Turning the Blue Sea Green

by Caeli Quinn

When oceanographer Dr. William Cochlan dangles a half-million-dollar, fully instrumental, trace-metal, clean rosette (algae analyzer) off the side of a research vessel, he knows no insurance company will cover him. There are high stakes in oceanographic research, and to pursue his current project, the Southern Ocean Iron Enrichment Experiment (SOFeX), Cochlan ventures into the wind-battered and stomach-churning Southern Ocean, where the Atlantic, Pacific, and Indian Oceans violently collide. Where past mariners sailed fast and prayed for safe passage, Cochlan, a Senior Research Scientist at the Romberg Tiburon Center for Environmental Studies, San Francisco State University's marine research facility, lingers for months, skirting icebergs and sampling the sea, in pursuit of one of modern oceanography's great mysteries—how tiny phytoplankton floating in frigid waters could affect our global climate.

Cochlan is investigating the effectiveness of iron enrichment—adding massive quantities of iron sulfate to the ocean to stimulate phytoplankton growth by minutely increasing the ambient concentrations of iron in the ocean. Cochlan and the multi-institutional SOFeX team suspect that iron accelerates the utilization of nitrogen by phytoplankton, revving up CO_2 absorption. Indeed, Cochlan wonders whether phytoplankton's formidable carbon-processing machine, which fuels the marine ecosystem, can pull CO_2 gas from the atmosphere and sequester it in the deep sea, like a sunken ship. From the National Science Foundation to the Department of Energy, scientists and entrepreneurs await the results and what they may proffer—a possible aid in combating global warming but certainly a much improved mechanistic understanding of the role of trace metals in the oceanic carbon cycle. This sort of speculation underscores the importance of the SOFeX expedition, and for Cochlan, the race is on to uncover iron enrichment's long-term effects.

In January 2002, Cochlan made his seventh foray into the Southern Ocean as one of 21 principal investigators aboard the research vessel *R/V Melville*, which followed the *R/V Revelle* and was later joined by the U.S. Coast Guard icebreaker *Polar Star* into the latitude known as the Furious Fifties. Its raucous waters protect an unspoiled wilderness where Cochlan and his research assistants, Julian Herndon of SFSU and Atma Roberts of the University of California at Santa Cruz, would endure 30-40 sea-tossed days. The trip began with scientists releasing a total of 1,800 kilograms (20,000 pounds) of acidic iron sulfate into the ocean, in the ship's wake. The ship tacked back and forth, crossing the Southern Ocean's invisible temperature divide, the Antarctic Polar Front Zone, dumping the iron in two patches: the high nitrate, low silicate warmer waters to the north (4-5 degrees Celsius); and the high nitrate, high

Cochlan and the multi-national SOFeX team suspect that iron enriches the phytoplankton nitrogen cycle, revving up CO_2 absorption.

silicate cooler waters to the south (-1.5 to 0 degrees Celsius). Ultimately, the ship enriched 500 square kilometers, the equivalent of 150,000 football fields, and Cochlan awaited the ocean's response to the alleviation of its suspected iron deficiency.

Cochlan and his fellow investigators aimed to test a prominent theory on climate—the late John Martin's "Iron Hypothesis." While a research scientist at Moss Landing Marine Laboratories south of San Francisco, Martin proposed that regions like the Southern Ocean, known as "HNLC" (High Nitrate Low Chlorophyll), lacked one ingredient necessary for phytoplankton growth—iron. These HNLC regions comprise nearly 20 percent of oceanic surface waters, yet phytoplankton, single-celled algae that form the base of the marine food chain, fail to thrive in the high-nutrient waters. In the Ice Ages, iron probably reached the HNLC regions as iron-rich dust, which blew from the deserts into the sea. Iron primed the "biological pump," triggering phytoplankton blooms. Phytoplankton began photosynthesizing and growing at great rates, soaking in carbon dioxide (CO_2) from surface waters, and locking it into their biomass.

Once the surface water was depleted of CO_2, atmospheric CO_2 gas diffused in. Primed by iron, the phytoplankton continued to grow, but now absorbing atmospheric CO_2. (Atmospheric CO_2 is a greenhouse gas that humans add to the atmosphere at a rate of two billion metric tons each year, primarily by burning fossil fuels.) Engorged phytoplankton either sunk to the sea bottom or were fed upon by other creatures like zooplankton and excreted as waste pellets. The overall result—CO_2 gas was pulled from the atmosphere and sequestered in the deep sea. Reducing atmospheric CO_2 reduced global warming, and the planet cooled. Martin half-joked, "Give me half a tanker of iron, and I will give you an Ice Age."

Cochlan's first journey to test the virtues of iron occurred in 1995, southwest of the Galapagos Islands. In the second large-scale attempt to make the ocean bloom, scientists fertilized a 72-square-kilometer patch with a half-ton of iron sulfate, and tracked the iron-enriched patch as it drifted 1,500 kilometers westward. The results were stunning—within days the ocean turned green as phytoplankton multiplied, even though iron concentration increased by only 100 parts per trillion. The bloom was a binge for sea creatures. "Once the algae bloomed, sharks, turtles, and squid flocked to it," Cochlan says. Ambient recordings showed that 2,500 tons of carbon as CO_2 were removed from the sea into planktonic biomass. Although considered an unqualified success, the experiment failed to answer a fundamental question about the long-term effects of iron on climate control: was the carbon dioxide sequestered into the deep sea or did it eventually return to the atmosphere? No one knew where the carbon ended up. Once iron fertilization ended, the bloom soon disappeared, along with the exact fate of the carbon.

Although iron fertilization in the Pacific Ocean was temporarily successful in decreasing dissolved CO_2 levels, the Pacific Ocean is like a country road, unable to handle large influxes of carbon traffic, compared to the carbon superhighway, the Southern Ocean. Computer simulations demonstrate that over the next 1,000 to 1 million years, the earth's CO_2 will migrate primarily to the Southern Ocean atmosphere. Furthermore, the southern latitudes are the source of abyssal water for all the oceans, where deep-sea exchanges swap and lock away atmospheric CO_2. The Southern Ocean is not the world's largest ocean, but if the right combination of iron, phytoplankton, and nitrogen were to suddenly coalesce, climatic models predict, glaciation might occur.

On the Southern Ocean expedition, the scientists had a strong hunch that the phytoplankton nitrogen cycles might reveal how carbon is locked away in deeper waters. This is Cochlan's specialty in the iron-carbon mystery—how phytoplankton use nitrogen, once iron deficiency is relieved. A phytoplankton's nitrogen use directly affects its photosynthetic growth and subsequent uptake of CO_2. Considering that there is more phytoplankton biomass in the ocean than plant biomass on Earth, phytoplankton are a photosynthetic goldmine. Nitrogen is fundamental in forming amino acids, proteins, and chlorophyll: no life can exist without it. The irony is that although the planet's oceans are full of dissolved nitrogen gas (N_2), few organisms can use it. Energy on par with a bolt of lightening is necessary to break nitrogen's resilient triple bonds. In HNLC regions, there is also an abundance of nitrate (the most oxidized form of nitrogen), but both

Dr. William Cochlan, Senior Research Scientist, RTC and Adjunct Professor of Biology

Nicholas Ladizinsky (left) and Julian Herndon, Research Biologists at RTC who participated on the SOFeX cruise in 2002 while both graduate students at Moss Landing Marine Lab and SFSU.

“The most effectiv

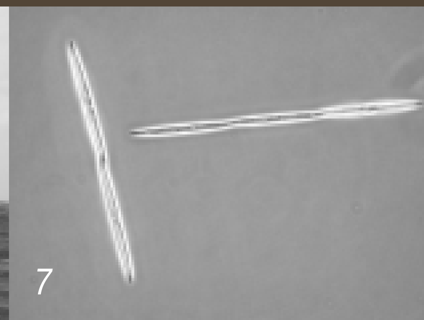
reducing power and iron are needed to utilize this nitrogen species for growth. Biological oceanographers have altered a line from “The Rhyme of the Ancient Mariner”: “Nitrogen, nitrogen everywhere, but not an energetically bioavailable form to drink.” For phytoplankton with limited energy, it makes more sense to reuse reduced nitrogen species like ammonium and urea. “The plankton are just recycling, like a spinning wheel. Using nitrate would equal something new,” Cochlan says.

Cochlan hypothesized that an influx of iron to the high nitrate Southern Ocean waters might alter the phytoplankton’s nitrogen cycle as it had in the Pacific Ocean, but to a different degree. Not all phytoplankton are the same—some are big, some are small, and their size is thought to be the main factor in controlling the movement of their biomass from the surface to deeper waters. The larger phytoplankton, called diatoms, are weighed down by a glassy external shell made from silicate in the surrounding water. They sink to the bottom, taking carbon with them. Cochlan believed that, based on the silicate concentrations, the northern waters would produce more of the shell-less phytoplankton, while the southern waters would bloom with diatoms. He wanted to know if the silicate-rich waters would interact differently with the iron-nitrate organic soup and alter the composition of the phytoplankton community. By breeding more diatoms, atmospheric CO_2 would be locked in and on its way to the deep sea. “The most effective way we can understand this ecosystem,” Cochlan says, “is to go out and perturb it.”

Cochlan’s experiments in the equatorial waters of the Pacific proved that adding iron sparked phytoplankton to use the abundant nitrate around them. Using isotope-labeled nitrogen, Cochlan precisely measured nitrogen uptake in the iron-fertilized and unfertilized (control) regions. He found that nitrogen consumption increased 14 fold during the Pacific bloom, the majority from nitrate, not the reduced forms, ammonium and urea. Larger phytoplankton responded vigorously, increasing from 15 to 90 percent of the total community nitrate uptake. Clearly, size mattered.

After the 200-kilometer-long bloom began to fade, Cochlan and crew packed up their isotope-spiked samples and returned to shore to analyze them by mass spectrometry. They found that diatoms did indeed bloom in the Southern Ocean, but the bloom took longer to develop than in equatorial waters—most likely a function of the frigid Antarctic waters. Without a doubt, phytoplankton were iron-limited, as in the Pacific Ocean. Furthermore, the iron addition stimulated the phytoplankton to reduce their use of urea and ammonia and switch to nitrate-based growth. So far the results were promising, but there was no significant change in the phytoplankton community composition in silicate-rich waters. “Everything grew faster, but essentially it was all the same stuff!” says Cochlan. While the ingredients were present, there was no explosive shift to large diatoms as might be expected. It appeared that silicate might limit the effectiveness of nitrogen uptake and iron fertilization particularly in silicate-poor waters.

Sequestration of CO_2 proved harder to measure. For SOFeX, a sediment trap was used to catch falling particles. This technique was not used on previous expeditions, and scientists had high hopes for proving the magnitude of carbon sequestered in the Southern Ocean. The traps revealed that the experiment was not as effective as predicted. Laboratory models estimated that one ton of iron would sink 100,000 tons of carbon. Current estimates suggest that the SOFeX *ve way we can understand this ecosystem, is to go out and perturb it."*



bloom fell short—perhaps sending only 1,000 tons of carbon below 100 meters. More carbon may sink over a longer time period, but how to measure it is the next hurdle.

While the SOFeX results are uncertain and still being analyzed and readied for publication, entrepreneurs have already filed for iron fertilization patents with the vigor of gold prospectors. The National Science Foundation, the Department of Energy, and the U.S. Coast Guard auspiciously funded SOFeX to learn how marine ecology may influence climate, but some private companies see iron fertilization as a quick fix for global warming. The experiment, Cochlan says, "was not designed to provide a Geritol fix for the greenhouse effect." But the potential reward of iron dumping has not gone unnoticed by many countries. Since the Kyoto Protocol, any nation that decreases its CO_2 output receives credits that can be sold to other nations. Cochlan is concerned that companies in the burgeoning ocean fertilization industry may dump one of John Martin's hypothetical tankers of iron into the ocean before scientists properly understand its long-term effects. Cochlan says that privately funded research projects abound, but their narrow focus on reversing global warming eclipses the need to understand the entire marine ecological response to iron fertilization. "If the point of the research is only CO_2 sequestering to combat global warming, then it's bad science," Cochlan says.

SOFeX was not intended to solve our greenhouse gas problems, but it uncovered more complex systems in marine ecology that will challenge Cochlan and fellow biological oceanographers for years to come. As the results came in, Cochlan was enroute to Tokyo to plan the next step—a 2004 experiment in the western subarctic Pacific, in conjunction with scientists from Japan and Canada. Modern oceanography parallels great sea-going ventures of the past century, and Cochlan revels in the urgent and collaborative effort. "This is very timely research that is receiving international attention," Cochlan says. Cochlan's research group will pick up where SOFeX left off and attempt to quantify the long-term ecological and chemical effects of iron enrichment. The deep blue waters of the North Pacific beckon, and while months at sea can wear even the hardiest soul, Cochlan is sustained by the ocean and its planktonic cast of characters.

Legend

1 *R/V (Research Vessel) Revelle skirting a small iceberg in the Southern Ocean.*
2 *Nick Ladizinsky preparing to hang a 30-liter Go-Flo water bottle to obtain ultra-clean water samples.*
3 *The trace-metal clean, instrumented rosette and Go-Flo water bottles used to obtain clean water samples during SOFeX.*
4 *Recovering the rosette on the starboard side of the R/V Melville. Julian Herndon is at far left.*
5 *Plankton collected during a net haul from outside (control) waters (Left) and inside (Right) the iron-enriched southern SOFeX patch.*
6 *Phytoplankton assemblages that responded to iron enrichment; the center phytoplankton is* Corethron spp.*, a single celled, centric diatom with many spines* (photo by K.E. Selph, University of Hawaii)
7 *A representative pennate diatom which bloomed due to alleviation of iron limitation of the Southern Ocean.* (photo by B.D. Bill, NWFSC)
8 *Recovering the sediment trap on the R/V Melville.*

All photos by KL Coale (Moss Landing Marine Laboratory) except where noted.