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SEQUESTRATION OF CO₂ BY OCEAN FERTILIZATION

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ABSTRACT

Sequestration of carbon dioxide (CO₂) to the deep ocean by the fertilization of high nutrient, low chlorophyll (HNLC) ocean waters can be an answer to the concerns arising from the increasing CO₂ content of the atmosphere. This approach has the potential to sequester CO₂ for 1000 to 2000 years for a cost of about \$2.00/ton of CO₂. A technology demonstration is planned to fertilize an area of 5,000 square miles of the equatorial Pacific that is expected to sequester between 600,000 and 2,000,000 tons of CO₂ in a period of 20 days. The ecological changes expected consist of the increase in diatoms, which double or triple each day until the limiting fertilizing element is used up. No adverse changes are expected, since this is exactly what happens naturally when episodic fertilization occurs in the open ocean. The concept is that fertilization of HNLC waters with chelated iron will cause a bloom of phytoplankton that sink below the thermocline into deep water after they die due to their high density. The experiment, while large by land comparisons, is small in terms of ocean area, about one square degree. The demonstration protocol will include measurements of the amount of inorganic CO₂ that is removed from the surface layer and the amount of organic carbon that is produced and exported downward as well as other effects in the water column over a period of 20 days. After this time no further effects of iron fertilization take place because macronutrient elements (N, P and Si) are depleted to limiting concentrations. Since the iron enrichment is transient, no steady-state modification of the food web will occur. The experiment will be carried out outside the EEZ of any nation, as were the previous five voyages, so, like them, no permits will be required. The five recent ocean experiments observed iron stimulation of phytoplankton growth, but the effects were difficult to quantify in the 9 to 28 square mile experiments since eddy diffusion along the edges of the patch diluted the bloom.

INTRODUCTION

The CO₂ content of the atmosphere has increased from about 280 ppm to about 365 ppm during the last 60 years¹. During the 1980's the rate of increase of CO₂ in the atmosphere, in terms of carbon metric tons, was about 3.3 gigatons of carbon per year (GtC/yr). Fossil fuel emissions were about 5.5 GtC/yr (20 Gt CO₂/yr*) and terrestrial emissions were about 1.1 GtC/yr during that period, so about 3.3 GtC/yr, 60% of fossil fuel emissions, were sequestered naturally. Of this, about 2.0 GtC/yr was absorbed by the oceans and 1.3 GtC/yr by the land.² The remaining 40%, 2.2 GtC (8.1 GtCO₂)/yr, contributed to the increasing atmospheric CO₂ concentration. This increase in the CO₂ content of the atmosphere has led to concerns that this increase will result in global climate change, which, over time, can have adverse effects on weather, sea level and human survival. This concern has led to the 1992 Rio Treaty, the IPCC Working Group³ and the Kyoto Protocol of 1997, which call for a reduction of emissions of 34% by 2050 and a reduction of 70% from the then-expected emissions from the industrial nations by 2100⁴. These reductions, if put into effect, would have serious adverse effects on the economy of the United States, causing loss of jobs, decrease in our standard of living and a reduction in the life span of our citizens. These required reductions would not address the concerns that demand an approach to permit the reversal of atmospheric CO₂ increase, should this become necessary.

* 1GtC = 3.67 Gt CO₂

THE PROBLEM

What is the basis for peoples' concerns? Part is the fear of the new and unknown. Any change that is not purposeful may be viewed with apprehension. "It is probably bad unless I can control it." The other part is the unknown aspects of the science. While the results of increased CO₂ in the atmosphere have generally been benign so far there is genuine concern that some point the atmosphere may become unstable and the oceans may freeze, the atmosphere may lose its water to outer space or the earth may become so hot that the atmosphere may become mostly water vapor. Here too, the key is to have available a technology that can be applied to the problem if required, to reverse the increased CO₂ content of the atmosphere at a cost that people are prepared to bear.

CURRENT APPROACH

The current approach to the problem of atmospheric CO₂ increase is to take specific actions now to reduce the risk of adverse consequences in the future. These actions are to increase the efficiency of energy production and use and to change our standard of living to reduce our dependence on energy in our lives. Energy efficiency can often be increased, but we have been doing this for over 200 years, so there is not a lot of gain remaining before we run into thermodynamic barriers. Even at 100% efficiency we still add CO₂ to the atmosphere, so this can never address peoples' concerns. We can also address the other side of the problem, which is to increase the rate at which CO₂ is removed from the atmosphere. If we could increase this enough we could bring the net increase in CO₂ emissions to zero, providing a solution to the problem of peoples' concerns. The availability of this solution will permit us to avoid precipitous actions and await the proven requirement to take steps to lower the atmospheric CO₂ level as may be prudent.

CO₂ is removed from the atmosphere by plants using the Sun's energy to convert it to biomass. This biomass may be used as food by bacteria, fungi and animals that obtain energy by reacting it with oxygen from the air and respiring CO₂ back to the atmosphere. Over time, a portion of the biomass formed has been sequestered in the earth and in the ocean bottom, forming fossil fuels that we burn to obtain energy to support our standard of living. Numerous projects have been undertaken to increase tree growth in the tropics. These projects suffer from a short lifetime, generally 20 to 50 years, and the difficulty of assuring that forest fires, poaching, etc., will not result in an early recycling of the carbon to the atmosphere. Other CO₂ sequestering technologies have been proposed, including injection of liquid CO₂ into geological formations or into the deep ocean.

The injection of CO₂ into coal seams and natural gas producing formations to increase methane production has been well proven and is commercially viable where relatively pure CO₂ is available. This is the case where natural gas wells produce a mix of CO₂ and methane, which is separated leaving a CO₂-rich stream at no additional cost. These CO₂-rich streams can also be disposed of in deep saline aquifers such as is being done in the North Sea. The capacity of these alternatives is low since not much pure CO₂ is available near disposal sites. A larger capacity alternative is to separate the CO₂ from flue gas at electric power plants, liquefy and transport it to a location where it can be transferred to a ship for transport to the deep ocean. There, the ship will lower a two-mile long injection pipe and pump the liquid CO₂ to the ocean floor. Each of these steps is expensive and energy intensive, with the result that the approach is expected to cost in the range of \$300 per ton of carbon or \$80 per ton of CO₂ sequestered.

There are environmental concerns since we would be adding a new chemical to the ocean floor, liquid CO₂, which may produce hydrates and other chemicals over time. Liquid fuels used for transportation are also difficult to burn so as to capture the CO₂ produced. While increased efficiency is usually advantageous it still results in CO₂ release to the atmosphere. This, again, indicates that sequestration of the CO₂ is likely to be the best approach.

OCEAN FERTILIZATION

The best approach is to sequester CO₂ in the deep ocean by causing a bloom of plant life that then sinks to the deep waters where it remains for about 1600 years⁵, as measured by the ¹⁴C to ¹²C ratio of upwelling of deep ocean water off of Peru. This process is possible because large areas of the oceans have excess, unused plant nutrients and much less than expected phytoplankton biomass, the so-called HNLC waters. The difference is that the HNLC waters are deficient in one or more of the micronutrients required for plants to grow. While several essential metals may be involved in the limitation of growth in HNLC areas, iron has been shown to be the major micronutrient. Generally, 100,000 moles of carbon biomass require 16,000 moles of fixed nitrogen, 1,000 moles of soluble phosphorous and one mole of available iron. The main difficulty is the iron. Since surface ocean waters are highly oxygenated, any soluble iron is converted to Fe⁺⁺⁺ with a half-life of about one hour and precipitates as Fe(OH)₃. A shovel full of earth is about 5.6% iron on the average. The ocean, on the other hand, has 0.0000000001 or less moles per liter of iron, too little to sustain plant growth. The first problem, then, is how to add iron to the ocean so that it will be available to the phytoplankton (plants). The phytoplankton themselves exude organic chelating compounds into the ocean that protect some of the iron that is there from precipitation. Adding iron in the form of a chelate so that it does not precipitate but remains available for plant fertilization can mimic this natural process.⁶ An essential element that may be in short supply in nutrient-depleted, tropical ocean waters is phosphorous. Most phosphates are soluble and can be added directly to the ocean. Since the phosphate may attack the iron chelate, it may be necessary to keep the concentrations of both fertilizers low. This can be done by adding them to the ocean separately in the form of small floating pellets that release the fertilizing element slowly over a period of days.⁷ This process has been tested by GreenSea Venture, Inc. (GSV) in the Gulf of Mexico with good results. The remaining required essential element is fixed nitrogen. Bluegreen algae or, as they are more properly called, cyanobacteria, have the ability to fix nitrogen, so inducing a bloom of nitrogen fixers might supply this requirement.

When the fertilizer mixed with water is added to the tropical ocean surface it mixes rapidly in the warm waters (the mixed layer) and starts the phytoplankton bloom. The plants, mostly diatoms, multiply rapidly, increasing their numbers by two to three times per day, until they run out of one of the required nutrients. They then cease growing, lose the ability to maintain buoyancy and sink through the thermocline at a rate of about 75 feet a day. The sinking biomass is trapped in the cold, dense waters where it is eaten by animal life and bacteria. This slowly converts the biomass back to CO₂ in the deep waters. Where high concentrations of biomass are generated and reach the ocean floor they may be covered by mud and debris, leading to anoxic digestion. The methane produced is converted to methane hydrates by the high pressure of the deep ocean. It has been estimated that there is twice as much carbon in the methane hydrates of the deep ocean floor than all the terrestrial fossil fuels combined. It is worth noting that the addition of CO₂ in this low concentration, natural process is not expected to have any adverse environmental impact on the ocean, which now has about 85 times as much dissolved inorganic carbon as the atmosphere.

Since our objective is to sequester CO₂ to the deep ocean it is important that we minimize the proportion of the biomass produced that is processed by animal life and bacteria in the mixing layer above the thermocline. This can be done by fertilizing in pulses, so that the slower-growing animal life cannot multiply effectively before the diatoms have bloomed, died and gone below the thermocline, a period of less than 20 days.⁸ The fraction of the biomass produced that is sequestered below the thermocline has been measured. It depends principally on the amount of animal life available to eat the biomass and convert it back into CO₂ in the highly oxygenated surface waters. Where the ecosystem is in balance with large amounts of animal life the sequestered carbon is about 10% of primary production and consists mainly of animal parts, scales, bones and fecal pellets. Where animal life is absent the ratio may go as high as 80% sequestered. Measurements made in the tropical Pacific Ocean off of Peru produced a ratio of 53% sequestered beneath the thermocline⁹. We have used this measurement in our calculations. We must also test the waters we intend to fertilize in order to add the correct amount and mix to produce the optimum result. To achieve this we select the waters for fertilization to include a strong, shallow thermocline, tropical sunshine and high nutrient, low chlorophyll (HNLC) conditions. These waters can be found in the tropical Pacific near the equator west of the Galapagos Islands. The cool wind-driven currents go directly to the west before reaching the Line Islands of Polynesia. The 3,000,000 square miles of these HNLC waters can sequester about 0.4 GtCO₂/yr. Recent studies have shown that, because of the rapidly growing forests and verdant agriculture, North America has an uptake of 1.7 GtCO₂/yr and an emission of 1.6 GtCO₂/yr¹⁰. While this rough balance is variable, depending on weather-stimulated growth it illustrates that sequestering capability such as that of the Pacific Equatorial Current can be significant in affecting the c content of the atmosphere.

TECHNOLOGY EXPERIMENTS TO DATE

The technology of ocean fertilization as a means of CO₂ sequestration is still in its infancy. Accurate estimates of the results of ocean fertilization cannot be obtained from bottle experiments. The iron tends to stick to the walls, increasing the response by as much as 100 times. Therefore, ocean voyages were started in 1993 to determine the response. The first voyage in the equatorial Pacific, IronEx I, spread 880 lbs. of Fe as FeSO₄ on a 25 square mile patch resulting in an increase in phytoplankton, but no measurable decrease in the CO₂ content of the water. This was due to the sinking of the patch under an intrusion of barren warmer water. A second voyage in the same area of the equatorial Pacific, IronEx II, spread 990 lbs. of Fe as FeSO₄ on 28 square miles of the ocean surface.¹¹ In order to mitigate the effect of iron precipitation, the iron was added in three infusions, half on day zero, one-fourth on day three and one-fourth on day seven. This resulted in a bloom of diatoms. The chlorophyll increased by a factor of 27 times, while the CO₂ partial pressure was reduced by 90 μatm in the patch.

Ocean Farming, Inc. (OFI), now renamed GreenSea Venture, Inc., has undertaken two voyages in the nutrient-depleted tropical waters of the Gulf of Mexico. Voyage 1 was carried out in the Gulf of Mexico in early January 1998. Three, 9 square mile, patches were fertilized: one with iron, only; one with iron and 6.35 times the molar ratio of phosphorous to iron; and one with iron and 63.5 times the molar ratio of phosphorous to iron. The iron was in the form of a chelate to protect it from precipitation and the phosphorous was in the form of phosphoric acid. The ocean and weather conditions, including a very deep thermocline and high winds, caused the fertilizer to mix much more rapidly, both vertically and horizontally, than planned. The result was a bloom of large diatoms to 4.3 times their initial concentration in a little over one day. After that, the mixing diluted the signal to about 1.5 times the initial chlorophyll concentration. These

results, while giving a positive indication of a large bloom were not definitive and did not provide a verifiable measure of phytoplankton increase over the period of the expected bloom of about two weeks.

Voyage 2 was carried out in the Gulf of Mexico in early May 1998. One 9 square mile patch was fertilized using the enhanced chelated iron-containing pellets. The ocean conditions were much more benign (no one got seasick) and we were able to follow the patch for six days. The floating pellets acted as expected, discharging the chelated iron over a period of four days. The result was a bloom of large diatoms that averaged five times background and reached seven times background. Further increase in phytoplankton was restricted by the absence of the next required fertilizing element, probably phosphorous, nitrate or both. However, extrapolating over the increased size to the patch gave an estimated 600 tons of diatoms per ton of fertilizer pellets, or 1,800 tons of diatoms per ton of chelated iron added to the waters. Both voyages in the Gulf of Mexico were in low nutrient, low chlorophyll (LNLC) waters, which are not favorable to the production of large blooms.

A fifth voyage, SOIREE, has been conducted in the Southern Ocean¹² south of New Zealand. Iron sulfate was added to the 20 mi² patch on days 1,3,5 and 7 to keep the concentration of dissolved iron at about 1.0 μ molar versus a background of 0.08 μ molar. The chlorophyll concentration went up by a factor of six and biomass by a factor of three with a preponderance of diatoms in the bloom. The increase in biomass was slower in these frigid waters than at the equator and the bloom concentration was less. However, the bloom lasted for about one month, as measured by satellite imagery.

These experiments have added greatly to our knowledge of the biodynamics and chemistry of the ocean. Other recent measurements have further increased our understanding. These have included the tethered buoy systems (TAO buoys) as well as the SeaWiFS satellite, instrumented buoys and drifter systems. These systems have, for the first time, provided continuous measurements of the ocean surface as well as at depth, instead of isolated measurements from intermittent ship cruises. This great increase in data has provided enough understanding that we can now design a technology demonstration aimed at proving the CO₂ sequestration potential of ocean fertilization.

PLANNED TECHNOLOGY DEMONSTRATION

All of these previous experimental voyages, while providing a compelling case for iron fertilization in HNLC waters, did not provide a solid basis for evaluating the potential for carbon sequestration. The fertilized patches were so small that they were all edge; that is, the diffusion in the ocean surface waters is so great that the result of the fertilization, especially the amount of the biomass that sinks below the thermocline, could not be measured. Therefore, we have designed a technology demonstration using the long-lived chelated iron fertilizer in the HNLC waters of the equatorial Pacific Ocean. The fertilized patch will be 5,000 square miles in area and designed to sequester between 600,000 and 2,000,000 tons of CO₂. The patch will be laid by a chemical tanker that will traverse a spiral path¹³ starting at a floating buoy that is maintained as the center of the pattern at all times. When the 5,000 square mile (80 miles in diameter) patch has been completed, in approximately four to five days, the commercial ship will return to port. It will leave a patch with an iron concentration of 2 to 4 η M Fe in the ocean, an increase of about 20 to 40 times background. Based on patch dissipation rates determined from the IronEx studies in the same general Pacific location, the reduction in concentration from diffusion for the center of the patch is expected to be about 2% during the 20 days of the test. A scientific team on a

research vessel using the most advanced technology, including direct measurement of the sinking biomass under the patch will measure the response to the fertilization. The research vessel will continuously transact the patch, taking samples to compare with the background measurements made before the patch is laid and, later, outside of the patch. The academic team will measure all relevant environmental impacts until the impacts vanish, which is expected to take about 20 days. The ocean area of the test site is shown in Figure 1.

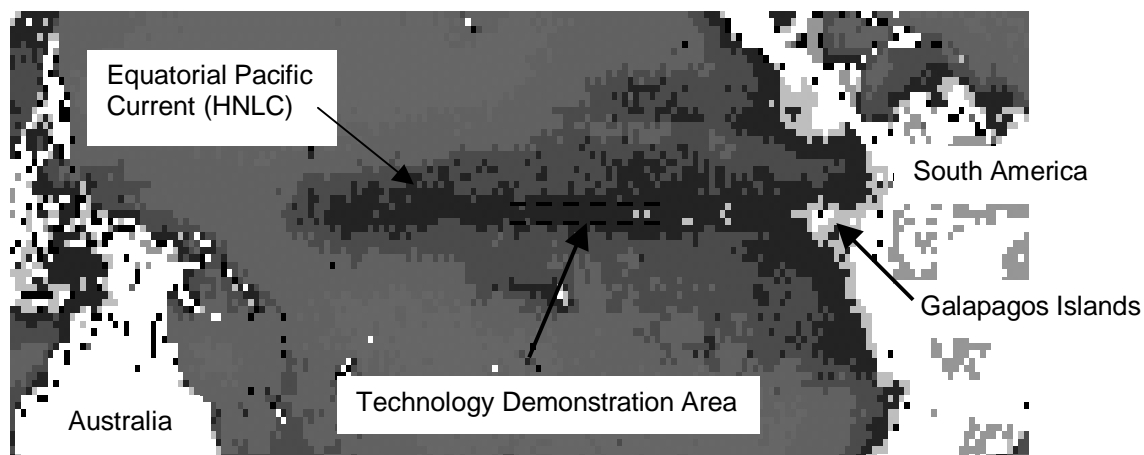


Figure 1. Location of Planned Technology Demonstration

This area is over 2,000 miles from any reef system and in waters 10,000 to 15,000 feet deep that have high oxygen content. Therefore, anoxia that can occur in shallow waters will not be a problem. Red tide and noxious algae typically occur only in shallow waters so should not be a concern. We will not be adding any new organisms to the ocean, only increasing the numbers of those already there. This controlled experiment will parallel the upwellings that occur off of the coast of Peru in all but the El Niño conditions, so we expect the environmental impacts to be benign.

POSSIBLE COMMERCIALIZATION

Should the increasing CO₂ content of the atmosphere be determined to have adverse impacts much worse than their advantages, the further demonstration of this technology can provide a solution, relieving the concerns regarding the continuous increase of these adverse net impacts. CO₂ sequestering could then be carried out in the equatorial Pacific and in other HNLC waters, especially off of Antarctica, the main areas of the oceans that have a high capacity of sequestering CO₂. For instance, if all the CO₂ in the atmosphere were sequestered in the ocean, it would raise the average concentration of CO₂ in the ocean by only about 1.2%. The ocean chemistry would not be altered significantly and the increase in outgassing of the CO₂ from the ocean surface would be minimal.

The cost of sequestering CO₂ on a commercial scale is expected to be about \$1.00 per ton of CO₂. The sales price for CO₂ sequestering credits, should they become tradable, would be about \$2.00 per ton of CO₂, to include the cost of verification, overhead and profit. It is expected that these credits would be highly valued since they would not suffer from the problems of fire hazard, leakage and additionality the forest projects for CO₂ sequestering face. Such credits could be produced within a few years of a successful technology demonstration. Alternately,

technology development could be continued with the objective of eventual large-scale CO₂ sequestration to address major climate perturbations.

EXPECTED IMPACTS

The expected impacts of a successful demonstration of the technology and the measurement of significant sequestration response by the ocean to the planned chelated iron addition could be significant. The costly early actions now being contemplated to counteract possible future impacts of increased CO₂ content of the atmosphere would no longer be needed and instead all responses could be tied to measured consequences, which could then be reversed. This would open new options, avoid the unnecessary use of scarce resources and refocus attention on actual problems rather than seeking to deal with possible future scenarios. Many entities, both governmental and industrial may decide to do very useful things based on these concerns, such as improved energy efficiency and the exploration of new energy resources. This is to the good of society where they make economic sense and should be implemented in any case.

A CO₂ credit system may be instituted that will allow trading of credits to generate the lowest cost. Credits from sequestering CO₂ in the oceans should be a part of this effort so as to take early advantage of this lower cost, environmentally benign, low human impact and robust capacity approach to solving the global warming concerns, should this become necessary.

CONCLUSION

Many approaches for dealing with the increase in the CO₂ content of the atmosphere have been proposed, but sequestration by ocean fertilization has received little attention. It is new, far away and poorly understood by many. The initial reaction is that not enough is known to warrant attention at this time. While this reaction may have had merit in the past, the last few years have seen a great increase in knowledge about the oceans, especially the equatorial Pacific, where moored and floating buoy systems, research vessel voyages and continuous satellite monitoring have all greatly increased our knowledge and understanding. The last remaining piece of the puzzle is to quantify the response of this HNLC ocean water to iron fertilization, which can be done by the large experiment described here. We now know enough to design and carry out this technology demonstration experiment, which can lead to solving the problem of peoples' concerns rather than just working on it, thereby saving time and costs while greatly reducing the risk of adverse consequences.

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