, lignin acid sulfonate (*14*), which is designed to keep iron in solution and is chemically different from atmospheric iron sources. Finally, in intensive commercial ocean fertilization, iron would be delivered to ecosystems at rates that do not mimic the 1000-year time scales of glacial transition periods.

Despite the claims of the proponents, carbon sequestration from ocean fertilization is not easily verified. Besides measuring carbon flux profiles and comparing them with a control basin, one would have to determine what fraction of the natural stores of N and P used up in the fertilized patch would no longer be available for phytoplankton growth in downstream ocean regions. This would require complex numerical models of large-scale ocean physics and biogeochemistry, the predictions of which cannot be validated through small perturbations such as patch fertilizations.

The proponents' claim that fertilization for carbon sequestration would be environmentally benign is inconsistent with almost everything we know about aquatic ecosystems. Fertilization changes the composition of the phytoplankton community (*10–13*); it is precisely this feature that gives it the potential for increasing carbon flux to the deep sea. Correspondingly, the oceans' food webs and biogeochemical cycles would be altered in unintended ways. We have learned this from inadvertent enrichment of lakes and coastal waters with nutrients from agricultural runoff, something we have been trying to reverse for decades.

Fertilization advocates try to counter these concerns by arguing that the oceans have already been compromised. Indeed, we have known for decades (*20*) that human activities have resulted in depleted fisheries, coastal eutrophication, heavy metal accumulation, and rising dissolved CO_2 in the surface waters. But does this unintended deterioration justify large-scale, purposeful interference with ocean ecosystems? The oceans provide valuable ecosystem services for the maintenance of our planet and the sustenance of human society (*1*, *21*), and the carbon cycle is intimately coupled with those of other elements, some of which play critical roles in climate regulation. One cannot sequester additional carbon without changing coupled biogeochemical cycles.

Models predict, for example, that sustained fertilization would likely result in deep ocean hypoxia or anoxia (*22*). This would shift the microbial community toward organisms that produce greenhouse gases such as methane and nitrous oxide, with much higher warming potentials than CO_2 (*23*). Some models predict that Southern Ocean fertilization would change patterns of primary productivity globally by reducing the availability of N and P in the Equatorial Pacific (*22*). The uncertainties surrounding these cumulative, long-term, consequences of fertilization cannot be reduced through short term, small-scale experiments.

To us, the known consequences and uncertainties of ocean fertilization already far outweigh hypothetical benefits. Models predict that if all of the unused N and P in Southern Ocean surface waters were converted to organic carbon over the next 100 years (an unlikely extreme), 15% of the anthropogenic CO_2 could be hypothetically sequestered (*22*). Because deep ocean CO_2 reservoirs are eventually re-exposed to the atmosphere through global ocean circulation, this would not be a permanent solution. It is argued, however, that it would buy us time. Given both the certain and likely consequences of widespread ocean fertilization, which at some critical scale would not be reversible, we do not find this justification compelling.

We are not arguing against selective small-scale iron enrichment experiments designed to answer questions about how ocean ecosystems function. Such experiments have proven to be extremely valuable scientifically (*10–13*) and produce very transient effects. Our objections are to commercialized ocean fertilization—the scaled-up consequences of which could be very damaging to the global oceans.

To put ocean fertilization as a carbon sequestration option into perspective, we need to remind ourselves why CO_2 is increasing in the atmosphere at such a rapid rate and to ask how sequestration could mitigate this rise. Two basic carbon cycles operate on Earth. The first cycle is driven by volcanic outgassing of CO_2 coupled to the metamorphic weathering of silicate rocks. This cycle operates on time scales of millions of years (*24*). The second cycle involves the biological reduction of CO_2 to organic matter and the subsequent oxidation of the organic matter by respiration. A tiny fraction of organic carbon escapes respiratory oxidation and is incorporated into the lithosphere, forming fossil fuels. This process transfers carbon from the fast, biologically driven cycle to the slow, tectonically controlled cycle.

By burning fossil fuels, humans are bringing carbon from the slow cycle back into the atmosphere. The biological sinks—chiefly forests and phytoplankton—cannot adjust fast enough, and do not have the capacity to remove all this anthropogenic carbon from the atmosphere. For carbon sequestration to work as a climate mitigation strategy, CO_2 must be sequestered back into the slow carbon cycle. Ocean fertilization does not do so; nor does direct injection of CO_2 into mid-ocean waters, another proposed method for carbon sequestration. Direct injection short-circuits the biological pump but it may trigger unknown effects on deep sea life and thus on biogeochemical processes (*4*).

Given all of the risks and limitations, why has the idea of industrial scale ocean fertilization not been summarily dismissed? One answer lies in carbon trading (*5*). One need not fertilize entire ocean basins to sequester an amount of carbon that could yield commercial benefits on this anticipated market. If scientifically sound verification criteria could be developed, relatively small-scale fertilizations could be very profitable for individual entrepreneurs. True, no single application would cause sustained ecosystem damage. But if it is profitable for one, it would be profitable for many, and the cumulative effects of many such implementations would result in large-scale consequences—a classic "tragedy of the commons" (*25*).

One simple way to avert this potential tragedy is to remove the profit incentive for manipulation of the ocean commons. We suggest that ocean fertilization, in the open seas or territorial waters, should never become eligible for carbon credits.

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