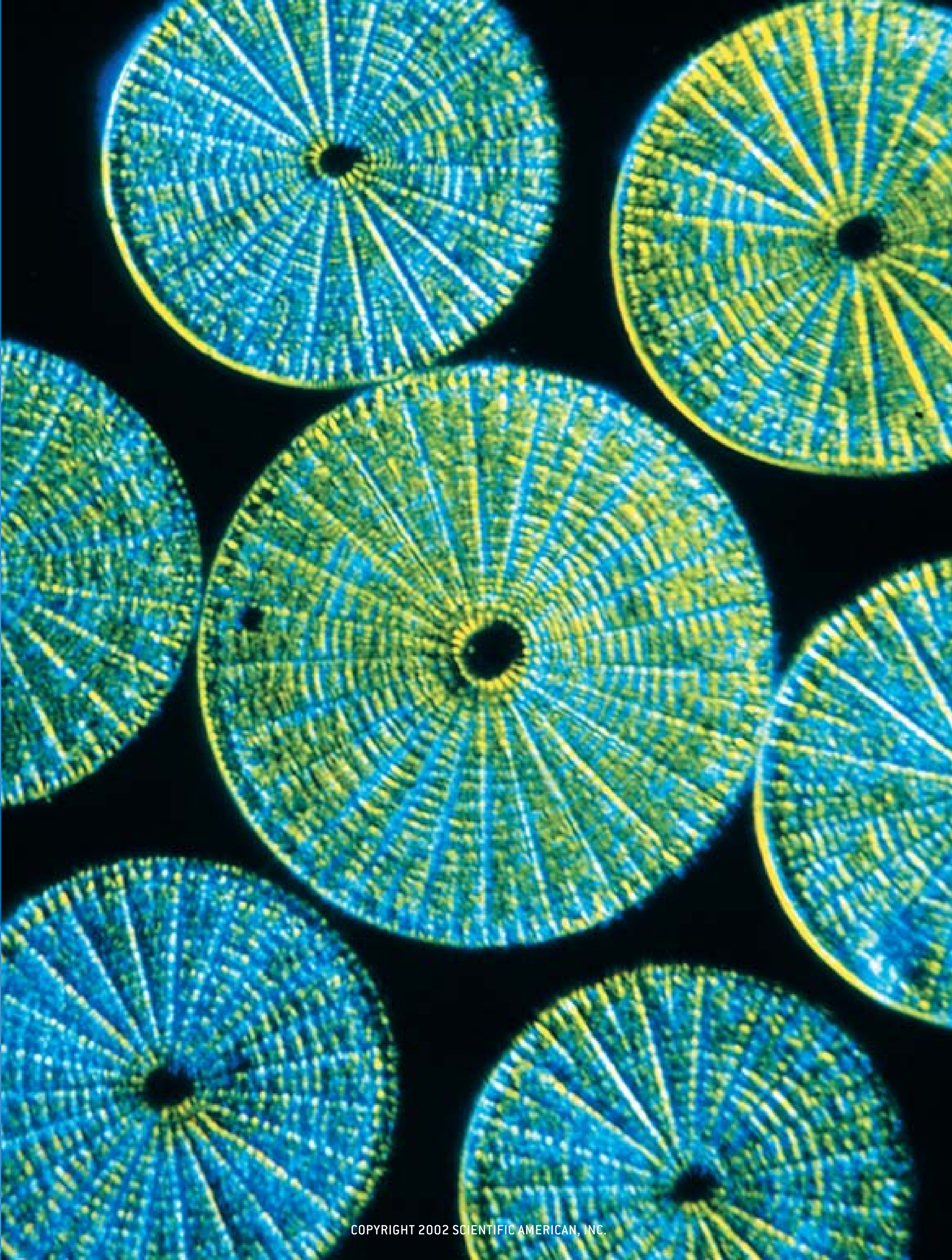
DIATOMS ARE THE GIANTS of the phytoplankton world. The species pictured here, *Actinocyclus sp.*, can measure up to a millimeter in diameter.

The Ocean's Invisible Forest

Marine phytoplankton play a critical role in regulating the earth's climate. Could they also be used to combat global warming?

BY PAUL G. FALKOWSKI



Every drop of water in the top 100 meters of the ocean

contains thousands of free-floating, microscopic flora called phytoplankton. These single-celled organisms—including diatoms and other algae—inhabit three quarters of the earth's surface, and yet they account for less than 1 percent of the 600 billion metric tons of carbon contained within its photosynthetic biomass. But being small doesn't stop this virtually invisible forest from making a bold mark on the planet's most critical natural cycles.

Arguably one of the most consequential activities of marine phytoplankton is their influence on climate. Until recently, however, few researchers appreciated the degree to which these diminutive ocean dwellers can draw the greenhouse gas carbon dioxide (CO_2) out of the atmosphere and store it in the deep sea. New satellite observations and extensive oceanographic research projects are finally revealing how sensitive these organisms are to changes in global temperatures, ocean circulation and nutrient availability.

With this knowledge has come a temptation among certain researchers, entrepreneurs and policymakers to manipulate phytoplankton populations—by adding nutrients to the oceans—in an effort to mitigate global warming. A two-month experiment conducted early this year in the Southern Ocean confirmed that injecting surface waters with trace amounts of iron stimulates phytoplankton growth; however, the efficacy and prudence of widespread, commercial ocean-fertilization schemes are still hotly debated. Exploring how human activities can alter phytoplankton's impact on the planet's carbon cycle is crucial for predicting the long-term ecological side effects of such actions.

Seeing Green

OVER TIME SPANS of decades to centuries, plants play a major role in pulling CO_2 out of the atmosphere. Such has been the case since about three billion years ago, when oxygenic, or oxygen-producing, photosynthesis evolved in cyanobacteria, the world's most abundant type of phytoplankton. Phytoplankton and all land-dwelling plants—which evolved from phytoplankton about 500 million years ago—use the energy in sunlight to split water molecules into atoms of hydrogen and oxygen. The oxygen is liberated as a waste product and makes possible all animal life on earth, including our own. The planet's cycle of carbon (and, to a large extent, its climate) depends on photosynthetic organisms using the hydrogen to help convert the inorganic carbon in CO_2 into organic matter—the sugars, amino acids and other biological molecules that make up their cells.

This conversion of CO_2 into organic matter, also known as primary production, has not always been easy to measure. Until about five years ago, most biologists were greatly underestimating the contribution of phytoplankton relative to that of land-dwelling plants. In the second half of the 20th century, biological oceanographers made thousands of individual measurements of phytoplankton productivity. But these data points were scattered so unevenly around the world that the coverage in any given month or year remained extremely small. Even with the help of mathematical models to fill in the gaps, estimates of total global productivity were unreliable.

That changed in 1997, when NASA launched the Sea Wide Field Sensor (SeaWiFS), the first satellite capable of observing the entire planet's phytoplankton

Overview/*Climate Regulators*

- Rapid life cycles of marine phytoplankton transfer heat-trapping carbon dioxide (CO_2) from the atmosphere and upper ocean to the deep sea, where the gas remains sequestered until currents return it to the surface hundreds of years later.
- If all of the world's marine phytoplankton were to die today, the concentration of CO_2 in the atmosphere would rise by 200 parts per million—or 35 percent—in a matter of centuries.
- Adding certain nutrients to the ocean surface can dramatically enhance the growth of phytoplankton and thus their uptake of CO_2 via photosynthesis, but whether intentional fertilization increases CO_2 storage in the deep sea is still uncertain.
- Artificially enhancing phytoplankton growth will have inevitable but unpredictable consequences on natural marine ecosystems.

PETER PARKS *imagequest3d.com (preceding page)*

populations every single week. The ability of satellites to see these organisms exploits the fact that oxygenic photosynthesis works only in the presence of chlorophyll *a*. This and other pigments absorb the blue and green wavelengths of sunlight, whereas water molecules scatter them. The more phytoplankton soaking up sunlight in a given area, the darker that part of the ocean looks to an observer in space. A simple satellite measurement of the ratio of blue-green light leaving the oceans is thus a way to quantify chlorophyll—and, by association, phytoplankton abundance.

The satellite images of chlorophyll, coupled with the thousands of productivity measurements, dramatically improved mathematical estimates of overall primary productivity in the oceans. Although various research groups differed in their analytical approaches, by 1998 they had all arrived at the same startling conclusion: every year phytoplankton incorporate approximately 45 billion to 50 billion metric tons of inorganic carbon into their cells—nearly double the amount cited in the most liberal of previous estimates.

That same year my colleagues Christopher B. Field and James T. Randerson of the Carnegie Institution of Washington and Michael J. Behrenfeld of Rutgers University and I decided to put this figure into a worldwide context by constructing the first satellite-based maps that compared primary production in the oceans with that on land. Earlier investigations had suggested that land plants assimilate as much as 100 billion metric tons of inorganic carbon a year. To the surprise of many ecologists, our satellite analysis revealed that they assimilate only about 52 billion metric tons. In other words, phytoplankton draw nearly as much CO_2 out of the atmosphere and oceans through photosynthesis as do trees, grasses and all other land plants combined.

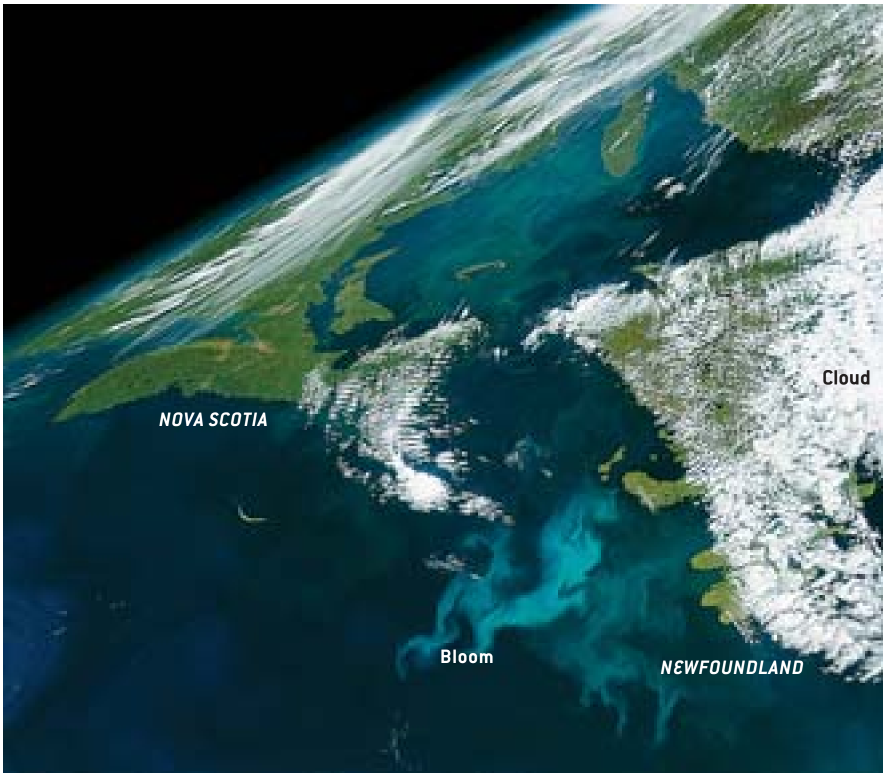
Sinking out of Sight

LEARNING THAT phytoplankton were twice as productive as previously thought meant that biologists had to reconsider dead phytoplankton's ultimate fate, which strongly modifies the planet's cycle of carbon and CO_2 gas. Because phytoplankton direct virtually all the energy they harvest from the sun toward photosynthesis and reproduction, the entire marine population can replace itself every week. In contrast, land plants must invest copious energy to build wood, leaves and roots and take an average of 20 years to replace themselves. As phytoplankton cells divide—every six days on average—half the daughter cells die or are eaten by zooplankton, miniature animals that in turn provide food for shrimp, fish and larger carnivores.

The knowledge that the rapid life cycle of phytoplankton is the key to their ability to influence climate inspired an ongoing international research program called the Joint Global Ocean Flux Study (JGOFS). Beginning in 1988, JGOFS investigators began quantifying the oceanic carbon cycle, in which the organic matter in the dead phytoplankton cells and animals' fecal material sinks and is consumed by microbes that convert it back into inorganic nutrients, including CO_2. Much of this recycling happens in the sunlit layer of the ocean, where the CO_2 is instantly available to be photosynthesized or absorbed back into the atmosphere. (The entire volume of gases in the atmosphere is exchanged with those dissolved in the upper ocean every six years or so.)

Most influential to climate is the organic matter that sinks into the deep ocean before it decays. When released below about 200 meters, CO_2 stays put for much longer because the colder temperature—and higher density—of this water prevents it from mixing with the warmer waters above. Through this process, known as the biological pump, phytoplankton remove CO_2 from the surface waters and atmosphere and store it in the deep ocean. Last year Edward A. Laws of the University of Hawaii, three other JGOFS researchers and I reported that the material pumped into the deep sea amounts to between seven billion and eight billion metric tons, or 15 percent, of the carbon that phytoplankton assimilate every year.

Within a few hundred years almost all the nutrients released in the deep sea find their way via upwelling and other ocean currents back to sunlit surface waters,



BLOOM OF PHYTOPLANKTON called coccolithophores swirls across several hundred square kilometers of the deep-blue Atlantic just south of Newfoundland. Such natural blooms arise in late spring, when currents deliver nutrients from the deep ocean to sunlit surface waters.

COURTESY OF THE SeaWiFS PROJECT, NASA GODDARD SPACE FLIGHT CENTER AND ORBIMAGE

Phytoplankton's Influence on the Global Carbon Cycle

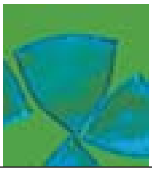
THE EARTH'S CARBON CYCLE can dramatically influence global climate, depending on the relative amounts of heat-trapping carbon dioxide (CO_2) that move into (*yellow arrows*) and out of (*green arrows*) the atmosphere and upper ocean, which exchange gases every six years or so. Plantlike organisms called phytoplankton play four critical roles in this cycle. These microscopic ocean dwellers annually incorporate about 50 billion metric tons of carbon into their cells during photosynthesis, which is often stimulated by iron via windblown dust (*1*). Phytoplankton also temporarily store CO_2 in the deep ocean via the biological pump: about 15 percent of the carbon they assimilate settles into the deep sea, where it is released as CO_2 as the dead cells decay (*2*). Over hundreds of years, upwelling currents transport the dissolved gas and other nutrients back to sunlit surface waters.

A tiny fraction of the dead cells avoids being recycled by becoming part of petroleum deposits or sedimentary rocks in the seafloor. Some of the rock-bound carbon escapes as CO_2 gas and reenters the atmosphere during volcanic eruptions after millions of years of subduction and metamorphism in the planet's interior (*3*). Burning of fossil fuels, in contrast, returns CO_2 to the atmosphere about a million times faster (*4*). Marine phytoplankton and terrestrial forests cannot naturally incorporate CO_2 quickly enough to mitigate this increase; as a consequence, the global carbon cycle has fallen out of balance, warming the planet. Some people have considered correcting this disparity by fertilizing the oceans with dilute iron solutions to artificially enhance phytoplankton photosynthesis and the biological pump. —*P.G.F.*

where they stimulate additional phytoplankton growth. This cycle keeps the biological pump at a natural equilibrium in which the concentration of CO_2 in the atmosphere is about 200 parts per million lower than it would be otherwise—a significant factor considering that today's CO_2 concentration is about 365 parts per million.

Over millions of years, however, the biological pump leaks slowly. About one half of 1 percent of the dead phytoplankton cells and fecal matter settles into seafloor sediments before it can be recycled in the upper ocean. Some of this carbon becomes incorporated into sedimentary rocks such as black shales, the largest reservoir of organic matter on earth. An even smaller fraction forms deposits of petroleum and natural gas. Indeed, these primary fuels of the industrial world are nothing more than the fossilized remains of phytoplankton.

Phytoplankton draw nearly as much CO_2 out of the oceans and atmosphere as all land plants do.



The carbon in shales and other rocks returns to the atmosphere as CO_2 only after the host rocks plunge deep into the earth's interior when tectonic plates collide at subduction zones. There extreme heat and pressure melt the rocks and thus force out some of the CO_2 gas, which is eventually released by way of volcanic eruptions.

By burning fossil fuels, people are bringing buried carbon back into circulation about a million times faster than volcanoes do. Forests and phytoplankton cannot absorb CO_2 fast enough to keep pace with these increases, and atmospheric concentrations of this greenhouse gas have risen rapidly, thereby almost certainly contributing significantly to the global warming trend of the past 50 years.

As policymakers began looking in the early 1990s for ways to make up for this shortfall, they turned to the oceans, which have the potential to hold all the CO_2 emitted by the burning of fossil fuels. Several researchers and private corporations proposed that artificially accelerating the biological pump could take advantage of this extra storage capacity. Hypothetically, this enhancement could be achieved in two ways: add extra nutrients to the upper ocean or ensure that nutrients not fully consumed are used more efficiently. Either way, many speculated, more phytoplankton would grow and more dead cells would be available to carry carbon into the deep ocean.

Fixes and Limits

UNTIL MAJOR DISCOVERIES over the past 10 years clarified the natural distribution of nutrients in the oceans, scientists knew little about which ocean fertilizers would work for phytoplankton. Of the two primary nutrients that all phytoplankton need—nitrogen and phosphorus—phosphorus was long thought to be the harder to come by. Essential for synthesis of nucleic acids, phosphorus occurs exclusively in phosphate minerals within continental rocks and thus enters the oceans only via freshwater runoff such as rivers. Nitrogen (N_2) is the most abundant gas in the earth's atmosphere and dissolves freely in seawater.

By the early 1980s, however, biological oceanographers had begun to realize that they were overestimating the rate at which nitrogen becomes available for use by living organisms. The vast majority of phytoplankton can use nitrogen to build proteins only after it is fixed—in other words, combined with hydrogen or oxygen atoms to form ammonium (NH_4^+), nitrite (NO_2^-) or nitrate (NO_3^-). The vast majority of nitrogen is fixed by small subsets of bacteria and cyanobacteria that convert N_2 to ammonium, which is released into seawater as the organisms die and decay.

Within the details of that chemical transformation lie the reasons why phytoplankton growth is almost always limited by the availability of nitrogen. To catalyze the reaction, both bacteria and cyanobacteria use nitrogenase, an enzyme that relies on another element, iron, to transfer electrons. In cyanobacteria, the primary energy source for nitrogen fixation is another process that requires a large investment of iron—the production of adenosine triphosphate (ATP). For these reasons, many oceanographers think that iron controls how much nitrogen these special organisms can fix.

In the mid-1980s the late John Martin, a chemist at the Moss Landing Marine Laboratories in California, hypothesized that the availability of iron is low enough in many ocean realms that phytoplankton production is severely restricted. Using extremely sensitive methods to measure the metal, he discovered that its concentration in the equatorial Pacific, the northeastern Pacific and the Southern Ocean is so low that phosphorus and nitrogen in these surface waters are never used up.

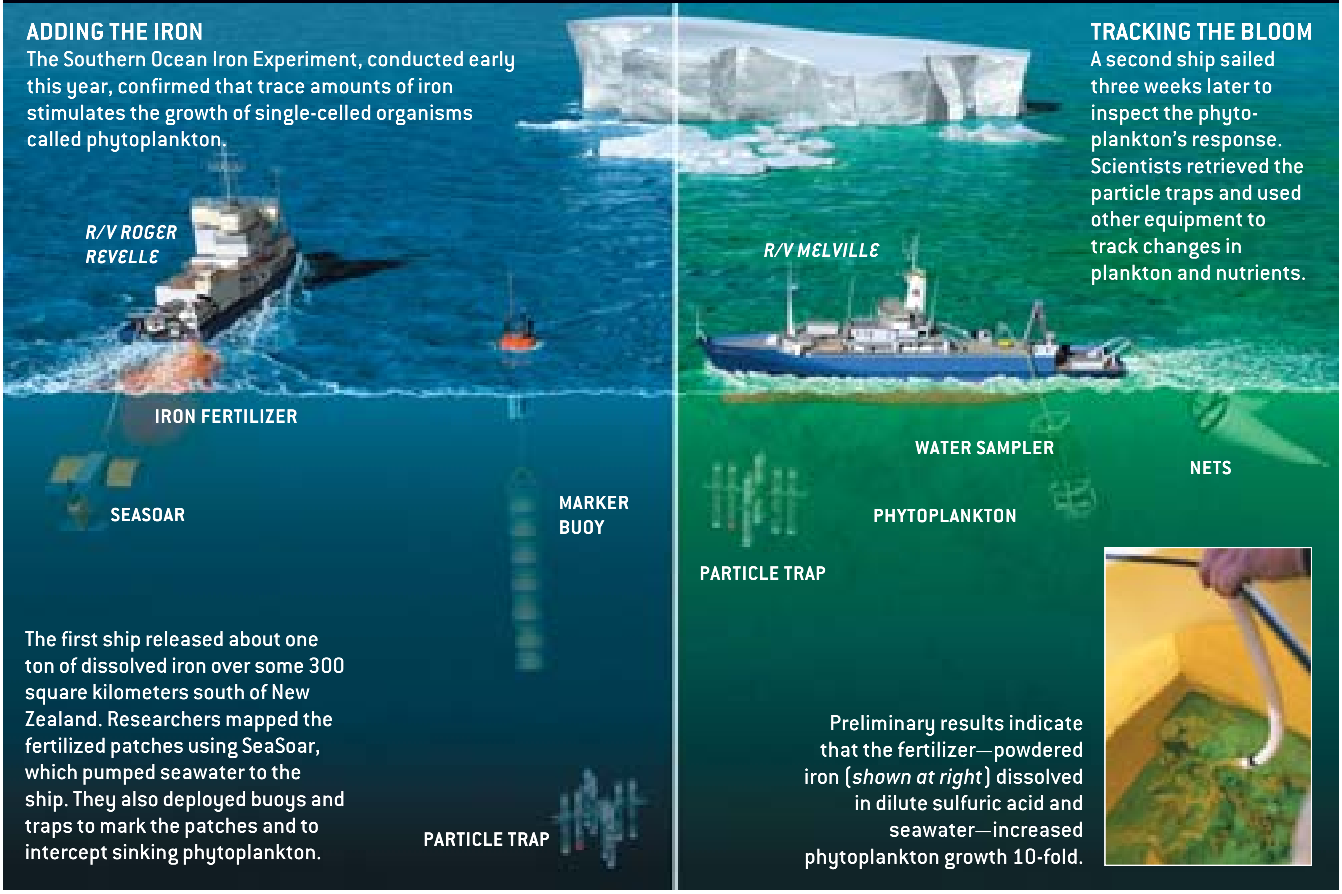
Martin's iron hypothesis was initially controversial, in part because previous ocean measurements, which turned out to be contaminated, had suggested that iron was plentiful. But Martin and his coworkers pointed out that practically the only way iron reaches the surface waters of the open ocean is via windblown dust.

THE AUTHOR

PAUL G. FALKOWSKI is professor in the Institute of Marine and Coastal Sciences and the department of geology at Rutgers University. Born and raised in New York City, Falkowski earned his Ph.D. from the University of British Columbia in 1975. After completing a postdoctoral fellowship at the University of Rhode Island, he joined Brookhaven National Laboratory in 1976 as a scientist in the newly formed oceanographic sciences division. In 1997 he and Zbigniew Kolber of Rutgers University co-invented a specialized fluorometer that can measure phytoplankton productivity in real time. The next year Falkowski joined the faculty at Rutgers, where his research focuses on the coevolution of biological and physical systems.

DAVID FIERSTEIN *(opposite page)*; PETER PARKS *imagequest3d.com* *(Triceratium)*

IRON FERTILIZER FOR PHYTOPLANKTON



ADDING THE IRON
The Southern Ocean Iron Experiment, conducted early this year, confirmed that trace amounts of iron stimulates the growth of single-celled organisms called phytoplankton.

The first ship released about one ton of dissolved iron over some 300 square kilometers south of New Zealand. Researchers mapped the fertilized patches using SeaSoar, which pumped seawater to the ship. They also deployed buoys and traps to mark the patches and to intercept sinking phytoplankton.

TRACKING THE BLOOM
A second ship sailed three weeks later to inspect the phytoplankton's response. Scientists retrieved the particle traps and used other equipment to track changes in plankton and nutrients.

Preliminary results indicate that the fertilizer—powdered iron (*shown at right*) dissolved in dilute sulfuric acid and seawater—increased phytoplankton growth 10-fold.

Consequently, in vast areas of the open ocean, far removed from land, the concentration of this critical element seldom exceeds 0.2 part per billion—a fiftieth to a hundredth the concentrations of phosphate or fixed inorganic nitrogen.

Historical evidence buried in layers of ice from Antarctica also supported Martin's hypothesis. The Vostok ice core, a record of the past 420,000 years of the earth's history, implied that during ice ages the amount of iron was much higher and the average size of the dust particles was significantly larger than during warmer times. These findings suggest that the continents were dry and wind speeds were high during glacial periods, thereby injecting more iron and dust into the atmosphere than during wetter interglacial times.

Martin and other investigators also noted that when dust was high, CO_2 was low, and vice versa. This correlation implied that increased delivery of iron to the oceans during peak glacial times stimulated both nitrogen fixation and phytoplankton's use of nutrients. The resulting rise in phytoplankton productivity could have enhanced the biological pump, thereby pulling more CO_2 out of the atmosphere.

The dramatic response of phytoplankton to changing glacial conditions took place over thousands of years, but Martin wanted to know whether smaller changes could make a difference in a matter of days. In 1993 Martin's colleagues conducted the world's first open-ocean manipulation experiment by adding iron directly to the equatorial Pacific. Their research ship carried tanks containing a few hundred kilograms of iron dissolved in dilute sulfuric acid and slowly released the solution as it traversed a 50-square-kilometer patch of ocean like a lawn mower. The outcome of this first experiment was promising but inconclusive, in part because the seafaring scientists were able to schedule only about a week to watch the phytoplankton react. When the same group repeated the experiment for four weeks in 1995, the results were clear: the additional iron dramatically increased phytoplankton photosynthesis, leading to a bloom of organisms that colored the waters green.

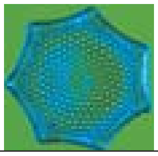
Since then, three independent groups, from New Zealand, Germany and the U.S., have demonstrated unequivocally that adding small amounts of iron to the Southern Ocean greatly stimulates phytoplankton productivity. The most extensive fertilization experiment to date took place during January and February of this year. The project, called the Southern Ocean Iron Experiment (SOFeX) and led by the Monterey Bay Aquarium Research Institute and the Moss Landing Marine Laboratories, involved three ships and 76 scientists, including four of my colleagues from Rutgers. Preliminary results indicate that one ton of iron solution

ILLUSTRATION BY DAVID FIERSTEIN; PHOTOGRAPH BY RON NICOLAYSEN

released over about 300 square kilometers resulted in a 10-fold increase in primary productivity in eight weeks' time.

These results have convinced most biologists that iron indeed stimulates phytoplankton growth at high latitudes, but it is important to note that no one has yet proved whether this increased productivity enhanced the biological pump or increased CO_2 storage in the deep sea. The most up-to-date mathematical predictions suggest that even if phytoplankton incorporated all the unused nitrogen and phosphorus in the surface waters of the Southern Ocean over the next 100 years, at most 15 percent of the CO_2 released during fossil-fuel combustion could be sequestered.

Adding iron to the Southern Ocean greatly stimulates phytoplankton productivity.



Fertilizing the Ocean

DESPITE THE MYRIAD uncertainties about purposefully fertilizing the oceans, some groups from both the private and public sectors have taken steps toward doing so on much larger scales. One company has proposed a scheme in which commercial ships that routinely traverse the southern Pacific would release small amounts of a fertilizer mix. Other groups have discussed the possibility of piping nutrients, including iron and ammonia, directly into coastal waters to trigger phytoplankton blooms. Three American entrepreneurs have even convinced the U.S. Patent and Trademark Office to issue seven patents for commercial ocean-fertilization technologies, and yet another is pending.

It is still unclear whether such ocean-fertilization strategies will ever be technically feasible. To be effective, fertilization would have to be conducted year in and year out for decades. Because ocean circulation will eventually expose all deep waters to the atmosphere, all the extra CO_2 stored by the enhanced biological pump would return to the atmosphere within a few hundreds years of the last fertilizer treatment. Moreover, the reach of such efforts is not easily controlled. Farmers cannot keep nutrients contained to a plot of land; fertilizing a patch of turbulent ocean water is even less manageable. For this reason, many ocean experts argue that that once initiated, large-scale fertilization could produce long-term damage that would be difficult, if not impossible, to fix.

Major disruptions to the marine food web are a foremost concern. Computer simulations and studies of natural phytoplankton blooms indicate that enhancing primary productivity could lead to local problems of severe oxygen depletion. The microbes that consume dead phytoplankton cells as they sink toward the seafloor sometimes consume oxygen faster than ocean circulation can replenish it. Creatures that cannot escape to more oxygen-rich waters will suffocate.

Such conditions also encourage the growth of microbes that produce methane and nitrous oxide, two greenhouse gases with even greater heat-trapping capacity than CO_2. According to the National Oceanic and Atmospheric Administration, severe oxygen depletion and other problems triggered by nutrient runoff have already degraded more than half the coastal waters in the U.S., such as the infamous "dead zone" in the northern Gulf of Mexico. Dozens of other regions around the world are battling similar difficulties.

Even if the possible unintended consequences of fertilization were deemed tolerable, any such efforts must also compensate for the way plants and oceans would respond to a warmer world. Comparing satellite observations of phytoplankton abundance from the early 1980s with those from the 1990s suggests that the ocean is getting a little bit greener, but several investigators have noted that higher productivity does not guarantee that more carbon will be stored in the deep ocean. Indeed, the opposite may be true. Computer simulations of the oceans and the atmosphere have shown that additional warming will increase stratification of the ocean as freshwater from melting glaciers and sea ice floats above denser, salty seawater. Such stratification would actually slow the biological pump's ability to transport carbon from the sea surface to the deep ocean.

New satellite sensors are now watching phytoplankton populations on a daily basis, and future small-scale fertilization experiments will be critical to better understanding phytoplankton behavior. The idea of designing large, commercial ocean-fertilization projects to alter climate, however, is still under serious debate among the scientific community and policymakers alike. In the minds of many scientists, the potential temporary human benefit of commercial fertilization projects is not worth the inevitable but unpredictable consequences of altering natural marine ecosystems. In any case, it seems ironic that society would call on modern phytoplankton to help solve a problem created in part by the burning of their fossilized ancestors.

PETER PARKS *imagequest3d.com* (*Triceratium*)

MORE TO EXPLORE

Aquatic Photosynthesis. Paul G. Falkowski and John A. Raven. Blackwell Scientific, 1997.

The Global Carbon Cycle: A Test of Our Knowledge of the Earth as a System. Paul G. Falkowski et al. in *Science,* Vol. 290, pages 291–294; October 13, 2000.

The Changing Ocean Carbon Cycle: A Midterm Synthesis of the Joint Global Ocean Flux Study. Edited by Roger B. Hanson, Hugh W. Ducklow and John G. Field. Cambridge University Press, 2000.

Ocean primary productivity distribution maps and links to satellite imagery are located at **http://marine.rutgers.edu/opp/index.html**

Details about the Southern Ocean Iron Experiment are located at **www.mbari.org/education/cruises/SOFeX2002/index.htm**