# Fertilizing the Ocean with Iron

## Is this a viable way to help reduce carbon dioxide levels in the atmosphere?

"Give me half a tanker of iron, and I'll give you an ice age" may rank as the catchiest line ever uttered by a biogeochemist. The man responsible was the late John Martin, former director of the Moss Landing Marine Laboratory, who discovered that sprinkling iron dust in the right ocean waters could trigger plankton blooms the size of a small city. In turn, the billions of cells produced might absorb enough heat-trapping carbon dioxide to cool the Earth's warming atmosphere.

Never mind that Martin was only half serious when he made the remark (in his "best Dr. Strangelove accent," he later recalled) at an informal seminar at Woods Hole Oceanographic Institution (WHOI) in 1988. With global warming already a looming problem, others were inclined to take him seriously.

At the time, ice-core records suggested that during past glacial periods, naturally occurring iron fertilization had repeatedly drawn as much as 60 billion tons of carbon out of the atmosphere. Laboratory experiments suggested that every ton of iron added to the ocean could remove 30,000 to 110,000 tons of carbon from the air. Early climate models hinted that intentional iron fertilization across the entire Southern Ocean could erase 1 billion to 2 billion tons of carbon emissions each year—10 to 25 percent of the world's annual total.

Since 1993, 12 small-scale ocean experiments have shown that iron additions do indeed draw carbon into the ocean—though perhaps less efficiently or permanently than first thought. Scientists at the time agreed that disturbing the bottom rung of the marine food chain carried risks.

Twenty years on, Martin's line is still viewed alternately as a boast or a quip—an opportunity too good to pass up or a misguided remedy doomed to backfire. Yet over the same period, unrelenting increases in carbon emissions and mounting evidence of climate change have taken the debate beyond academic circles and into the free market.

Today, policymakers, investors, economists, environmentalists, and lawyers are taking notice of the idea. A few companies are planning new, larger experiments. The absence of clear regulations for either conducting experiments at sea or trading the results in "carbon offset" markets complicates the picture. But economists conclude that the growing urgency to solve our emissions problem will reward anyone who can make iron fertilization work.

In past experiments "we were trying to answer the question, 'how does the world work?'—not 'how do we make the world work for us?' " Kenneth Coale, the present-day director of Moss Landing Marine Lab, said recently. "They're totally separate. We have not done the experiment to address the issues that we're talking about today."

"We're in a learning process that involves a balance of science, commercial, and a whole variety of social activities and interests," said Anthony Michaels, director of the Wrigley Institute for Environmental Studies at the University of Southern California. "We've got to set up a measured process for moving forward."

The two scientists were speaking at a fall 2007 conference that brought together some 80 participants representing the

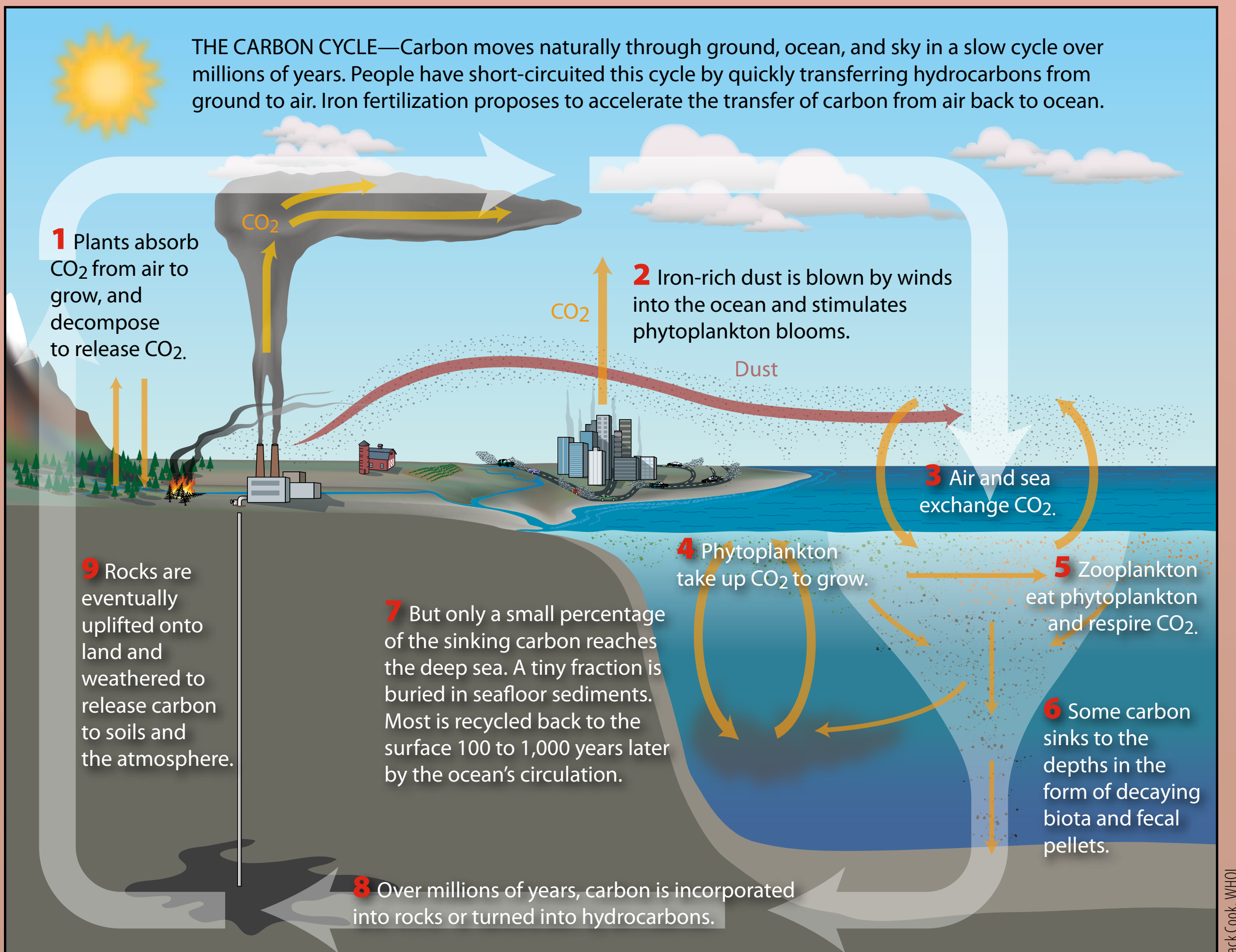
### Ocean Iron Fertilization

**An argument for:** Faced with the huge consequences of climate change, iron's outsized ability to put carbon into the oceans isn't just an opportunity, it's a responsibility.

**An argument against:** It's a meager, temporary, unverifiable proposition involving private individuals dumping materials into the common waters of the world's oceans.

**A middle ground:** Careful experiments conducted by scientists are our best hope for learning how much carbon can be sequestered without harming the ocean ecosystem.

1000 1200 1400 **Year**




scientific, commercial, regulatory, and economic sides of the debate. The conference was convened by WHOI marine geochemists Ken Buesseler and Scott Doney, and Hauke Kite-Powell of the WHOI Marine Policy Center. In talks and wide-ranging discussions, participants raised serious doubts about the practicality, efficacy, and safety of large-scale iron fertilization. Yet many also seemed to accept that more science—in the form of carefully designed and conducted experiments—is the best way to resolve those doubts, one way or the other.

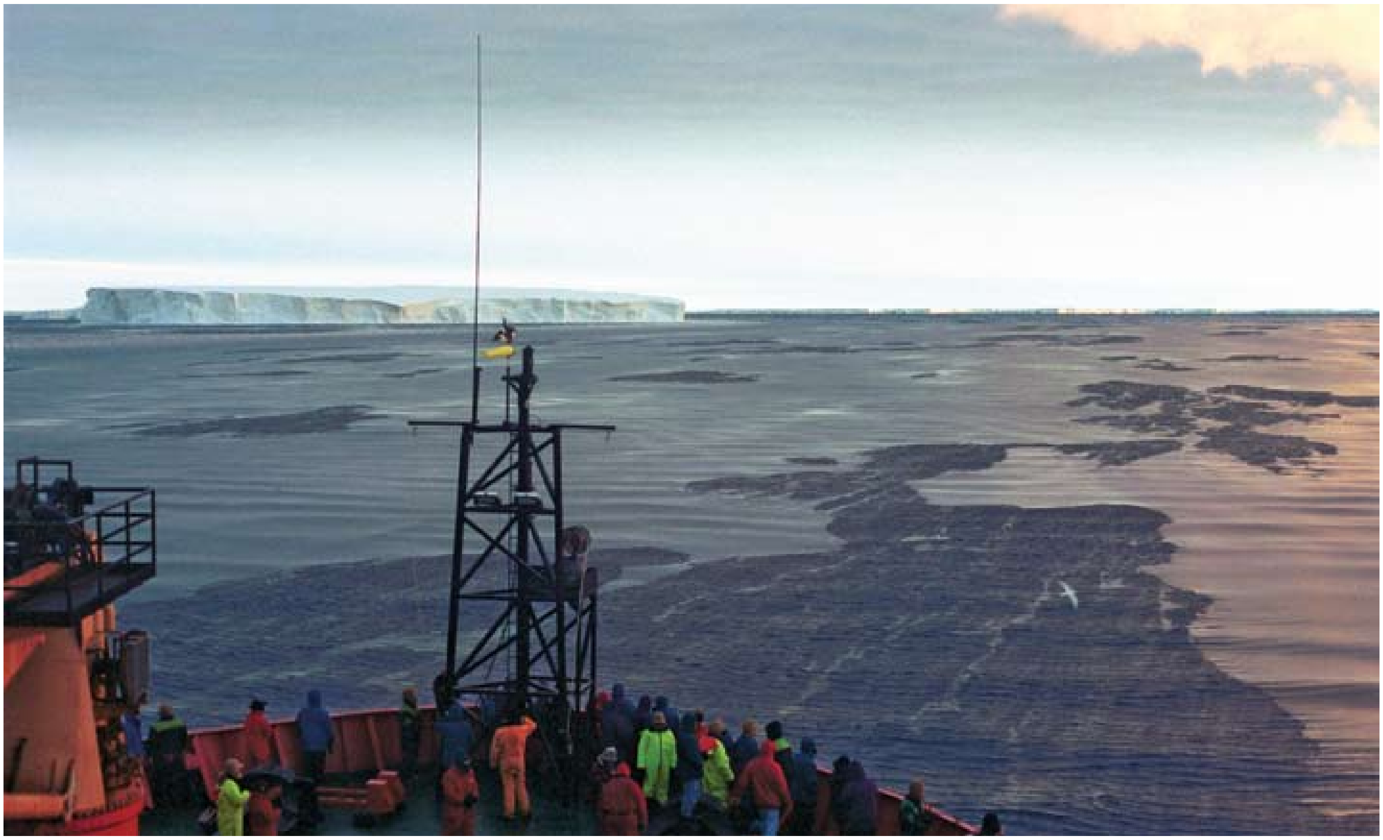
### Not as simple as it sounds

Martin made his pronouncement jokingly because he knew that he was glossing over several hindrances to using iron fertilization to sequester carbon in the ocean. Opponents to the idea are quick to point out the three major ones: It may be less efficient than it at first seems; it raises a host of new, worrying consequences; and its effectiveness is difficult for anyone to measure.

In certain regions, including the equatorial and north Pacific and the entire Southern Ocean, a simple iron addition does cause phytoplankton to grow rapidly. But tiny zooplankton, known as “grazers,” eat much of the bloom almost as soon as it starts. This begins a chain of recycling that ensues from the sea surface to the seafloor as grazers, krill, fish, whales, and microbes eat, excrete, and decompose. Much of the immense carbon prize won by iron addition

Atmospheric $CO_2$ (ppm): 280, 300, 320, 340, 360, 380 — 1600, 1800, 2007

Atmospheric carbon dioxide levels have increased precipitously since the 1850s, and continue to rise.



Ken Buesseler, WHOI

**IRON EXPERIMENTS OFF ANTARCTICA—Scientists aboard the Australian research vessel *Aurora Australis* studied the natural cycling of iron in the Southern Ocean in 2001. Ken Buesseler, a marine chemist at Woods Hole Oceanographic Institution, was aboard that expedition, and in 2002 he served as chief scientist of the Southern Ocean Iron Experiment (SOFeX). The three-ship operation investigated the results of adding iron to stimulate a phytoplankton bloom in the Southern Ocean.**

quickly leaks back into the atmosphere as carbon dioxide gas.

What is critical for the effectiveness of iron fertilization schemes is the amount of organic carbon that actually sinks from the surface and is sequestered in the depths (see Page 10). Only a small percentage of carbon—in the form of dead cells and fecal pellets—falls to the seafloor and stays there, unused, for millennia. A higher percentage (between 5 and 50 percent) will at least reach middle-depth waters, where the carbon will remain for decades. Proponents consider this result good enough to buy society time to come up with other, more permanent solutions to greenhouse gas increases.

Beyond the inefficiency of carbon sequestration, iron fertilization would likely cause other changes "downstream" of the ocean patches where iron was added (see Page 14). The huge green phytoplankton blooms would take up not just iron but other nutrients, too—nitrate, phosphate, and silica—essentially depleting nearby waters of the building blocks needed for plankton growth.

"You might make some of the ocean greener by iron enrichment, but you're going to make a lot of the ocean bluer," said Robert Anderson, senior scholar at Lamont-Doherty Earth Observatory.

Other participants at the WHOI conference—John Cullen, a biological oceanographer at Dalhousie University in Canada, Andrew Watson, a biogeochemist at the University of East Anglia, U.K., and Jorge Sarmiento, a modeler at Princeton's Geophysical Fluid Dynamics Laboratory—pointed out several other ecological concerns. Large-scale iron fertilization, in altering the base of the food chain, might lead to undesirable changes in fish stocks and whale populations. Increased decomposition of sinking organic matter could deprive deep waters of oxygen or produce other greenhouse gases more potent than carbon dioxide, such as nitrous oxide and methane. The plankton-choked surface waters could block sunlight needed by deeper corals, or warm the surface layer and change circulation patterns.

On the other hand, more plankton might produce more of a chemical called dimethylsulfide, which can drift into the atmosphere and encourage cloud formation, thus cooling the atmosphere and helping to counteract greenhouse warming. And others argue that increased plankton supplies might enhance fish stocks.

Then there is the practical problem of verification. Iron fertilization companies would earn profits by measuring how much carbon they sequester and then selling the equivalent to companies (or people) that either wish to or are required to offset their emissions. Any plan to sell sequestered carbon requires a reliable accounting, and this promises to be difficult in the ocean.

So far, only three of 12 iron addition experiments have been able to show conclusively that any sequestration happened at all, according to Philip Boyd of the New Zealand National Institute of Water and

Atmospheric Research. Perhaps more worrying to an investor, those sequestration numbers were low—about 1,000 tons of carbon per ton of iron added, as opposed to the 30,000 to 110,000 suggested by laboratory experiments.

**Carefully designed research**

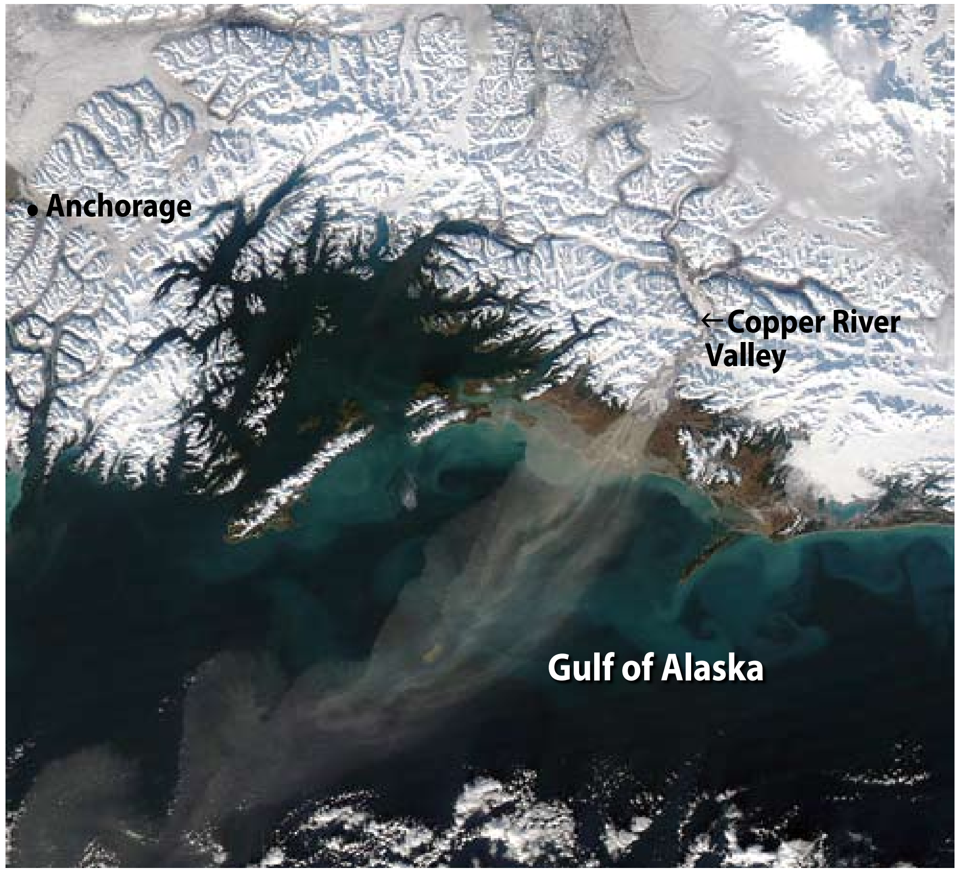
Despite the suspected drawbacks to full-scale iron fertilization, private companies—and many scientists—support the idea of further experiments. Learning more about the ocean is in everyone's interest, they argue, and the larger experiments now being proposed are still far too small to wreak environmental havoc.

While the past experiments showed widely variable results, proponents read this as an opportunity for refinement through engineering. For millennia, humans have been repeating processes that at first were marginally useful and tuning them to our purposes. Continued research could address a number of key questions (see box on Page 9), and those answers could point the way to higher yields and efficiency.

Proponents of iron addition do acknowledge the possibility of environmental ill effects. Still, no such effects have been detected during the past 12 experiments, probably because the experiments were small—around a ton of iron added over a few hundred square kilometers of ocean. By incrementally scaling up, they believe they can detect and avoid environmental problems.

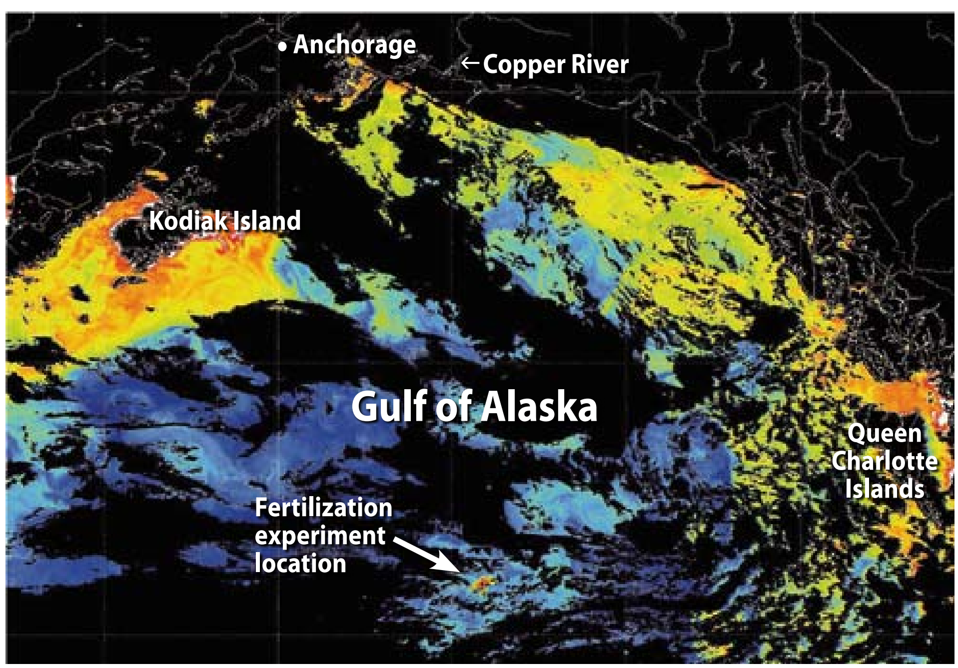
As for the verification problem, both carbon markets and international ocean law are moving to accommodate so-called "carbon sink" projects, such as iron fertilization, which capture and sequester carbon from the air, according to Till Neeff of EcoSecurities, a leading trader of carbon credits, based in London. By the time the science is worked out, he said, the economics may be worked out as well.

Anchoring all arguments for continued research is the brutal fact of global carbon emissions. The most practical hope for dealing with emissions at the moment lies in a piecemeal strategy of "stabilization wedges." Under this proposal, the world develops a portfolio of emissions reductions and carbon-capture projects, each of which offsets one piece of the global emissions pie (see Page 23). Combined, these wedges must




Jeff Schmaltz, MODIS Rapid Response Team, NASA Goddard Space Flight Center

**IRON ADDITIONS, NATURAL AND EXPERIMENTAL—Top, a plume of dust from glacial sediments in Alaska blows far into the North Pacific Ocean. Storms like this, or from vast deserts such as the Sahara, are the natural way that iron gets into oceans to fertilize phytoplankton blooms. Bottom, a bloom resulting from an intentional addition of iron in roughly the same region (during the experimental Subarctic Ecosystem Response to Iron Enrichment Study in 2002) shows up in the bottom center of the satellite image below as a red patch (indicating high levels of chlorophyll from the microscopic marine plants).**



"The worst possible thing we could do for climate change technologies would be to invest in something that doesn't work and that has big impacts that we don't anticipate."
—Lisa Speer,
Natural Resources Defense Council


Tom Kleindinst, WHOI

"Let's look at [iron fertilization] in our portfolio for mitigation. Uncertainty about the impacts shouldn't preclude careful research."
—Margaret Leinen,
Climos

**A wide range of stakeholders offered different perspectives on the ocean iron fertilization debate at a conference in September 2007 at Woods Hole Oceanographic Institution, including Lisa Speer, director of the Natural Resources Defense Council's Oceans Program (left) and Margaret Leinen, chief science officer of Climos, a company exploring iron fertilization projects.**

slow the growth of, and eventually lead to a net reduction in, our current global emissions of 7 billion to 8 billion tons of carbon per year. But with minimal progress so far on any wedges, and with China and India set to increase emissions as they develop, iron fertilization beckons as one tool in a toolbox of partial solutions.

"No option is without its impacts," said WHOI marine biochemist Ken Buesseler, "whether we use wind turbines, grow biofuels, or use energy-saving fluorescent bulbs, which contain mercury."

### But is it legal?

At present, iron fertilization falls into a gray area in both international law and formal carbon-trading markets, but this is changing (see Page 22).

Iron fertilization would happen on the open ocean, which is not owned by any country, according to David Freestone, senior adviser in the Legal Office of the World Bank, who briefed the symposium participants. While international treaties such as the London Convention, which governs ocean dumping and pollution, might address iron addition, treaty nations have not yet decided whether it might constitute pollution because its possible side effects remain unknown. Further, no overarching international agency exists to enforce the treaty, so responsibility falls to individual nations, he said. Ship crews intending to flout an international treaty could do so by electing to fly the flag of a country that has not signed it—a route that has already been publicly considered by one company.

"There are plenty of ways to do it wrong, but done right, [iron fertilization] does actually sequester carbon for hundreds of years in the place that it would ultimately end up anyway."

*—Andrew Watson, Univ. of East Anglia*

Carbon trading markets are young but growing, Neeff said. Strictly regulated markets, set in motion by the Kyoto Protocol treaty, last year traded 430 million tons of carbon offsets (worth billions of dollars) among companies required to reduce total emissions. (One ton of carbon equals 3.67 tons of carbon dioxide.) Regulatory markets don't allow for iron fertilization at present, but this may change as more carbon sink projects gain approval.

Then there are voluntary markets, Neeff said, in which concerned individuals or companies buy carbon offsets to assuage their conscience or "green" their image. Traders would be free to sell offsets from iron fertilization in these markets. Voluntary markets are growing rapidly, Neeff said, but so far they are equivalent to 7 million tons of carbon, worth about $100 million, per year—much smaller than regulatory markets.

Voluntary markets represent one more worry for opponents of iron fertilization. Iron fertilization companies might make superficial estimates of the amount of carbon they sequester and enter a hefty balance in their trading ledgers. Any large profits made from underregulated credits would encourage other outfits to go into business. The collective impact to the world's international waters could be both disastrous and impossible to trace to any single liable party, Cullen said.

But those are future scenarios. By the time iron fertilization moves from experiment to industry, laws may well be in place to regulate it, said Kite-Powell. Over the same period, increasing demand for carbon offsets is likely to ensure that iron fertilization is profitable, he said, referring to a recent economic analysis indicating a potential value of $100 billion over the next century.

### Next steps: scientists and industry

Iron fertilization is being pulled in two directions, as comments during a panel discussion at the conference made clear.

Iron fertilization is not a silver bullet, said Margaret Leinen, the chief science officer at Climos, a firm exploring iron fertilization projects, and former assistant director of geosciences at the U.S. National Science Foundation. But given the magnitude of the greenhouse gas problem and the lack of progress so far, "let's look at it in our portfolio for mitigation," she said. "Uncertainty about the impacts shouldn't preclude careful research."

Lisa Speer of the Natural Resources Defense Council took a different view: "There is a limited amount of money, of time, that we have to deal with this problem," she said. "The worst possible thing we could do for climate change technologies would be to invest in something that doesn't work and that has big impacts that we don't anticipate."

Between these viewpoints a middle ground emerged: "There are plenty of ways to do it wrong, but done right, [iron fertilization] does actually sequester carbon for hundreds of years in the place that it would ultimately end up anyway," Watson said. That may be a tremendous advantage compared with more familiar but less secure approaches like planting trees, he said. Skeptics should not dismiss the idea out of hand before scientists have had the chance to work out the details.

One way to quell doubts lies with carefully conducting larger experiments. But iron fertilization is unlikely to receive much more U.S. federal funding. It falls to entrepreneurs concerned about the climate problem to fund the work, and they need scientists' participation to make sure the right questions are asked and answered.

In a parallel with the way universities routinely conduct trials of the safety and efficacy of potential pharmaceuticals, Michaels pointed out that oceanographers may need to learn how to be involved with tests of iron fertilization. "We have to evolve a set of skills within our community to have those kinds of roles," he said. "Who else should be figuring that out but us?"

Though many scientists are keen on the idea of future research, fewer are willing to team up with a private company to do it, for fear of a real or perceived effect on the impartiality of their research. Still, researchers may need to convince themselves that just because the idea is potentially profitable doesn't mean it's wrong—or simply accept that further research is going to happen.

"Commercial efforts are moving forward with or without scientific input," Buesseler said. "We need to be able to evaluate their impacts and changes to the ocean carbon cycle, based upon the best possible oceanographic methods."

For their part, private companies hope to collaborate with researchers. Of the handful already in business, one—Climos—recently proposed a code of ethics supporting involvement by scientists and full environmental audits of experiment plans. Russ George, president of rival company Planktos, who also attended the conference, agreed in principle to the code. On Nov. 5, 2007, Planktos announced that it had dispatched a ship equipped for an iron fertilization experiment but made no statements about how it might comply with the code.

What's emerging for the next few years is the prospect of a round of experiments involving around 100 tons of iron, which is 100 times larger than previously tried. Financed by private companies, they could either be conducted by private interests with limited sampling gear or by teams of scientists through grants. New, autonomous technology promises to extend the duration of monitoring and improve measurements of how carbon sinks through the ocean.

Yields from previous experiments cannot be used to project whether larger-scale fertilizations would send millions, thousands, or fewer tons of carbon into the oceans' middle depths, Buesseler said. Still, commercial groups sponsoring new experiments hope to sell those carbon dioxide equivalents as voluntary offsets. While scientific research would focus on learning more about how the ocean works, the companies involved would be looking for ways to increase efficiency, make larger blooms in the future, and monitor any negative effects. As government-sponsored research on iron fertilization moves ahead in different countries, funding for larger experiments could develop into private and public partnerships.

Experiments on such a scale drive home one final point: that the near future of iron fertilization is probably modest on all counts—size of experiments, likely profits, environmental side effects, and amount of carbon sequestration. However profitable iron fertilization becomes, the dent it puts in atmospheric carbon levels in coming years will remain a small one. As these ocean scientists work to assemble their stabilization wedge to mitigate carbon dioxide emissions, they remind the rest of the world that many more wedges must be found.

*—Hugh Powell*

## Unresolved Questions

Twelve small experiments have shown that blooms of phytoplankton consistently result from intentional addition of iron to the ocean. But the efficacy and ecological impacts of iron fertilization remain uncertain, particularly with larger-scale experiments. If and when a new round of experiments is begun, these questions will be first on the list:

- How long will carbon be sequestered in the ocean?
- How deep is deep enough to accomplish this?
- How can sequestration efficiency be increased?
- How does the ocean food web change during and after a bloom?
- Which phytoplankton and grazers raise sequestration efficiency?
- Which parts of the ocean are best for iron fertilization?
- What size and what shaped patch should be fertilized?
- How often and how continually should iron be added?
- What kinds of currents and surface conditions give the best results?
- How can the amount and fate of carbon from a bloom be verified?
- How can effects downstream of experiments be detected?
- How can the production of other greenhouse gases be monitored?