Ocean Fertilization: Ecological Cure or Calamity

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ABSTRACT

The late John Martin demonstrated the paramount importance of iron for microscopic plant growth in large areas of the world's oceans. Iron, he hypothesized, was the nutrient that limited green life in seawater. Over twenty years later, Martin's iron hypothesis is widely considered to be the major contribution to oceanography in the second half of the 20th century. Originating as an ecosystem experiment to test Martin's iron hypothesis, iron fertilization experiments are now used as powerful tools to study the world's oceans.

Some oceanographers are concerned that these experiments are catapulting ocean science into a new era. The vast stretches of ocean play a key role in the global carbon cycle, and thus in regulating Earth's climate. Some scientists, engineers and international policy makers claim that dissolving iron in the ocean will help stop global warming. Adding large amounts of iron to the oceans may drastically increase the amount of carbon dioxide that phytoplankton can capture from the atmosphere, thereby reducing the most common greenhouse gas.

But intentional iron fertilization over great expanses of the ocean may have unintended consequences for the world's largest ecosystem. The open ocean is one of the planet's last frontiers and a part of the global commons. As such, using the open ocean as a means to solve the complex problem of global warming raises deep questions about how humans think of and use the Earth. The question remains: Should humans use the ocean as a means to regulate a changing climate?

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Christchurch, New Zealand clings to the edge of the Earth. On the eastern shore of the south island, there is little to buffer the city from bitter winds blowing up from the Antarctic. A coast of contrasts, great rolling hills of coarse grass the color of burnt pottery surge skyward before collapsing into the sea. Boulders dot the shore. Scoured smooth by salt winds, they provide perches for seabirds and the occasional tourist. The views, though pretty, are not kind.

For the crew aboard the *R/V Melville* streaming south from Christchurch Harbor even less kindness awaits them on the open ocean. Only wind, waves and the occasional drifting iceberg separate them from Antarctica's snow and ice.

Captain James Cook sailed this same sea over 200 years ago in search of the great southern land continent. He too had to navigate the treacherous waters of the Southern Ocean in the name of exploration, and he wrote of the dangers – the same that face the *R/V Melville* – in his Captain's Log. "We spent the night, which was exceedingly stormy, thick, and hazy, with sleet and snow…surrounded on every side with danger." Subsequent explorers nicknamed the southern latitudes for their perilous conditions; the *R/V Melville* will cruise south past the Roaring Forties, into the Furious Fifties and skirt the boundary of the Screaming Sixties.

Although not claiming continents for king and country, the scientists aboard the *R/V Melville* do have an important commission. The second of three vessels to embark on one of the largest research projects ever undertaken by the U.S. oceanographic fleet, the 300-foot *R/V Melville* is heading southeast to a designated site in the middle of the Southern Ocean. Once there it will work alongside two other research vessels, battling forty-foot seas and gale-force winds for weeks, conducting science at sea. Their collective mission: to investigate how enormous blooms of phytoplankton, created by the scientists, affect the ocean, the atmosphere, the climate of our planet.

The late John Martin demonstrated the paramount importance of iron for microscopic plant growth in large areas of the world's oceans. Iron, he hypothesized, was the nutrient that limited green life in seawater. Over twenty years later, Martin's iron hypothesis is now widely considered to be *the* major contribution to oceanography in the second half of the 20th century. According to Richard Barber, Professor of Oceanography at Duke University, "Most of the rules of biological oceanography were in place by World War II, and we spent the second half of the 20th century showing that these hypotheses were true. The iron hypothesis was a paradigm vision that took place in this period." Armed with this powerful new knowledge, oceanographers were able to interpret many new things about the workings of the ocean. However, Barber also acknowledges that "this knowledge has come at a price, and the price is a controversy about whether we should manipulate the ocean as a service to society."

Fertilizing the ocean with iron originated in the scientific community as a grand ecosystem experiment to test Martin's iron hypothesis. Oceanographers now use iron fertilization as a powerful tool to study one of the world's largest ecosystems. By manipulating the ocean through these experiments, oceanographers can better understand the complex physical, chemical and biological cycles of the ocean. Just as a photograph captures a moment in time and space, an ocean fertilization experiment captures a portrait of the cycles and systems in a fluid and ever-changing environment.

The vast stretches of ocean play a key role in the global carbon cycle, and thus in regulating Earth's climate. Marine plants and animals come into contact with almost one hundred billion tons of carbon each year. And some of the world's smallest organisms – microscopic plants drifting in the surface water of the oceans – partly power this essential global mechanism. Each ocean fertilization experiment reveals new and basic components of marine science. And understanding present-day ocean cycles can help scientists to peer backward in time to learn about our planet's past. Iron enrichment experiments are especially useful in investigating how the climate swerved and swayed millions of years ago, initiating warming and inciting ice ages.

But some oceanographers are concerned that these experiments are catapulting ocean science into a new era. Kenneth Coale, Director of the Moss Landing Marine Laboratory, believes that within the last decade there has been a profound shift in the nature of ocean fertilization research. "Here's an experiment we devised to understand how the world works. And now people are trying to use this to understand how to make the world work for us."

Iron fertilization has grown from the exclusive arena of science into the fertile minds of venture capitalists as a means of manipulating the ocean ecosystem for human gain. Some scientists, engineers and international policy makers claim that dissolving iron in the ocean will help stop global warming. Adding large amounts of iron to the oceans may drastically increase the amount of carbon dioxide that phytoplankton can capture from the atmosphere. In our gas-guzzling society, employing the biological processes of phytoplankton as a way to regulate a changing climate is an alluring idea, and one that is gaining momentum.

But many oceanographers are worried that intentional iron fertilization over great expanses of the ocean will have unintended consequences for the world's largest ecosystem. Critics don't have to look far for evidence of how humans have damaged the environment; the ozone hole over the Antarctic is an often used example. Although Richard Barber has partnered with a venture capital firm, Ocean Farming Inc., to investigate the commercial viability of fertilizing the ocean with iron, he remains cautious about using the oceans for human gain. "The issue isn't commercialization of this manipulation of the ocean, but it's the manipulation of the ocean, period."

The open ocean is one of the planet's last frontiers and a part of the global commons. As such, using the open ocean as a means to solve the complex problem of global warming raises deep questions about how humans think of and use the Earth. Human history is rife with conquests over nature. We have molded the planet to fit our needs. Global warming is perhaps one of the largest problems we have faced as a species and the fate of the planet rests in our hands. The advocates and critics of ocean fertilization believe that they have the planet's – and humanity's – best interests in mind; both groups believe that they are saving the world.

Joseph Priestley, a minister living in late 18th century England, was the first to understand the key processes of the natural carbon cycle. He conducted experiments with sealed jars in which he found that a candle flame and animals' breath "injured" the air within the jar, but that by adding a sprig of green mint, the air was "restored". Priestley wrote of his experiments, "The injury which is continually done to the atmosphere by the respiration of such a large number of animals...is, in part at least, repaired by the vegetable creation." Although he did not name the gases at work in his experiments, we now credit him for discovering oxygen.

In its simplest form, the global carbon cycle is much like Priestley's experimental jar, only larger. Carbon dioxide is released from living things as they breathe and decay, which is then taken up by plants that, through photosynthesis, convert the carbon dioxide into oxygen. Occurring on both land and in the sea, terrestrial vegetation alone utilizes 60 billion metric tons of carbon per year.

Hundreds of millions of years ago, when the photosynthetic processes in plants exceeded the respiration processes in animals, an excess of carbon dioxide was removed from the atmosphere. This excess carbon was transferred through the food chain, settled in reservoirs like the deep ocean, and over great spans of time formed the coal, oil and natural gas in the fossil fuel stores on which our economy relies. Carbon is also stored, on a much shorter time span, as biomass in our houseplants, as algae in our fish tanks, in our backyard gardens, and in grasslands, thickets and forests.

But as eternal and essential as the carbon cycle may seem, a great global change is currently underway, ignited and fueled by humans.

The average American adds more than five metric tons of carbon into the atmosphere each year. Each time you start your car, flip a light switch or warm up leftovers in the microwave - never mind breathing out - you are contributing to the build up of atmospheric carbon dioxide. Prior to the Industrial Revolution – about the time Priestley was conducting his jar experiments – the carbon cycle was in a relative equilibrium. When humans released the great carbon reserves buried deep within the Earth by burning fossil fuels, the stored carbon returned to the atmosphere through exhaust pipes and power plant smokestacks in the form of carbon dioxide.

Altering the landscape also contributes to the problem. As forests are cleared and timber burned, carbon in the leaves, branches and trunks are converted to carbon dioxide. Like a saturated sponge, the global carbon cycle can't absorb any excess carbon dioxide. It remains hovering in the atmosphere, trapped.

Since the onset of the Industrial Revolution, the amount of carbon dioxide in the atmosphere has increased by almost 30 per cent. In the 21st century, the composition of the atmosphere bears a human thumb mark. Although carbon dioxide is the most common of the so-called greenhouse gases in the atmosphere, other gases such as methane, nitrous oxide and chlorofluorocarbons have been added to the mix.

The greenhouse effect is a natural process. Acting like a blanket enveloping the Earth, the atmosphere helps maintain a temperature conducive to life. Without the natural greenhouse effect, the average temperature on Earth would be about minus18 degrees Fahrenheit. In our present gas guzzling world, when greenhouse gases such as carbon dioxide build up in the atmosphere, radiation from the sun that would otherwise escape back into space is trapped beneath the thickened atmosphere, which acts like a greenhouse, and increases the earth's ambient temperature.

The Intergovernmental Panel on Climate Change (IPCC) was set up by the World Meteorological Organization and the United Nations Environment Program to monitor the changing climate and to establish an international consensus about global change science. Composed of more than 2,000 scientists, who have reviewed more than 20,000 scientific papers on weather and climate, the IPCC has concluded that human activities have indeed induced global warming.

For people who have seen the numbers, this makes sense. Humans expel almost 8 billion metric tons of carbon into the atmosphere each year, 6.5 billion tons from burning fossil fuels and 1.5 billion tons from clearing forests. Three billion tons remain in the atmosphere with nowhere to go. The ambient temperature of the planet has risen by almost 1.5 degrees Fahrenheit since the middle of the 19th century. And the warming trend observed during the 20th century may be the largest of any century in the last 1,000 years, with the 1990s being the warmest decade.

The effects of climate change are clear. We've already seen a rise in sea levels and an increase in ocean temperatures. The polar ice caps are melting; the permafrost in the tundra is receding. Should recent trends continue, the permanent ice cap on Mt. Kilmanjaro will be gone in less than 15 years. As humans continue to emit an excess of carbon dioxide into the atmosphere – more than likely another 200 to 600 parts per million to the atmosphere by late in the century – the global effects scientists are predicting are scary.

One effect of climate change not often included in the larger discussion on global warming is the effect of warming on the life cycles of plants and animals. Evidence mounts that a warming climate is altering the life cycle events of wildlife, and recent studies find that birds, amphibians, and plants are affected. "People need to understand that we are finding that plants and animals are already responding, very strongly, when we have only had a 1.5 degree Fahrenheit average global temperature warming," said Terry Root, a Senior Fellow at the Center for Environmental Science and Policy in the Institute for International Studies at Stanford University.

Root studies range shifts in North American animals, primarily songbirds. In North America, spring is coming two weeks earlier and fall is coming about a week later than would be expected without climate change. Species can't adapt fast enough to the rate at which the climate is warming. Root suggests that "there may be a day one spring when you wake up and there are no honeybees to pollinate the flowers in your backyard because they've all moved north."

According to Root, the vast majority of the members of the IPCC agree that changes in the biological events of wildlife and the poleward range shifts of species are important indicators of a warming climate. "Except for the six or seven individuals who deny that climate change is occurring, all of my colleagues in the IPCC accept life cycle changes in wildlife as indicators of climate change," said Root.

Species shifting their natural ranges is just one example of what we are already observing in nature. Root predicts that we are seeing only the beginning. "Ecological systems are very complex and if you push on one species, there is a domino effect, and we don't really know what all the dominos are or how they are going to fall." Assuming the planet continues warming over the next 100 years, Root suggests that the ecological domino effect may be staggering and will ultimately pose serious concerns for human

Some scientists are considering carbon sequestration – seizing carbon dioxide from the atmosphere and imprisoning it - as one way to curtail the growing stock of atmospheric carbon dioxide. The Carbon Sequestration Leadership Forum, an international climate change initiative, defines carbon sequestration as, "the capture, from power plants and other facilities, and storage of carbon dioxide (CO2) and other greenhouse gases that would otherwise be emitted to the atmosphere." If carbon dioxide is captured at its source, such as power plants that burn fossil fuel, it can then be transported and stored in either deep underground reservoirs or injected into the deep ocean where it will remain trapped at the bottom of the sea.

The U.S. Department of Energy in the Office of Fossil Energy quotes President George W. Bush in 2001 as saying, "We all believe technology offers great promise to significantly reduce [greenhouse gas] emissions -- especially carbon capture, storage and sequestration technologies." Although the U.S. has yet to implement sequestration technologies, either in geologic or ocean reservoirs, other countries, especially European nations are seriously considering carbon sequestration as a viable method to reduce carbon emissions. In 1996, Norway completed the world's first commercial carbon dioxide capture and storage project, sequestering about one million metric tons of carbon dioxide in the deep ocean each year.

Although carbon sequestration is often temporary – on the scale of hundreds to thousands of years – Howard Herzog, a Principal Research Engineer for the MIT Laboratory for Energy and the Environment, says that it may complement global efforts to conserve energy, create energy efficient technologies, and ultimately adopt a non-carbon economy. "The bottom line is that fossil fuels are critical to the world's economy and well being. They're not going to be given up overnight and there are no viable substitutes today," said Herzog. "One of the only answers, if you believe that fossil fuels are going to be around for awhile, is that we need to take care of the emissions produced by the fossil fuels. That's where capture and storage come in."

That's also where ocean fertilization may come in.

Phytoplankton – plant-like, free-floating, single-celled organisms – are responsible for most of the photosynthesis in the world's oceans. The word plankton, like planet, is derived from a Greek root that means "wanderer." Infinitesimally small, hundreds of thousands of phytoplankton can fit inside a space of one cubic centimeter, roughly the size of the end of your fingertip. Although they make up less than one per cent of the biomass for all the photosynthetic organisms on Earth, phytoplankton are responsible for converting almost half of the atmospheric carbon dioxide in the global cycle into solid, organic carbon. Think of them as the marine equivalent of forests. The oceans are breathing.

As the base of the marine food web, phytoplankton are the central engine for what oceanographers have dubbed the biological pump. This pump cycles carbon dioxide from the atmosphere to the ocean and back to the atmosphere through the complex biological processes of the marine food web. As phytoplankton photosynthesize in the surface waters of the ocean, they suck carbon dioxide out of the atmosphere. Zooplankton, microscopic marine animals, eat the phytoplankton, which are then eaten by other small animals. Larger and larger animals enter the food chain. Big predator fish reign supreme at the top of the web. And as all of these animals respire, carbon dioxide is released back into the surface water of the ocean and the atmosphere.

But some fraction of the phytoplankton, the remains of organisms that feed on them, and animal fecal matter, sink, by force of gravity, into the deep ocean. Stored in solid, organic form in descending dead plants and animals, carbon accumulates in great reservoirs at the bottom of the ocean. This movement of carbon to the deep ocean is critical in regulating Earth's climate. If the biological pump were to suddenly stop, the amount of carbon released from the deep sea would more than double the amount of carbon dioxide in the atmosphere. The global carbon cycle would be violently disrupted, throwing an equilibrium out of whack.

That the ocean is a natural sink for carbon dioxide has been known for much of the 20th century. But in some parts of the ocean, carbon dioxide moves from the atmosphere to the deep ocean much less efficiently, due to extremely low phytoplankton populations. Without adequate fuel for its central engine, the biological pump is sluggish. Up until the last few decades, these vast stretches of barren oceans were an enigma to oceanographers. The equatorial Pacific and the Southern Ocean were particularly puzzling; there was a sufficient light and nutrients, but no phytoplankton. Where were the phytoplankton and what was preventing them from growing?

Like all plants, phytoplankton require light, water and nutrients to flourish. Macronutrients, such as nitrogen and phosphorous, are often found in great abundance in the oceans. And until recently, many scientists believed that these were the only vital nutrients that phytoplankton required. But like almost all other organisms, including humans, these tiny plants cannot survive without some metals in their diet. One of them is iron.

Iron is an important micronutrient for all of life's processes, especially if you are a plant. Involved in the production of chlorophyll, iron is also a component of many enzymes associated with energy transfer in a cell. Ferrodoxin, an iron-containing protein, is present in all green plants and carries electrons throughout cells during photosynthesis. Geologic records show that many of cell proteins containing iron, like ferrodoxin, can be traced back to 3.5 billion years ago, suggesting that iron played a key role in the evolution of plant life on this planet.

Like almost all micronutrients, iron exists in trace quantities in the ocean. Recent measurements indicate that it is present at picomolar concentrations or one part per quadrillion in seawater. To help imagine the scale of this concentration, Kenneth Coale likened it to placing one postage stamp on the surface of the state of Texas. Imagine you were a single-celled organism looking for iron to survive. Searching for iron in seawater would be like flying over Texas and looking for that one postage stamp.

Enter Alfred Redfield. In 1934, an animal physiologist at Harvard University, Alfred Redfield, proposed that marine phytoplankton use elements, such as carbon and nitrogen, in a predictable – and measurable – manner. Through his research in aquatic chemistry, Redfield established the major pattern of the composition of main elements in phytoplankton and demonstrated that these ratios of main elements were similar to those found in seawater. That is, photosynthetic organisms utilize elements, such as carbon and nitrogen, in the proportion that they are found in the ocean. After rigorous experimentation in which the ratios of the main elements in phytoplankton were shown to be a constant, the Redfield ratio of 106 carbon: 16 nitrogen: 1 phosphorous (by atoms) was embraced by the oceanographic community.

Now considered to be a key foundation in biogeochemistry and marine science, the Redfield ratio is an accepted empirical observation. It is often compared to other physical constants in science, such as Avagadro's number or the speed of light in a vacuum. Knowing the constant elemental composition of phytoplankton in seawater is a valuable tool for oceanographers; they don't have to habitually sail the seas to collect measurements.

Oceanographers use the Redfield ratio to estimate micronutrient concentrations, and they incorporate the ratio into computer simulations to model ocean chemistry. The Redfield ratio has been extended to include iron and looks like this: 106 carbon: 16 nitrogen: 1 phosphorous: 0.001 – 0.005 iron. Because iron exists at picomolar concentrations in seawater, it is extremely difficult to obtain exact measurements of this micronutrient. Oceanographers, therefore, have allowed for a wide range of iron concentrations in the Redfield ratio. Even so, as the smallest constituent in the ratio, iron exerts a tremendous force in how nutrients are used by phytoplankton. It is the limiting factor. In other words, adding one atom of iron forces phytoplankton to photosynthesize up to 100,000 times more carbon dioxide.

Scale this idea up to the open ocean and the implications are huge. Questions arise: How would the chemical and biological composition of the ocean change once iron was added to surface waters? If iron was no longer the limiting factor for phytoplankton, could the sluggish biological pump be jump started in barren ocean waters? How much carbon dioxide would be removed from the atmosphere? How would the global carbon cycle – and Earth's climate – be affected?

John Martin, an oceanographer from the Moss Landing Marine Laboratory, was one of the first scientists to detect that common species of phytoplankton and zooplankton contained trace metals, such as copper, zinc and iron in their chemical make-up. He realized that trace metals must be integral to phytoplankton growth if the microscopic organisms were using them at the molecular level. Martin developed new techniques for measuring metals in seawater that were clean and contaminant free. Armed with their new equipment techniques, Martin and his researchers went to work cataloging components of ocean water.

The results of the seawater testing shocked the oceanography community. Concentrations of trace metals known to be in ocean waters, such as iron, were detected at orders of magnitude lower than previously thought. And new trace metals, including zinc, cobalt and manganese, that had never before been documented, were found to be common in seawater.

During his trace metal experiments, Martin turned his attention to understanding the role phytoplankton play in regulating the global climate. He was intrigued by the barren ocean waters and set the task to try and figure out why these desolate zones were devoid of life. For lack of a better explanation, up to this point in time most scientists believed that zooplankton feeding on phytoplankton kept the plant-life low in these areas by voracious grazing, much like the way a field of cows eats a grass field bare. But Martin thought that there was something other than overeating zooplankton keeping parts of the ocean barren.

Martin developed a hypothesis that iron was a micronutrient needed for phytoplankton reproduction and growth, and the lack of this trace metal was the sole reason for the barren ocean waters. This became known as the iron hypothesis. Open ocean waters, like those of the Antarctic, equatorial Pacific, and Southern Oceans, Martin reasoned, were too far away from land masses to be naturally fertilized by dust storms blowing off the edge of continents that contained micronutrients, such as iron. According to Kenneth Coale, Martin "was the kind of guy who could put a bunch of seemingly disconnected information together...and whip it up into a theory that was all connected. [His iron hypothesis] was beautiful."

To test his iron hypothesis, Martin sent a team of researchers to the Antarctic Ocean to collect samples of phytoplankton-barren seawater. Iron was added to some seawater samples, while other samples, the controls, were left untreated. After several days under the same conditions, phytoplankton was thriving in the samples containing iron. The control samples were still barren. Further bottle experiments strengthened the hypothesis's standing, and rocked both the oceanographic and the remainder of the scientific community. The iron hypothesis was, as Barber mentioned, a paradigm shift for oceanographers.

Martin then took his hypothesis even farther and suggested that the iron-ocean interactions may be partly responsible for past ice ages. During the ice ages, the climate was much drier than it is today. The atmosphere was a grimy swirl of dust swept up from vast stretches of deserts covering the land. If large amounts of this iron-rich dust were blown into areas of the ocean that lacked iron, the fertilized ocean would increase photosynthesis in plants, thereby sucking more carbon from the atmosphere into the ocean and cooling the planet.

Seeing the possibility of how close iron limitation may be linked to the global climate, Martin followed this conjecture with another, even more provocative speculation: dump enough iron into the ocean and you could reverse global warming. At a lecture at the Woods Hole Oceanographic Institute in 1988, Martin uttered what is undoubtedly his most famous quote: "Give me a tanker of iron, and I'll give you an ice age."

After publishing the results of his iron hypothesis bottle experiments and his ice age claims in the prominent British journal, *Nature*, Martin was courted by the press. His findings were published in many of the major science magazines, and the iron hypothesis – and the man behind it – soon surfaced in popular magazines and newspapers. Martin found himself on the talk-show circuit, discussing his iron hypothesis on Good Morning America, CNN, and the United Kingdom's BBC.

Even though Martin's bottle experiments strengthened his hypothesis, he faced doubts from other oceanographers, as it was yet to be shown that iron was the limiting nutrient to phytoplankton growth in the real world: the open ocean. Martin was challenged at every turn. According to colleagues, this contentious atmosphere was the kind he liked best.

To help resolve the controversy, Martin proposed to conduct ecosystem enrichments of the open ocean. But many scientists believed that experiments on whole ecosystems were risky, and it took several years to convince the National Science Foundation to endorse and fund an iron fertilization experiment.

Though Martin died of cancer shortly before the first iron fertilization experiment, dubbed Ironex I, his colleagues insisted that his research be continued. The first iron addition to the equatorial Pacific Ocean took place in the fall of 1993. Scientists involved with Ironex I fertilized a 64 square kilometer patch of ocean with iron. The results were astounding. The phytoplankton levels increased threefold. By all accounts, the ocean turned green.

Ironex II was launched with Kenneth Coale, the current Director of the Moss Landing Marine Laboratory, at the helm in 1995. Following a similar scientific experiment, Ironex II brought in similar results: yes, iron was a limiting nutrient for phytoplankton growth in the open ocean. "We had predicted the response," recalled Coale in a 1995 interview, "but none of us was really prepared for what it would look like or feel like. There were some of us who were quite pleased and others of us who would walk out on the fantail and burst into tears. It was a profoundly disturbing experience for me."

Zackary Johnson, currently a postdoctoral fellow at the Massachusetts Institute of Technology, was aboard the Ironex II expedition as a graduate student of Barber's. Johnson studies phytoplankton community structure, and is a member of Sallie (Penny) Chisholm's Lab at MIT, one of the top phytoplankton research centers in the world. He recalls the success of the two expeditions with awe. "The second one was even more successful than the first one, in terms of logistics, and the biological response was incredible." Ten years later, Coale is still amazed by this first experience. "To think that this type of manipulation would turn – would produce this result…and *whammo*, you turn the ocean green for miles! That's a powerful realization."

Ironex I and Ironex II demonstrated that iron was the limiting factor to phytoplankton growth in the equatorial Pacific Ocean. But what about the other HNLC waters around the globe? Would they respond similarly? A new slew of questions regarding the complex physical, chemical and biological cycles of the ocean and atmosphere were uncovered by the Ironex experiments. A new form of oceanographic science was born.

Coale believes that ocean fertilization experiments are extremely valuable tools to study ocean processes. "These (ocean fertilization) experiments are unique in that they enable one to perform a specific experiment." Coale was chief scientist in charge of the 2002 Southern Ocean Iron Experiment (SOFeX), and he helped formulate hypotheses for the cruise with John Martin back in the late 1980s. "The SOFeX experiment was one that was planned in the late 80s, and we didn't really have an opportunity to test it until 2002," said Coale.

Involving 76 scientists from 18 different institutions, the SOFeX cruise was the third iron fertilization field experiment conducted by American scientists. Jointly funded by the National Science Foundation, the Department of Energy, and the U.S. Coast Guard, the SOFeX cruise had two goals: to add to scientists' understanding of how biological processes in the ocean may regulate the planet's climate and to answer some lingering questions about how iron-ocean interactions may have triggered past ice ages. It was a massive undertaking and a logistical nightmare.

Under a porcelain blue sky and with a crisp wind blowing down the harbor, the *R/V Revelle* left Christchurch on January 6, 2002 and headed southeast into the Southern Ocean. The job of the *Revelle* team, led by Dr. Ken Johnson (no relation to Zackary) of the Monterey Bay Aquarium Research Institute, was to add iron to two locations: one north and one south of the Antarctic Polar Front Zone. This is a zone along 170°W that is characterized by low salinity water and provides one of the main incentives for conducting the SOFeX project in this part of the Southern Ocean. The region north of the Antarctic Polar Frontal Zone has low concentrations of silicate and high concentrations of nitrate. The waters south of the Zone have high concentrations of both silicate and nitrate. Both regions are limited by iron.

Diatoms, a species of phytoplankton that require silicate to make an outer shell, should be thriving in the southern region where both nitrate and silicate are abundant. But due to the lack of iron in the waters, diatoms, and other phytoplankton, are absent. Scientists involved with SOFeX were confident that once iron was added to the region south of the Antarctic Polar Front Zone, diatoms would grow, as all the nutrients needed for diatom life would be available. However, in the region north of the Antarctic Polar Front Zone, the scientists were not so sure; the low concentration of silicate complicated the problem. This northern region, an area approximately the size of the United States, contains most of the HNLC waters, where, if implemented, large-scale iron fertilization may best work.

The primary job of the *Revelle* was to distribute iron in two 15-kilometer by 15-kilometer square patches, one on either side of the Antarctic Polar Frontal Zone. In each of the 4,000-gallon tanks used in the experiment, seawater was mixed with 2,200 pounds of iron sulfate. To fertilize the ocean patches the iron mixture was pumped through the *Revelle's* propellers along with an inert gas tracer that allowed the scientists to remotely measure chemical and biological effects of the iron fertilization. The 300-foot *Revelle* zigzagged back and forth in 15-kilometer stints, fertilizing the ocean patch, much like a neighbor fertilizes his backyard.

In combination with the gas tracer, the center of each patch was marked with buoy-like instruments called drifters that were outfitted with Global Positioning Systems and optical and chemical sensors. The drifters followed the iron as it dissolved and dispersed in the water. As the square patches morphed with the ocean currents, the drifters provided continuous reference positions of the patches to the three ships.

After the *Revelle* fertilized the two patches with iron, the *R/V Melville* arrived on the scene. Coale's group on the *Melville* was responsible for taking daily measurements of phytoplankton and zooplankton growth rates and biomass, as well as determining levels of iron and other trace metals in seawater samples. Particle traps – instruments that gauge the amount of carbon that sinks from the ocean's surface – that were deployed by the *Revelle* were retrieved by the *Melville* team. At each sampling site within the two patches, the *Melville* stayed for one day to collect all the needed measurements.

Each scientist onboard the *Melville* had a particular duty, a scientific specialty, and questions about the ocean that he or she hoped the six-week cruise would be able to answer. The main lab space where many of the daily experiments took place was approximately 50 feet by 30 feet. A flexible area, the lab had removable lab benches and tables and long fluorescent lights on 24 hours a day. Because it was a floating lab that had to withstand the rocking and rolling of the *Melville* as it took on Antarctic swells, everything was bolted to the floor, strapped to the walls, stuck in place with duct tape, bungee cords, rope and some good luck.

During the week it took the *Melville* to get to the fertilized patches, Zackary Johnson and the rest of the crew fiddled with their equipment, took water samples, performed test runs, and made sure that everything would work without a hitch when they met up with the *Revelle*. It was imperative to collect data continuously for all biological and chemical parameters from the beginning of the experiment to the end. They knew that there would be no second chances if things weren't working tickety-boo.

Like a well-choreographed dance, the three ships and the 76 crew members worked in unison, counterpoint and syncopation, nearly all at the same time, and without much of a dress-rehearsal. As chief scientist, the task of choreographer landed on Coale and for him, more than anyone else, the SOFeX experiment was a monumental challenge.

The Southern Ocean didn't make this any easier for Coale and his crew. A vast, barren landscape, it is achingly cold. Looking from the deck of the *Melville* onto the open water, nothing breaks the continuity of the horizon. Sky converges with water, wind mixes with waves: a tumultuous relationship that is both violent and beautiful. Zackary Johnson recalled that the barren landscape became familiar, but was never the same. In a matter of moments, the ocean could mutate from a serene turquoise blue into a gray heaving mass that churned and beat and shook the ships sideways with ten-foot waves towering over the deck rails.

Both Zackary Johnson and Coale were quick to point out that the three research vessels were not cruise ships, but industrial ships with few amenities. "It's not like the normal Princess Cruises people think of when you say, 'I'm going out to sea for two months,'" said Coale. The white deck of the 300-foot *Melville* is littered with winches, cranes, metal drums, plastic barrels, large nets and an array of blue plexi-glass water tanks. "There is a real danger when you're working on the ship deck, and most days it is very cold," said Zackary Johnson. The ocean at the southern most point on the SOFeX cruise is three degrees Celsius – certain death if a man overboard is not rescued in minutes. The ship's crew and scientists wear full-body insulated personal floatation devices when on deck.

Coale described the experience of living on a research vessel for two months with gusto and dry humor. "You live and work and eat in your office. Imagine that they bring you food once in a while and it's crappy food and they run out of milk and bread. And imagine that in your office they're driving forklifts all around and moving big pieces of equipment. If you go outside you have to wear a life vest because it's life threatening out there. Now make everything move – lurch from side to side and heave up and down 30 to 40 feet – and you're living there for two months."

On some mornings at sea, an iceberg, massive and morose, drifted into view. Uneven melting created weird shapes in the ice and Zackary Johnson remembers that sometimes they seemed to move and come to life, like immense, ghostly beings riding the waves. All three of the SOFeX ships had sonar that alerted the crew to icebergs. On the sonar screen, five story icebergs looked like small green, unoffending blips. But the danger of the great shifting blocks of ice was real. An impatient and unguarded ship's captain ran the risk of slamming into one.

The U.S. Coast Guard Ice Cutter *Polar Star* arrived at the fertilized patches on February 12, almost five weeks after the *Revelle* left Christchurch Harbor. The *Polar Star* came from McMurdo Sound, Antarctica, and the crew's primary job was to measure how much carbon was removed from the fertilized patches. This final step in the SOFeX expedition was an essential test of the experiment's hypothesis: knowing how much carbon was removed from the ocean's surface, and thus the atmosphere, by an iron-triggered phytoplankton bloom was crucial.

Scientists aboard the the *Polar Star*, led by Ken Buesseler of Woods Hole Oceanographic Institute, quantified for the first time the amount of carbon that sank into the deep sea. In the northern iron patch, Buesseler and his crew used a robotic multi-sensor instrument called an autonomous profiler to continually measure ocean parameters in the water column. The profiler was "parked" 100 meters below the ocean's surface for 50 days to measure how much carbon sank below that depth. The results of their experiment demonstrated that carbon sank several-fold times more in the fertilized patch than in the neighboring HNLC waters. What this means is that scientists now have a best estimate for knowing that when X-amount of iron is added to the Southern Ocean, X-amount of carbon will be removed from the surface waters and sink below 100 meters. Useful for modeling how iron-ocean interactions influenced ice ages, this ratio can also help predict the effectiveness of ocean fertilization to curb global warming.

The results of the SOFeX experiment were significant and wide reaching. Reported in three separate papers in the 16 April 2004 issue of *SCIENCE,* a colorized scanning electron micrograph of a diatom chain collected on the SOFeX cruise was featured on the front cover. SOFeX revealed not only information about iron-ocean interactions, but also an astonishing amount of basic science about ocean processes. The experiments in both fertilized patches "were remarkably successful and...[the results] indicate that large blooms resulted in both locations," said Coale. There was also a striking difference in the species composition between the two patches: diatoms dominated in the southern patch, while in the northern patch, diatoms and other species of phytoplankton were equally abundant. Together, the fertilized phytoplankton blooms consumed over 30,000 tons of carbon dioxide.

The SOFeX results astounded even a seasoned scientist like Coale. Since both the northern and southern regions are iron limited, the area important for carbon cycling in the Southern Ocean has doubled. Coale recalled that the entire SOFeX crew was captivated by their duty and aware of their responsibility to the world's largest ecosystem. "Everyone has the sense that they are doing something unique and very important and very dramatic. People pushed themselves very hard to capture everything they could about this incredible gift the ocean was giving to us."

Despite the successes of SOFeX, there likely won't be another iron fertilization experiment to match it in size and grandeur for quite some time. The years of intricate planning, along with the ten million dollar price tag, are deterrents to any oceanographer wanting to follow in Coale's wake. "They are incredibly difficult experiments to do," said Coale. "That is, it takes the coordination of three major oceanographic vessels and a whole lot of equipment to go down to an area of the world characterized by the highest wind stress on the planet, and then try and do something in sort of an oceanographic tag-team approach. We had about 75 or so scientists bobbing around for months at a time. This could be simplified."

Until the next SOFeX cruise, oceanographers have other resources; they can turn to modelers for help. Questions about ocean processes that can't be immediately answered by open ocean experiments can be estimated by using computer simulations, their likely accuracy enhanced by data from ocean expeditions like SOFeX. Models are used to both conceptualize – to imagine – the workings of an ecosystem and to hypothesize and quantify how the system functions in the past, present and future. Although they attach much uncertainty to their predictions, models are invaluable tools.

Mick Follows is a principal researcher in the Program in Atmospheres, Oceans and Climate at MIT. Using numerical models, Follows investigates the relationships between ocean circulation and biogeochemical cycles. Scientists and policy makers often want modelers like Follows to make predictions, something about which he is skeptical. "A lot of what I think models are perceived to be used for is for quantitative questions, defining boundaries, making policies, but there is a whole other way in which you can use models in exploring questions in a very qualitative way."

Follows prefers to use models to illustrate the movements of ocean systems and cycles. He has spent much of the last year designing a model that demonstrates how iron may couple at the molecular level with other elements, such as sulfur and phosphorous, in the ocean's biological pump. Even though his model provides some insight into how iron fits into the oceans' biogeochemical cycling, Follows is very cautious about predicting how much carbon will be stored in the deep sea from iron fertilization. "I think that what a lot of people want from models are quantitative answers like, 'How effective would [iron] fertilization be?' And that's the most hard thing to do," said Follows. "I don't think we can deliver that [answers] because we don't know enough about the basic processes and the basic distribution of iron in the ocean at this time to create credible models."

Penny Chisholm, Professor of Environmental Studies at MIT, often uses computer models to defend her stance that iron fertilization should never be used for curbing global warming. She is in favor of continued iron fertilization experiments, but *only* if they are used for advancing knowledge of ocean processes. "Iron fertilization experiments are, regardless of industry, very important tools for basic research. It is essential to do experiments to [get information] to model the global carbon cycle and make predictions for climate change."

Chisholm uses models to not only better understand ocean biogeochemical cycles, but also to predict what may happen should ocean fertilization ventures be operated on a grand scale. One possible unintended consequence is irrevocably altering the complex marine food web that took thousands of years to evolve. Using models, Chisholm envisions this possible scenario: In large fertilized ocean patches, dead phytoplankton build up in the surface waters. Bacteria throng to consume this drifting detritus. Feeding, breeding and continually multiplying, the bacteria use up all of the oxygen in a region, creating a dead zone, killing all marine life.

One of the most prominent American oceanographers involved with the iron fertilization debate, Chisholm is often in the public arena. She has published commentaries in *Science* and has been quoted in publications from *Wired* to *Discover* to *Nature*. She is unabashedly vocal about terminating any ventures to commercialize ocean fertilization for carbon sequestration. However, the publicity is not something she enjoys. "I wish it [commercializing ocean fertilization] would go away."

Chisholm is by and large an ecologist. She thinks that tinkering with the Earth's largest ecosystem will undoubtedly have enormous unintended consequences, not only for the localized ecosystem that is fertilized, but for the entire Earth's oceans and potentially, atmosphere. "Oceans are dynamic and connected ecosystems. What goes down somewhere comes up somewhere else," said Chisholm. "Scientists need to look at the downstream ecological and economic response, and the [ecosystem's] long term response to ocean fertilization are impossible to predict."

Howard Herzog, a colleague of Chisholm's in MIT's Center for Environmental Initiatives and a member of the International Carbon Sequestration Leadership Forum, agrees that ocean fertilization as a means to sequester carbon brings heavy baggage to the debate: uncertainty and potential unintended consequences. "At least in my eyes, and I assume that in a lot of other people's eyes, the mountain of doubt [surrounding it] is pretty large," said Herzog.

Although the fertilization experiments have demonstrated that iron limits phytoplankton growth, there is so much uncertainty about the exact workings of the physical, chemical and biological processes that control the movement of carbon dioxide from the atmosphere to the deep oceans, even beginning to quantify this movement has scientists stumped. For large-scale fertilizations what is not known is: How much carbon will be removed from the atmosphere? How long will it remain stored in the ocean? And what will be the net effect on the ocean ecosystem?

Both Chisholm and Herzog agree that this amount of scientific uncertainty should stop venture capitalist companies from continuing to push towards iron fertilization as a method to curb carbon emissions – and to make money. Herzog puts forth his own version of the precautionary principle in a succinct and resounding fashion. "I have never been a proponent of iron fertilization because you can't show to a reasonable certainty that it helps resolve the problem."

"Precaution is better than cure," said Sir Edward Coke, an English judge and politician, in the 17th century. Today, the precautionary principle is quickly becoming a value (more so in Europe) to which our society is subscribing. Succinctly stated in the Wingspread Statement, from a gathering of scientists, philosophers, lawyers and environmental activists in 1998, the precautionary principle is:

> "When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically. In this context the proponent of an activity, rather than the public, should bear the burden of proof. The process of applying the precautionary principle must be open, informed and democratic and must include potentially affected parties. It must also involve an examination of the full range of alternatives, including no action."

Based on the principle of *Vorsorge* or forecaring, the precautionary principle became the maxim for German environmental law in the 1970s. When environmentalists brought to the attention of the government that vast stretches of national forest were dying, the government decided to drastically reduce power-plant emissions before there was a scientific consensus on the harmful effects of acid rain on vegetation. In the face of uncertainty, the German government decided to act with precaution, hoping to avoid serious or irreversible potential harm to their environment.

The precautionary principle has since been embraced by much of Europe. It has been incorporated into many of the rules and protocols established by the European Union in the 1990s and influenced treaties, such as the 2000 Cartagena Protocol on Biosafety. This treaty greatly relies on the precautionary principle and seeks to "protect biological diversity from the potential risks posed by living modified organisms from modern biotechnology" and allows countries to prohibit genetically modified organisms from entering their borders. In 2002, UK Prime Minister Tony Blair gave a speech to the Royal Society on the achievements of British scientists, in which he stated, "Responsible science and responsible policy making operate on the precautionary principle." Although Blair wants to promote and improve British science and technology, he still stands by the old adage, it's better to be safe than sorry.

While European scientists and policy makers advocate the precautionary principle, their American associates still largely stick to the risk analysis model. Evolving out of the world of engineering, the risk analysis model calculates the mathematical likelihood of the risks new technologies pose to the public. As Michael Pollan writes in a 2001 essay on the precautionary principle published in the *New York Times Magazine*, the risk analysis model is "very good at measuring what we can know - say, the weight a suspension bridge can bear - but it has trouble calculating subtler, less quantifiable risks." Pollan goes on to say that, "Whatever can't be quantified falls out of the risk analyst's equations, and so in the absence of proven, measurable harms, technologies are simply allowed to go forward."

The New York Times Magazine listed the precautionary principle as one of the most influential ideas of the year in 2001. Yet, Americans, especially those involved in industry, generally mistrust it because it shifts the burden of proof from those who oppose change to those who champion it. With risk analysis, the scientific uncertainty around unquantifiable risks allows new technologies to go forward, thus working in industries' favor, whereas with the precautionary principle, scientific uncertainty calls for proceeding slowly. Critics of the precautionary principle assert that it stifles innovation. Proponents argue that it stops us sliding down the slippery slope.

In the early 1900s, Alfred Alder, an Austrian psychiatrist and psychologist, stated that, "The chief danger in life is that you may take too many precautions." Sometimes, as in the case of ocean fertilization, there is a paradox: no one knows whether precaution is better than the cure. Both sides of the issue – the proponents and the detractors – believe that they are helping the planet.

At the UN Conference on Environment and Development in Rio de Janeiro in 1992, world leaders adopted Principle 15, promoting the widespread international application of the precautionary principle. Principle 15 states that: "In order to protect the environment, the precautionary approach shall be widely applied by states according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

And yet, when worded in this way, both advocates and opponents of ocean fertilization can embrace the precautionary principle. Both sides of the issue believe that they are 'protecting the environment'; the advocates want to mitigate global warming, and the opponents want to preserve the ecological integrity of the oceans. Climate change brings with it 'threats of serious or irreversible damage', as does tinkering with one of the world's largest ecosystems. Enormous uncertainty surrounds the issue. Which approach better prevents environment degradation?

Ocean fertilization provides a paradoxical lens with which to view the saying, "better safe than sorry". However, ocean fertilization is not the only way to curb climate change; there is only one ocean on which to experiment.

One of the proponents of ocean fertilization who is forging ahead in the face of scientific uncertainty is on a mission to save the seven seas. Russ George is the CEO of the Planktos Foundation, a company devoted to reducing atmospheric carbon dioxide – for a price. With a seductive website the Planktos Foundation sets out its mission to "foster active research and stewardship of the ocean and work to relieve and mitigate the impacts brought on by our changing environment." After detailing the science behind global warming and ocean fertilization, Planktos advertises Blue Green Tags that for four dollars each, the purchaser can offset their personal carbon contribution to the atmosphere. Planktos asserts that the average US household produces about 15 tons of carbon dioxide each year. By buying Blue Green Tags, one person can make a difference by supporting Planktos' research in creating "forests at sea."

A close inspection of Planktos' web site reveals that there are no scientists, let alone marine biologists or oceanographers, associated with the Foundation. The Board of Friends and Advisors is made up of a metallurgical engineer, an engineering student, an environmental philanthropist, a writer, a technical architect, a business consultant, business entrepreneurs – one man is the first successful vendor of scheduling and employee management software to large organizations – and Russ George, a professional businessman. His research vessel is a 100-year-old wooden Baltic schooner that belongs to the Canadian rock legend, Neil Young.

The only journalist who has ever met Russ George and seen the Planktos Foundation research facilities in California is Wendy Williams. Working on a story for *Living on Earth*, Williams met with George, but "I didn't get to meet any scientists. I didn't see any evidence of on-going research, and I didn't receive any professional publications." Yet, without scientific credentials, George and his Planktos Foundation get a lot of press. He was recently the subject of a two-page feature in *Nature*, he's been interviewed by BBC, he's been quoted in newspapers all over the world; he's being taken seriously. Perhaps George is just a fantastic public relations person. But with a large amount of capital funneled into his foundation, George might be one of the first proponents of ocean fertilization to be commercially viable.

When he was contacted for an interview for this article, George responded with a curt email reply, "I am sorry but we won't have any time available in the next few months nor are we seeking any publicity at the moment."

Mike Markels Jr., another ocean fertilization entrepreneur, takes pains to distance himself from Russ George. Markels is the founder and CEO of GreenSea Ventures and Ocean Farming Inc. and entrenches himself – and his ideas – in science. He has patented various iron pellets with which to fertilize the ocean, is partnered with Richard Barber of Duke University, one of the preeminent oceanographers in the United States, and is friends with many of the top marine scientists in the United States. A very successful chemical engineer and inventor, Markels designed noncombustible atmospheres for proposed space stations in the 1960s. Formerly the CEO of Versar Inc., a national environmental engineering and consulting company, the 75-year-old Markels has turned his attention to even bigger things.

Markels begins every conversation with the phrase, "Well, I'm an engineer…" And as such, he solves problems – any problems. The mission of GreenSea Ventures is "to develop iron fertilization of marine phytoplankton as a means of managing atmospheric carbon dioxide. GreenSea believes that iron fertilization of marine phytoplankton is a needed and promising means of managing atmospheric carbon." Ocean Farming Inc. proposes to fertilize the oceans for both carbon sequestration and fish production.

As someone who believes that the world is in great danger of collapsing under the pressures of a ballooning population – he predicts 20 billion by the end of this century – and the lack of resources, Markels believes that his venture to fertilize the ocean will indeed save the world. "The world is coming to an end because we are using up the world's ability to service us," said Markels. "We've gone from a few million to 6 billion going on to 7 billion people and we're going to have this great die off in the next few centuries. I've thought about that and asked [myself], 'what can we do to make the world more productive.' "

Markels suggests that because 70% of available sunlight falls on the ocean and is therefore unusable for mankind to produce food, there should be an engineering solution to make use of this unproductive portion of the globe. "Since we started agriculture on the land, we've increased the output of the land by about 2,000 times," said Markels. "But in the ocean, we are still hunters and gatherers, and couldn't we do something to increase the output of the ocean." According to Markels, only about two per cent of the ocean's surface is productive and he wants to make "some more of that roughly 98% of the ocean out there that's such a barren non-productive area" like the other productive two per cent.

Markels proposes to do this by ocean fertilization. He's patented an iron pellet "that would have a lifetime of several months in the ocean." He's partnered with Richard Barber of Duke University. He writes scientific papers that are published in *The Journal of Chemical Engineering* and a poster presentation for the NETL Conference on Carbon Sequestration. He funds some of the nation's best oceanic modelers to better understand the role of iron in the ocean. He has conducted two open ocean experiments. Markels should be being taken seriously.

Markels believes that the idea of iron fertilization to sequester carbon from the atmosphere into the oceans has merit. Although he agrees that there isn't enough scientific knowledge to predict how long the carbon is stored in the ocean, he doesn't believe that there will be unintended consequences to the ocean ecosystem. "We will fertilize the ocean, and when we're done, we will stop and the ocean will go back to the way it was."

This is the way of engineering, and Markels knows this. "I'm a chemical engineer, not an oceanographer. My take on the oceanography community is that oceanography over the history has been an observational science. That is, they go out to the ocean and they look and they observe and then they come back and write about it," said Markels. "When I come along and say, 'I'm and engineer and I want to change the ocean to make it more productive for the ocean, but also for mankind,' [many] oceanographers think that's something you should never do, changing the ocean."

To Markels, conservation is an ideal. "I think that to oceanographers, conservation means 'not changing.' If you're changing [the ecosystem] you're not conserving it – it will be different than it was before. And for them, that's the end of the story." Markels thinks that the ocean has enormous potential to help mankind - to mitigate global warming and increase fish production to feed the hungry. When challenged about his beliefs, Markels turns the question around and reframes the query, "Take a look at what's happened since the time we were hunter gatherers until the present: have we preserved biodiversity, the land, and what have you? No! We haven't! And thank God!" To Markels, the oceans are an untapped resource for humanity, and one that we will need to access to save the future of our species.

But Markels doesn't often talk about money, although it is central to his proposals. Carbon trading – selling units of sequestered carbon dioxide among countries and companies – will likely be an enormous industry if nations can agree on an international global warming treaty. As one of the flexibilities permitted under the Kyoto Protocol, carbon trading allows countries to meet their specific emission reduction targets. A country with high carbon dioxide emissions, such as the United States, would be able to buy carbon certificates – essentially "space" for more carbon – from another country with low emissions. If an accord is reached, nations will have carbon credits and debits to trade on the global market.

Markels is looking ahead to the future when a carbon sink, like the deep ocean, will be hugely profitable. He knows that there is money to be made. But Herzog thinks that iron fertilization is at the bottom of the list of carbon sequestration options that governments are considering. "With the people I deal with in the U.S. government, iron fertilization is really off the radar screen – I mean they don't even think about it," said Herzog. For climatologists who work with national governments and international forums, such as Herzog, the uncertainty surrounding iron fertilization takes it off the shelf as a means of carbon sequestration. "You can make the case that iron fertilization will never succeed politically because you can never answer these questions [about uncertainty]," said Herzog.

However, Herzog also says that governments do strange things when confronted with complex environmental problems. And in the end, sometimes money talks. "It's not unprecedented that proponents won't go ahead with something even if the scientific basis of it is not there," said Herzog. Coale agrees that money drives the ocean fertilization debate. "The economics behind this [carbon sequestration] are huge. It's a two trillion dollar industry!" As ocean fertilization is one of the cheapest carbon mitigation strategies, it might be the first to be implemented.

But Markels is certainly not the only person to suggest that iron fertilization is the only way out of an increasingly warming climate. The American Society of Limnology and Oceanography suggested that, "On the basis of available scientific information, we cannot dismiss ocean fertilization with iron as a carbon mitigation option." And even the Executive Secretary of UNESCO's Intergovernmental Oceanographic Commission, Patricio Bernal, stated in a 2003 interview that "the best argument against ocean carbon storage would be to prove that it is environmentally unsound. However, we must not be naïve. Carbon trading is a profitable business. The only thing holding back many potential traders from storing carbon in the ocean tomorrow is the cost of the technology."

As the world's last frontier, do we want to use the open oceans in the same manner that we used the coastal waters and the continents? Perhaps, as many oceanographers contend, the open ocean should be used as an arena to learn about the blue planet, a place to preserve, a global commons that can be passed down to generations of plants, animals, and humans.

Yet, an ever warming climate complicates scientists' ideals. A scientist who obviously cares deeply about the health of the oceans, Coale believes that doing nothing to solve the problem of global warming is almost a sin – even if it means that ocean carbon sequestration may be a possible choice for future generations. "Atmospheric carbon dioxide marches slowly on. By 2050, we will have doubled atmospheric CO2 and to suggest that the ocean are sacred and we don't want to mess with them…we've messed with them!" said Coale. Elevated carbon dioxide levels will likely decrease the pH of the surface water in the oceans. "We're about to monkey with half the animal biomass on this planet if we let the pH of the surface waters dip by 0.3 units," said Coale. Although not solving the root of the global warming problem – reducing carbon dioxide emissions – carbon sequestration is a likely scenario in the future that Coale imagines for the world.

After the results of ocean experiments, such as SOFeX, are published, the debate surrounding ocean fertilization heightens. At the American Association for the Advancement of Science Annual Meeting in February of 2004, five oceanographers, including Coale and Chisholm, convened to discuss the current science of ocean fertilization in a symposium entitled *Taking the Heat: What is the Impact of Ocean Fertilization on Climate and Ocean Engineering*. The results of the SOFeX expedition took center stage. Although some of the participants often had disparate arguments, they all agreed on at least one aspect of the issue: there needs to be an international dialogue about ocean fertilization.

At the close of the symposium, a tall thin man with a buoyant voice jumped up and made a passionate plea. John Ogden, the Director of the Florida Institute of Oceanography, pointedly remarked that, "Wide-spread ocean fertilization is unjustified as a means of controlling carbon emissions because we are not doing anything about the source of the problem."

Ogden believes that American capitalism often shrouds environmentally complex issues like ocean fertilization and that a certain amount of restraint, judgment and a precautionary approach should be taken in these matters. Ogden also thinks that an open dialogue between scientists, industry and advocate groups, environmentalists and policy makers are integral to finding answers to complicated environmental problems, especially at the national and international level.

A major symposium on *The Ocean in a High CO_2 World* is scheduled to take place in Paris, France in May of 2004. Sponsored by the Intergovernmental Oceanographic Commission of UNESCO and the Scientific Committee on Oceanic Research, organizers hope to "pool present scientific knowledge in order to determine whether – and at what levels – increasing carbon dioxide will affect the oceans" A co-author of a paper on iron fertilization submitted to the symposium, Coale hopes that "there will be an international discussion about ocean fertilization. I think we're going to have these experiments for some time. But we do need to advance an inform the debate on carbon cycle science so that people understand really what's involved and what's at stake."

UNESCO's Patricio Bernal takes a pragmatic view of on the growing debate over global warming. He believes that "over the centuries we have engineered an artificial world for ourselves, to a point where more than 60% of the natural landscape is of our own making. The temptation has always been to engineer a new world rather than to respect the boundaries of the existing one."

But, isn't this a compartmentalized view of the planet? How can one view the Earth as a series of interdependent systems – as we know that it is – and still believe that adjusting one planetary process won't affect the other systems in a possibly negative and unsalvageable way? In *Silent Spring*, Rachel Carson states that, "This is an era of specialists, each of whom sees his own problem and is unaware of or intolerant of the larger frame into which it fits. It is also an era dominated by industry, in which the right to make a dollar at whatever cost is seldom challenged. The public must decide whether it wishes to continue on the present road, and it can only do so when in full possession of the facts." How much has this statement changed in the last 50 years? The oceans are a part of the global commons, and as such, the use of them to mitigate the effects of the other global commons – the atmosphere – should be in the hands of the people.

But global warming is an intensely complex issue, with political, economic and environmental facets to boot. No one has the right answer – or any answer – to this enormous puzzle. Howard Herzog says that there is no silver bullet solution to solving the climate change problem. "Climate change is such a massive problem, even thinking about using carbon sequestration, it's hard for me to see how we are going to get out of this hole," said Herzog. "Climate change is the biggest problem we are facing in the 21st century."

Iron fertilization may end up being a last-ditch effort to save the planet. Or, it may disappear from the public eye long before the planet warms to a desperate degree. Markels will continue to persevere in his endeavor, convinced that he is saving mankind from a disastrous end. All Penny Chisholm would ask us to remember is that once we begin fertilizing the ocean we can never go back, "It works because it changes the ecosystem. It's intentional planetary manipulation on a global scale."

Biographical Note

Megan Ogilvie grew up on a family farm in southern Ontario. Her childhood was shaped by riding horses with her sisters, reading old books, and taking long walks with her grandfather in the back woods of the farm. She attended Sweet Briar College, a small woman's liberal arts college nestled in the Blue Ridge Mountains of Virginia, and graduated *Phi Beta Kappa* in 2002 with a Bachelor of Science in Environmental Science. After working as an ecologist for one year at a prominent environmental consulting firm in Toronto, ON, Megan decided that what she really wanted to be was a Writer. She will graduate with a Masters in Science Writing from the Massachusetts Institute of Technology in the fall of 2004.

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