

*Is Ocean Fertilization a
Good Carbon
Sequestration Option?*

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IS OCEAN FERTILIZATION A GOOD CARBON SEQUESTRATION OPTION?

A critical review of ocean fertilization methods proposed for addressing the problem of anthropogenic CO₂ emissions in the atmosphere.

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EXECUTIVE SUMMARY

The Policy Issue

The proliferation of fossil fuel-based technologies in the face of a discernible impact of anthropogenic “greenhouse gas” (GHG) emissions on global climate presents an urgent challenge to develop other mechanisms for mitigation of the “greenhouse effect”. Much attention has focussed upon ways to curtail the growing stock of atmospheric carbon dioxide (CO₂), a major greenhouse gas, by enhancing the natural “sinks” or processes that remove CO₂ from the atmosphere. Among the various approaches proposed, a set of controversial – and increasingly prominent – ideas involve efforts to “short circuit” or “enhance” the natural transfer of atmospheric carbon dioxide into the deep ocean. One such approach involves the addition of otherwise scarce (“limiting”) nutrients to surface ocean waters to manipulate marine biological production, thus potentially changing the flux of carbon dioxide between the atmosphere and ocean.

It has been hypothesized that releasing limiting nutrients into the euphotic (i.e., sunlit) surface layer of the ocean on a large-scale could stimulate the growth of marine phytoplankton, thus increasing the biologically-mediated uptake of atmospheric CO₂ by the ocean and mitigating the greenhouse effect. Results from four open ocean experiments have shown that dissolved iron limits primary production in certain nutrient rich regions of the ocean. Results of these scientific experiments, which were designed without specific applications in mind, have catalyzed a variety of commercial interests in manipulating the biological carbon pump by varying the availability of nutrients. While continuing scientific research effort addresses the many ecological uncertainties associated with nutrient manipulation in the marine environment, entrepreneurs have been busy marketing different methods for large-scale ocean fertilization (hereafter simply “fertilization”) to remove carbon dioxide from the atmosphere. Seven US patents for fertilization methods have been issued during the past seven years and an application for an eighth was filed in January 2001. Meanwhile, corporations and governments have shown a growing interest in “early action” in order to hedge their bets with respect to the adoption of some kind of GHG trading system in the future. Patented fertilization methods are actively being marketed to such corporations and governments, and coastal nations have also been propositioned to serve as “hosts” for the generation of potentially valuable carbon credits by ocean fertilization in the prospective hosts’ territorial waters. Despite these remarkable developments, *the necessary dialogue on scientific evaluation criteria for large-scale ocean fertilization is seriously lacking*. As a result, most corporations, governments and other stakeholders are ill equipped to properly assess the risks, benefits and true costs associated with proposals for fertilization.

Recommendations

Large-scale field experiments to test specifically for carbon sequestration by fertilization are not warranted at present. We feel that concerns regarding the technical efficacy and ecological impacts of fertilization should be resolved first by a more thorough synthesis of disciplinary knowledge in the aquatic sciences, including input from ecologists and limnologists. Then, if the

arguments are still not compelling enough to support sound policy making *limited, scientific* testing of carbon sequestration methods may be justified.

Policy makers should recognize that carbon sequestration in the ocean is nothing more than a partial, stopgap measure to combat the accumulation of atmospheric CO₂. “Partial”, because the amounts of CO₂ captured by fertilization (or other approaches), if the approach were successful, would not substantially mitigate the potential for global climate change. “Stopgap”, because any CO₂ that is trapped in the deep ocean will eventually re-surface, though the timing will depend upon ocean circulation and the duration of the fertilization program. Even if the “quick-fixes” for atmospheric GHG reduction such as ocean fertilization emerge as technically and economically viable options, there is a need for renewed political commitments to promote the adoption of “cleaner” energy systems, many of which have been studied intensively for over a generation now. Carbon sequestration may buy human societies a little more time to make the desirable technological and cultural transition to a sustainable system of development, but sequestration is not a sustainable solution to the global warming problem.

State of the Science

At this time in the Earth’s history, with the supply of CO₂ from the land exceeding the oceans ability to assimilate it, the atmosphere acts as a “bottleneck” in the exchange of carbon between the terrestrial and oceanic reservoirs. The ocean carbon cycle is controlled by two global mechanisms, called the “solubility pump” and the “biological pump. The “biological pump” is driven by photosynthetic productivity of phytoplankton floating in the sunlit surface layer of the ocean and is characterized as the production and transport of biogenic organic and inorganic carbon. The biological pump plays a very important role in the maintenance of a CO₂ gradient between the surface and deep waters. Hence, there is an interest in exploring methods to transport of CO₂ into the deep ocean – reliably, efficiently and expeditiously – by manipulating the mechanisms regulating the global carbon cycle.

Light and nutrients are the main factors regulating the growth of marine algae. Essential "macro-nutrients" such as nitrogen (N), phosphorus (P) and silicon (Si), along with "micro-nutrients" such as iron (Fe), are pumped up from the deep ocean by physical circulation. On average, phytoplankton are considered to use nutrients in the following ratio:

106 C: 16 N: 1 P: 0.001 – 0.005 Fe

In other words, under iron limitation, adding one atom of iron can catalyze the biological uptake of approximately 100,000 atoms of carbon– an uptake factor of 10⁵.

Three open ocean regions have been identified, where *high* dissolved concentrations of most nutrients occur year-round, and photosynthetic biomass is quite low. These “high-nutrient-low-chlorophyll” (HNLC) zones are found in:

1. the Eastern Equatorial Pacific,
2. the NE Subarctic Pacific and
3. the Southern Ocean

It is now widely accepted that phytoplankton growth is limited by the availability of iron in parts of the Equatorial Pacific and in the Southern Ocean, in effect limiting the biological assimilation of other nutrients such as nitrogen and phosphorus. *However, the limitation by iron does not preclude simultaneous limitation by other factors.* Other possible limiting/co-limiting factors for production and growth of phytoplankton: low light conditions, vertical mixing, temperature, silicate concentrations and zooplankton grazing.

Diatoms account for upwards of 75% of the primary production occurring in typically high productivity coastal and nutrient-replete waters around the world. When photosynthetic diatom blooms occur growth rates of these organisms are dependent upon the availability of dissolved silicon (Si), because silicates are used to form intricate exoskeletons for the diatoms.

Iron fertilization in the ocean typically stimulates the growth of diatoms. However, the proliferation of diatoms could also have serious negative consequences for the ecosystem as a whole, including the inhibition of zooplankton growth and the production of a powerful biotoxin.

“New production” is defined as the steady-state fraction of marine primary production that is available for export to the deep ocean. New production, and not total primary production, determines the maximum amount of carbon that may be exported from the surface ocean. Specifically, only “true” new production, which is fueled by nutrients (e.g. nitrogen gas from the atmosphere, or iron dust) derived from *outside* the ocean system generates a net export of carbon to the deep ocean.

Four scientific field experiments have been carried so far to test the “iron hypothesis”- IRONEX I (in 1993) and IRONEX II (in 1995) in the Equatorial Pacific Ocean, and SOIREE (in 1999) and EISENEX (in 2000) in the Southern Ocean. There are five key lessons from the field experiments in the HNLC ocean:

1. It is clear that iron limits primary production;
2. Phytoplankton biomass can be increased over the short term (weeks) by the addition of iron,
3. There is no evidence of increased carbon “export” following fertilization in the time frame of these experiments;
4. The composition of the phytoplankton community changes dramatically upon the addition of iron, with diatom biomass increasing preferentially;
5. Dimethyl Sulfide (which nucleates cloud formation) production is increased by iron fertilization

There is remarkable agreement among results of computer simulations by different research groups, all showing that iron-fertilization in HNLC ocean regions would not consistently “zero out” global CO₂ output under any realistic global CO₂ emissions scenario. The Southern Ocean is generally held as the most important sink for atmospheric carbon dioxide in the past glacial period and for the potential climate regulation in the future. The effect of iron fertilization in the Equatorial Pacific Ocean alone on the accumulation of CO₂ in the atmosphere would be practically irrelevant from the perspective of mitigating global warming.

Revised modeling estimates span a wide range - from 50 to 150 Gt C exported after 100 years of continuous iron fertilization in the Southern Ocean. However, since the Southern Ocean is a source for deep waters that re-emerge in the tropics, severe depletion of nutrients in the Southern Ocean could decrease equatorial primary production by at least 30% and by as much as 70%. The loss in tropical productivity may even outstrip the amount of atmospheric carbon that would be captured – a tradeoff that requires very careful assessment. According to the Redfield ratio, the capture of 100 Gt C/yr by macro-nutrient fertilization in the oligotrophic subtropical ocean gyres would require the supply of 15 Gt N/yr (not counting losses), plus other nutrients as they are consumed. The sheer logistics of undertaking macronutrient fertilization at that scale present enormous challenges given the size and remoteness of the target areas.

In all cases, any atmospheric carbon uptake due to fertilization would be rapidly returned to the atmosphere unless fertilization is sustained for extended periods of time. Furthermore, drawdown of dissolved CO₂ in surface waters by a phytoplankton bloom may be largely replaced by the equilibration of dissolved CO₂ between the fertilized area and adjoining water masses. *In other words, the impact on atmospheric CO₂ would be small even if fertilization results in substantial export of carbon.*

In general, the challenges facing us in evaluating commercial ocean fertilization for carbon sequestration fall under three main categories:

1. *Extrapolation of Results:* Commercial fertilization proposals must extrapolate results from short-term (days-weeks), small (about 100 km² or smaller) field experiments to long-term (centuries), large (greater than 100,000 km²) operations.
2. *Verification of Carbon Sequestration:* Measurement and prediction of the amount of carbon exported to ocean depths as a result of fertilization with any degree of certainty is at present impossible even in field experiments, let alone over vast expanses of ocean.
3. *Ecological Monitoring:* It is not yet possible to measure subtle but potentially damaging changes in ecosystem states in either a precise manner or in real time. Long-term manipulation of marine ecosystems may fundamentally and permanently alter the cycling of nutrients and functioning of food webs.

Conventional scientific wisdom suggests that large-scale commercial fertilization enterprises in the open ocean are neither ecologically acceptable, nor likely to be economically rewarding in the long run. If returns on investment in large-scale ocean fertilization appear attractive, it is often only due to the externalized costs borne by the greater environment. It is commonly observed that heavy subsidy of energy and materials may be required to sustain large, managed ecosystems such as those proposed by the proponents of ocean fertilization.

Commercial Proposals

Three methods (see Table A) are being promoted actively, aiming to either flip the chemical “switch” that would jump-start the inefficient biological machinery (e.g., in the HNLC regions), or boost existing high levels of primary production in efficient ecosystems (e.g., in coastal upwelling zones) further and sustain it at high levels by fueling it with a continuous supply of fertilizer.

Table A. Fertilization Methods Proposed by Commercial Interests

Organization	GreenSea Venture, Inc. (formerly Ocean Farming) www.greenseaventure.com	Ocean Technology Group (U. of Sydney, Australia) www.otg.usyd.edu.au	Ocean Carbon Science, Inc. (Formerly Carboncorp USA) www.rsrch.com/carboncorp
Principal	Michael Markels, Jr.	Ian S.F. Jones	Russ George/ Robert Falls
Fertilizer	Fe-chelate (lignic acid sulphate)	NH ₃ solution in seawater	Proprietary nutrient supplements, Fe + ?
Approach	<ul style="list-style-type: none"> - Fertilizer released along a "spiral fertilization" path - Small, floating nutrient pellets 	<ul style="list-style-type: none"> - Atmospheric nitrogen fixed as ammonia (NH₃) via industrial process (using fossil fuels) - Ammonia pumped from a land- or ocean-based (i.e., floating) facility for release into the surface ocean near the edge of the continental shelf - Ammonia discharged via multiple "diffuser points" 	<ul style="list-style-type: none"> - Retrofit commercial ocean liners for releasing mix into the propeller wash at an "appropriate" time(s) during a voyage - Algal response monitored by satellite imaging and shipboard instrumentation
Ocean Area(s) Targeted for Fertilization	Equatorial Pacific Ocean (for demonstration experiment)	<ul style="list-style-type: none"> - Chilean coastal upwelling zone - Coastal waters of "Low income food deficient" nations 	- "Plankton domains" along major shipping lanes
Claimed Efficacy	0.6-2 Mt CO ₂ sequestered over 5,000 sq. mi. of HNLC ocean in 20 days	1 Gt N/yr sequesters about 5 Gt C/yr	Not specified
Claimed Cost	\$7 to \$7.5 /tC (at "commercial scale")	Approx. \$30 /t C	Not available

Overview of International Treaties and Laws

In 1990, the Inter-Governmental Panel on Climate Change (IPCC) findings on global warming led to the adoption of the United Nations Framework Convention on Climate Change (UNFCCC). *The overall objective of the UNFCCC was to promote the stabilization of greenhouse gases (GHGs) by ecologically sound means.* Since carbon dioxide (CO₂) is considered to be the major GHG of global concern, much effort has been focussed on developing ways to either remove CO₂ directly from the atmosphere, or capture CO₂ emissions power plants for storage in various natural reservoirs (See Sequestration Options Table in Appendix C). Whereas the current emphasis appears to be on the development of revenue-producing technological options such as CO₂-enhanced recovery of oil and methane, the ocean remains an important “natural sink” in the DOE’s carbon sequestration research portfolio.

Whereas the growing problem of coastal eutrophication has prompted various national laws and international agreements to control the deliberate efflux of nutrients into coastal seas, there are no direct legal precedents for ocean fertilization in the open ocean. The UNFCCC urges nations to seek ways to mitigate the effects of global climate change expeditiously and inexpensively—without dallying to develop the most scientifically sound solution - and allows the classification of the oceans as a potential sink for CO₂ to be developed as such. It remains to be established if and what role the 1972 London (Anti-dumping) Convention and 1996 Protocol to the London Convention may have in regulating carbon sequestration. For example, it is not known if sequestered carbon dioxide could be classified a “waste” under international marine law, since it is derived substantially from air “polluted” with anthropogenic emissions?

There is some worry that the legal vacuum regarding the rights on the high seas and historically weak enforcement could lead to a “carbon-rush”, with various entrepreneurs commandeering vast patches of ocean water for implementing their patented fertilization methods. The unregulated proliferation of large-scale fertilization schemes could ultimately lead to a situation analogous to the “Tragedy of the Commons” scenario, wherein the chemistry and biology of marine ecoregions are altered significantly from their current state, ultimately leading to detrimental consequences for all stakeholders. It is of the highest importance that a coherent set of science policy guidelines be established to govern the deployment of the proposed technologies.

Is Ocean Fertilization a Good Carbon Sequestration Option?

To the title’s question, one of us feels the answer is “no”, while the other thinks “it depends”. This dichotomy of like minds speaks to the complexity of the issue. The answer “no” is based on the Precautionary Principle. Given the known risks of ocean fertilization, and the inherent uncertainties, it is a classic precautionary situation. The answer “it depends” is based on a more objective analysis of the inevitabilities inherent in decision-making to address complex policy problems. In particular, it is recognition of the fact that there is no natural mathematical scale

relation between economic cost and ecological impact that allows them to be compared easily¹, which, incidentally, may also be the reason why the Precautionary Principle frequently fails to be proven persuasive in environmental policy-making. From that viewpoint, the answer depends not only on which other viable alternatives for reducing atmospheric GHG accumulation are available to, and considered by, policy makers, but also on stakeholders' preferences regarding risks and tradeoffs associated with each of the considered policy options.

As we finished this White Paper, a group of experts — including scientists, policy makers, and entrepreneurs intent upon commercializing ocean fertilization — convened by the American Society of Limnology and Oceanography (ASLO) came up with their own answer to this question. “On the basis of available scientific information”, they argue, “we cannot dismiss ocean fertilization with iron as a [carbon] mitigation option. However, computer models predict that it would at the very best reduce the expected increase of atmospheric CO₂ by a small percentage. Achieving this degree of sequestration would entail major alterations of the ecosystem — such as changes in food web structure and biogeochemical cycles — as has been demonstrated in several research experiments to date. These changes will have unknown consequences, some of which will be inherently unpredictable.”²

To some, the ASLO statement appears to be an oxymoron: The last two sentences seem incompatible with the first. But to others, the limitations and risks do not appear compelling enough to rule out large-scale commercial ocean fertilization. We must recognize, however, that to keep the question of large-scale ocean fertilization alive is to keep the research dollars flowing in this direction, and this may be a confounding factor. There is no doubt that research on this question will provide some valuable insights into how the oceans work. But is that adequate justification for keeping the question alive?

We think not.

¹ Some economists claim that ecological value can be “priced out”, but that is an area of active debate.

² Report of a workshop on “The Scientific and Policy Uncertainties Surrounding the Use of Ocean Fertilization to Transfer Atmospheric Carbon Dioxide to the Oceans” April 25, 2001 Washington D.C. , Sponsored by the American Society of Limnology and Oceanography (ASLO). Complete summary can be found at www.aslo.org.

TABLE OF CONTENTS

1. Prologue	1
The United Nations Framework Convention on Climate Change and the Kyoto Protocol	1
The Rise of Carbon Sequestration	1
Carbon Sequestration in the Ocean	2
2. The State of the Science	3
The Ocean Carbon Cycle	3
Factors Limiting Primary Production	6
Harmful Algal Blooms in Ocean Ecosystems	7
Export Production and <i>In Situ</i> Iron Fertilization Experiments	8
Model Analyses of Large Scale Ocean Fertilization Scenarios	9
3. Commercial Proposals	13
Greensea Venture Inc.	13
“Ocean Nourishment”: Supplementing Nutrient Upwelling with Ammonia	15
Ocean Carbon Science, Inc.: Distributed Fertilization	18
The duPont Method: Gradual Release of Nutrients from Synthetic Substrates	18
4. Unresolved Scientific Issues	20
Extrapolation of Results	20
The Problem of Verification	21
Ecological Monitoring	22
Key Topics for Future Research	23
5. The Policy Challenge	27
International Agreements on Marine Conservation and Protection	27
An Intergenerational View of the Oceans	29
6. Concluding Remarks	31
References Cited	33
Appendix A: US Patents Issued For Methods of Ocean Fertilization	41
Appendix B: Annotated Bibliography	45
Appendix C: Comparative Table of Carbon Sequestration Options	57

LIST OF FIGURES

Figure 1. A schematic of the global carbon cycle showing the major reservoirs of carbon.	3
Figure 2. A schematic of the major global carbon fluxes.	5
Figure 3. Model results for atmospheric CO₂ levels (units: ppm) in the IPCC business-as-usual and constant emission scenarios as modified by (i) nutrient depletion in the Southern Ocean , with continuous nutrient depletion for 100 yr, and (ii) 50 yr of nutrient depletion in the Southern Ocean followed by 60 yr without depletion.	11
Figure 4. A simulation of change in global export production following complete nutrient depletion in the HNLC Southern Ocean. Carbon export in the Southern Ocean would increase dramatically, while the production in the tropics decreases. The relative changes in export production across latitude are dependent upon ocean circulation.	12
Figure 5. Schematic of the OTG “ocean nourishment” system.	16

LIST OF TABLES

Table 1. A Comparative Overview of Ocean Carbon Sequestration Options.	2
Table 2. Approximate Fluxes of Carbon in the Ocean.	4
Table 3. Ranked 3-D Ocean Model Estimates for Changes in Average Atmospheric CO₂ Levels and Total New Production (i.e., Carbon Export) for Different Ocean Regions After 100 Years of Continuous Nutrient Depletion in that Ocean Region.	10
Table 4. A Comparison of Simulation Results for Reduction in Atmospheric CO₂ Concentrations due to Sequestration After 100 Years of Complete Nutrient Depletion in the Southern Ocean.	10
Table 5 : Effect of Ocean Circulation in Simulations of Ocean Fertilization Effectiveness.	11
Table 6. Fertilization Methods Proposed by Commercial Interests.	14
Table 7. Average Values of Gross Primary Productivity for Different Parts of the World Ocean.	17
Table 8. Qualitative ranking of some policy-relevant uncertainties regarding fertilization.	24

LIST OF BOXES

Box 1. Guidelines for Decisions Regarding Ocean Ecosystem Management.	29
Box 2. Marine Ecosystem Goods and Services.	30

PROLOGUE

The United Nations Framework Convention on Climate Change and the Kyoto Protocol

In 1990, the Inter-Governmental Panel on Climate Change (IPCC) findings on global warming led to the adoption of the United Nations Framework Convention on Climate Change (UNFCCC). The overall objective of the UNFCCC was to promote the stabilization of greenhouse gases (GHGs) by ecologically sound means (UN, 1992a). Subsequently, the Kyoto protocol was crafted during negotiations in the third Conference of Parties (COP-3) in 1997. A key feature of the now imperiled Kyoto Protocol (Reuters, 2001c) is that it allows the achievement of GHG emissions to occur partly through the trading of GHG emissions permits³ and credit received for emission reduction activities undertaken by countries, jointly or individually⁴. Whereas trading of GHG emissions has not yet been formalized anywhere in the world, there is growing anticipation of a future GHG market (Ney and Schnoor, 2000). Various corporations and trading organizations have arranged for the purchase of relatively inexpensive “proto-credits” and buying options for future credits from farmers, foresters and others (IEA, 1997b; Ney and Schnoor, 2000)⁵. Since carbon dioxide (CO₂) is considered to be the major GHG of global concern (IEA, 1997), much effort has been focussed on developing ways to either remove CO₂ directly from the atmosphere, or capture CO₂ emissions power plants for storage in various natural reservoirs (See Sequestration Options Table in Appendix C).

The Rise of Carbon Sequestration

The US annually emits GHGs equivalents⁶ to 1.8 to 1.9 Gt C⁷, and rising, including 25% of world’s CO₂ emissions (i.e., approx. 5.5 Gt CO₂ per year⁸) (USEPA, 2000). It is not known what magnitude of global emissions reductions is necessary to “stabilize” atmospheric GHG concentrations at “safe” levels. Globally, in order to achieve stabilization of atmospheric CO₂ levels at 450ppm by 2100AD, CO₂ reductions of approximately 850 Gt C over 100 years would be required⁹. Large reduction in GHG emissions would be required to stabilize atmospheric CO₂ concentrations even at double the current levels.

GHG reductions may be achievable by a suitable combination of the following three approaches:

³ Credits and permits are distinct instruments and imply different, but not necessarily mutually exclusive, trading regimes. Permits are allowances that might be used under a “cap and trade” system that limits the total emissions for a region or country. Credits would be awarded for net reductions that are achieved with respect to an established baseline for regional or national emissions. Conceivably, credits could supplement permits.

⁴ Under “Actions Implemented Jointly” (AIJ) countries with emissions targets may get credit towards their targets through project-based emission reductions in other such countries. The private sector may participate in these activities. The “Clean Development Mechanism” (CDM) allows for “joint implementation for credit” in *developing* countries.

⁵ See also <http://www.co2e.com> and <http://www.carbonmarket.com>

⁶ Carbon equivalents are calculated on the basis of the global warming potential of a GHG relative to CO₂. For example, one molecule of methane traps 21 to 25 times more heat in the atmosphere relative to one molecule of CO₂ over 100 years. IPCC (1996)

⁷ 1GtC = 1 gigaton C = 1 billion metric tons C = 3.67 billion metric tons CO₂.

⁸ US emits 25% of world’s CO₂ emissions (ie 0.25*6 GtC*3.67 tCO₂/tC = approx. 5.5 Gt CO₂ per year).

⁹ Based on difference between projected emissions under IS92a scenario (1500 Gt C) and Stabilization at 450 ppm scenario (650GtC). [see www.ieagreen.org.uk/pfghgt4b.htm]

1. Efficiency-improvements in energy production and usage.
2. Substitution of fossil energy by nuclear power or renewable energy such as wind, solar, geothermal, etc.
3. Sequestration of GHGs, either by separation from large point source emissions, or directly from the atmosphere.

Because of population growth and economic development, CO₂ emissions worldwide are likely to maintain an upward trend in the foreseeable future, and efforts to find ways of capturing and storing CO₂ (the third option) in natural reservoirs is gathering momentum. Natural reservoirs for carbon are the following:

1. Terrestrial biomass and surface soils (e.g., forests and agricultural soils)
2. Geologic reservoirs (e.g., aquifers, coal mines, oil and gas traps)
3. Deep ocean waters

The current emphasis appears to be on the development of revenue-producing technological options such as CO₂-enhanced recovery of oil and methane. The ocean is a very important “natural reservoir” for massive amounts of carbon in the global carbon cycle, however, and the idea of using it for additional storage has attracted some attention in the DOE’s carbon sequestration research portfolio (Reichle et al., 1999).

Carbon Sequestration in the Ocean

The two main approaches for CO₂ capture in oceans, (a) Direct Injection and (b) Ocean Fertilization, are similar in their ultimate goal, but very different in all other dimensions (Table 1). Direct Injection involves capturing carbon dioxide from large point sources such as power plants, and delivering it in concentrated form to the deep sea by some technological means. In contrast, fertilization aims to remove CO₂ directly from the atmosphere by stimulating the natural biological processes in the surface oceans. This paper is focused solely on fertilization. The reader is directed to reviews by the IEA Greenhouse Gas R&D Program (IEA, 1999; IEA, 2000; IEA, 2000b), the MIT Energy Lab (Herzog et al., 1997; Herzog et al., 2000) and the US Department of Energy Center for Research on Ocean Carbon Sequestration (<http://www-esd.lbl.gov/DOCS>) for further information on the Direct Injection approach.

Table 1. A Comparative Overview of Ocean Carbon Sequestration Options.

Approach	“Direct Injection”	“Ocean Fertilization”
CO₂ Capture Mechanism	Separation from flue gas by Membrane or Amine solvent	Nutrient-enhanced phytoplankton photosynthesis and cell growth
Target Source of CO₂	Large point sources (e.g., coal/gas-fired power plants)	Atmospheric CO ₂ (via uptake of dissolved CO ₂ by phytoplankton)
Target Reservoir for Captured CO₂	Deep ocean, offshore oil/gas reservoirs and saline aquifers	Deep ocean (water layer lying below the thermocline)
Process for Transfer of Carbon into Storage	Compression and pumping of liquefied CO ₂	Sinking of dead phytoplankton cells and their by-products

STATE OF THE SCIENCE

Evaluating the promise and risks of ocean fertilization for carbon sequestration must rely on our understanding of the natural role of the oceans in regulating the global carbon cycle and the factors that limit biological production in the oceans.

The Ocean Carbon Cycle

The deep ocean represents an enormous natural reservoir for carbon in the global carbon cycle (Figure 1), dwarfing the atmospheric reservoir and that of the terrestrial biosphere. At this point in the earth's history, with the supply of CO₂ from the land exceeding the oceans ability to assimilate it, the atmosphere represents a "bottleneck" in the exchange of carbon between the terrestrial and oceanic reservoirs (Post et al., 1998).

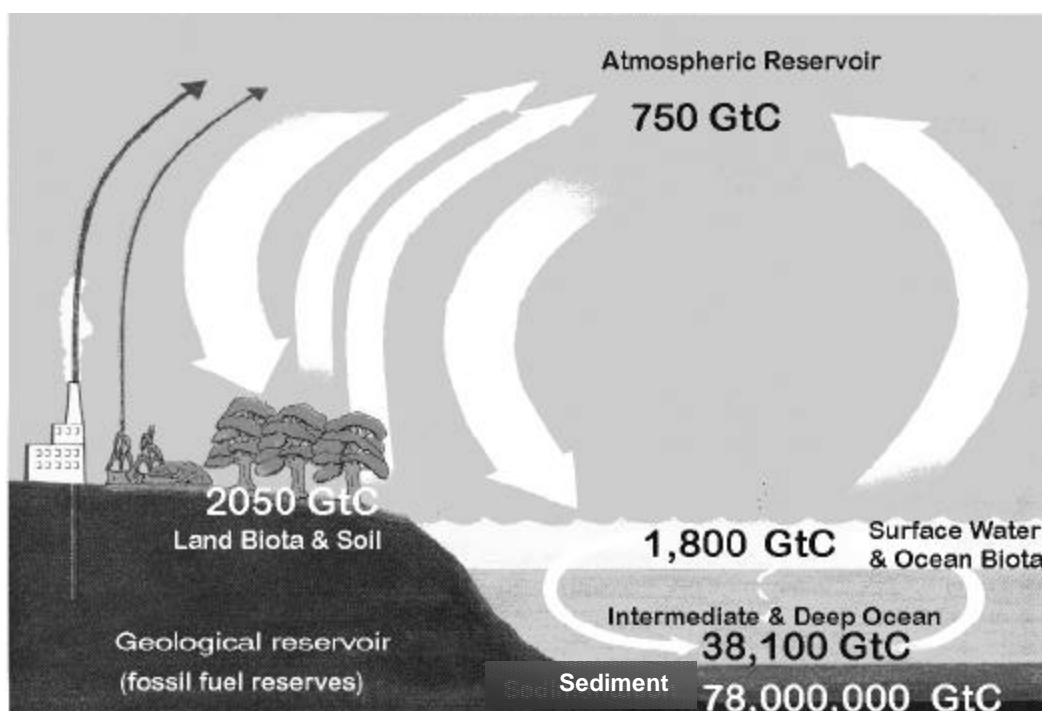


Figure 1. A schematic of the global carbon cycle showing the major reservoirs of carbon {Adapted from (Post et al., 1998)}.

The ocean carbon cycle is controlled by two global mechanisms, called the "solubility pump" and the "biological pump". The fundamental processes controlling the physical exchange of CO₂ between atmosphere and ocean (i.e., the solubility pump) are somewhat better understood than the more complex biological pump. The rate at which the ocean physically removes CO₂ and heat from the atmosphere depends upon the rates of thermohaline circulation. Thermohaline circulation is driven by the sinking of cold and salty water masses in the Polar regions

particularly in the North Atlantic and the Southern Ocean¹⁰. Cold water contains more dissolved CO₂, because the solubility of the gas increases at lower temperatures and at higher pressure. Sinking water masses trap the dissolved CO₂ in the deep ocean until the water re-surfaces many centuries later.

The “biological pump” is driven by photosynthetic productivity of phytoplankton floating in the sunlit surface layer of the ocean (Volk and Hoffert, 1985) and is characterized as the production and transport of biogenic organic and inorganic carbon (Murnane et al., 1999). The microscopic plants constitute the base of the marine food chain that also includes zooplankton (herbivores), bacteria and larger marine animals. During intense phytoplankton blooms, the large cells¹¹, often dominated by diatoms, sink out of the surface layer (Buesseler, 1998; Nelson and Brzezinski, 1997). Microbial degradation remineralizes¹² the organic matter descending into the deep ocean and the “regenerated” nutrients, including inorganic carbon (CO₂), are slowly returned to the surface waters by the movement of water along the “global ocean conveyor belt” (Siegenthaler and Sarmiento, 1993). On average, it takes a molecule of water (or elements dissolved in it) roughly 1000 years to make the global excursion from the surface waters to deep, and back again.

Marine net primary production¹³ is estimated at 45 to 50 Gt C/yr (Longhurst et al., 1995), which nearly equals the primary production occurring on land globally. Annually, 5-6 % (approx. 2.3 Gt C/yr) of the global marine primary production is exported to 1000 m depth, the remainder being regenerated to CO₂ in the upper ocean (Table 2). Only 1 to 2 % of the global marine primary production reaches the ocean floor (Christensen, 2000; Lampitt and Antia, 1997).

Table 2. Approximate Fluxes of Carbon in the Ocean (Christensen, 2000; Lampitt and Antia, 1997; Longhurst et al., 1995).

Process	Amount (Gt C/yr)	% of Biogenic Carbon Uptake
Global Marine Net Primary Production	45 to 50	100 %
Carbon exported below 1000m depth	2.3	5-6 %
Carbon exported to ocean floor	0.74	1-2 %

¹⁰ The area of the world’s oceans that lies south of the 40° S is known as the Southern Ocean (Deacon, G., 1984. The Antarctic Circumpolar Ocean. Cambridge University Press.)

¹¹ Typically cells larger than 5 micrometer in size.

¹² Remineralization is the process of dissociating complex organic matter into its component inorganic elements.

¹³ Net primary production (NPP) is the total amount of carbon converted into organic compounds (sugars) via photosynthesis, less the amount returned to the atmosphere as carbon dioxide during respiration by the plants themselves. NPP is given as Gt C/yr in Table 1, but may be also measured as g C/m²/yr.

In pre-industrial time, the global carbon cycle was in “equilibrium”, with terrestrial and oceanic system contributing equally to both emissions and uptake of CO₂ from the atmosphere (Figure 2). The solubility pump and the biological pump have made roughly equal contributions to the uptake of CO₂ by the ocean (Sarmiento and Orr, 1991). Since then, increasing fossil fuel combustion and land use changes have caused the release of relatively small, but significant, amounts of CO₂ into the atmosphere. Some of that “extra” CO₂ has diffused into the ocean and the ocean currently absorbs about one-third (approx. 2 Gt C/yr) of annual anthropogenic emissions (5-6 Gt C/yr and rising). Therefore, the stock of atmospheric CO₂ is growing at an ever-increasing rate, currently 3-4 Gt C/yr.

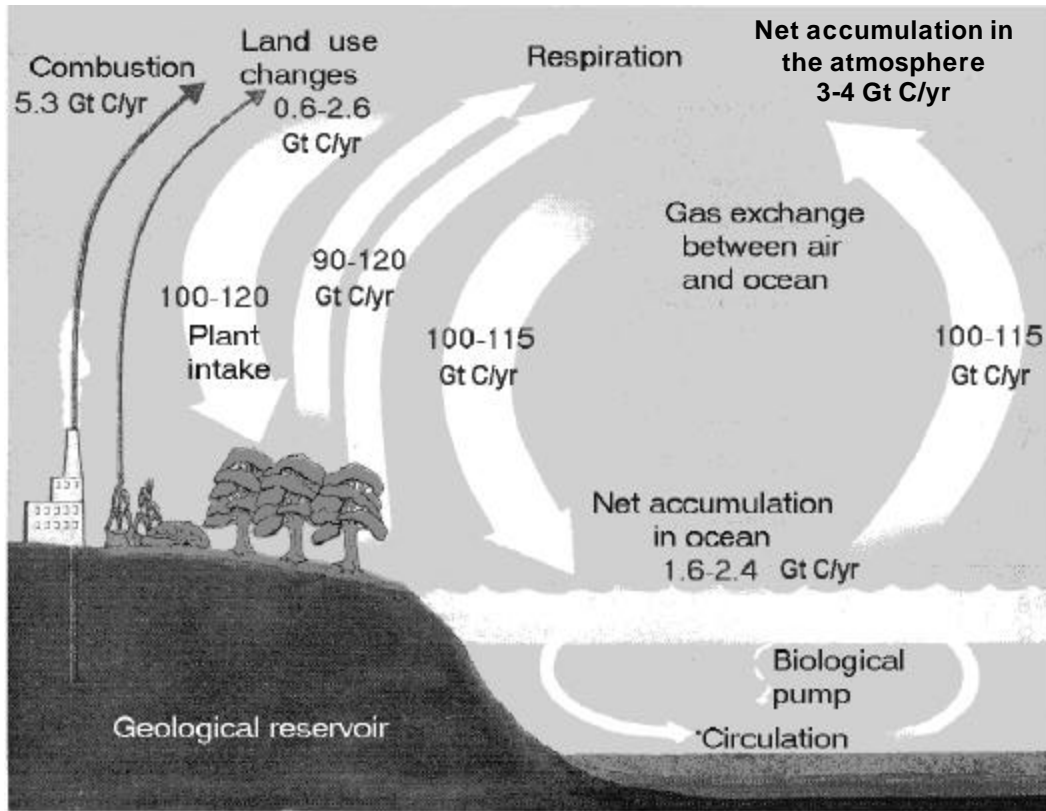


Figure 2. A schematic of the major global carbon fluxes {Adapted from (Post et al., 1998)}. The annual fluxes in and out of the oceans are roughly equivalent to those of the terrestrial biosphere. The relative sizes of oceanic fluxes due to the biota and physical processes approximately equal. The net flux from the land to the atmosphere is balanced (within the uncertainties) by a net accumulation in the atmosphere and ocean. Note that although the anthropogenic fluxes are but a small fraction of the natural fluxes, they have a striking impact on the atmospheric reservoir.

Models suggest that up to 95% of the total oceanic uptake of *anthropogenic* CO₂ to date was due to the solubility pump (Murnane et al., 1999). However, the biological pump is considered to be very important in maintaining a CO₂ gradient between the surface and deep waters (Sarmiento and Toggweiler, 1984; Volk and Hoffert, 1985; Watson et al., 2000). Hence, there is an interest

in exploring methods to transport of CO₂ into the deep ocean – reliably, efficiently and expeditiously – by manipulating the mechanisms regulating the global carbon cycle¹⁴

The Southern Ocean has for long been proposed as the most important sink for atmospheric carbon dioxide in the past glacial period and for the potential climate regulation in the future (Barth et al., 2000; Raven and Falkowski, 1999; Sarmiento and Orr, 1991). Not only is the Southern Ocean an important area of deep water formation, but it is also hypothesized that a large aeolian influx of iron dust (believed to be the limiting nutrient in these waters – see below) triggered enhanced atmospheric CO₂ uptake and carbon export to the deep sea during the last ice age (Martin, 1990a). However, recent modeling results suggest that the estimates for role of the Southern Ocean productivity in controlling past (and future) atmospheric CO₂ levels may have been exaggerated (Gnanadesikan et al., 2000; Lefevre and Watson, 1999). One alternative explanation to the iron hypothesis for lower glacial atmospheric CO₂ is that an expanded area of sea ice blanketed the Southern Ocean, effectively forming a barrier against the release of CO₂ from the ocean to the atmosphere (Elderfield and Rickaby, 2000). This hypothesis is further corroborated by the strongly diminished utilization of silicic acid (compared to the present interglacial) by diatoms in the Southern Ocean during the last glacial period (De La Rocha et al., 1998). Another hypothesis attributes the last glacial CO₂ minimum primarily to changes in ocean ventilation and stratification (Toggweiler, 1999). Hence, the Southern Ocean-climate connection is still a matter of considerable scientific uncertainty.

Factors Limiting Primary Production

Light and nutrients are the main factors regulating the growth of marine algae. Essential “macro-nutrients” such as nitrogen (N), phosphorus (P) and silicon (Si), along with “micro-nutrients” such as iron (Fe), are pumped up from the deep ocean by physical circulation. This physical process is called “upwelling”. Changes in the nutrient composition of surface waters induce changes in species composition (Taylor, 1993; Turner et al., 1998), but the specific responses of plankton to changing nutrient levels remain difficult to predict. On average, phytoplankton are considered to use nutrients in the following ratio (Martin et al., 1990; Redfield, 1934; Sunda and Hunstman, 1995):

106 C: 16 N: 1 P: 0.001-0.005 Fe

In other words, under iron limitation, adding one atom of iron can catalyze the biological uptake of approximately 100,000 atoms of carbon¹⁵ – an uptake factor of 10⁵. The macronutrients (N, P, Si) are consumed by phytoplankton in much higher amounts relative to micronutrients (Fe, Zn, etc.). Since the dissolved concentrations of these nutrients in the deep ocean are determined by marine life processes and originate from the decay of phytoplankton, the nutrients in upwelling waters tend to vary in these proportions, though exceptions have been observed (Arrigo et al., 2000; Daly et al., 1999; Rubin et al., 1998).

¹⁴ It is often pointed out that if it were possible to incorporate all of the atmospheric carbon dioxide (750 Gt C) into the deep ocean, it would increase its content by about 2 % (for example, see Raven and Falkowski, 1999). Whereas 2% may seem like a small amount, we note that even relatively small increases in the amounts of CO₂ dissolving in the upper ocean, in the recent past, have impacted corals in many parts of the world.

¹⁵ In weight terms, 1 ton of Fe can facilitate the photosynthetic uptake of 23,000 tons of C (for 1 mole Fe: 106,000 moles C).

Diatoms account for roughly 75% of the primary production occurring in typically high productivity coastal and nutrient-replete waters around the world (Nelson and Smith, 1986; Nelson et al., 1995). When diatom blooms occur, growth rates of these organisms are dependent upon the availability of dissolved silicon (Si), because silicates are used to form intricate exoskeletons for the diatoms (Dugdale and Wilkerson, 1998; Pondaven et al., 1999; Taylor, 1993). The larger Spring blooms in the temperate or sub-polar latitudes typically result in heavy sedimentation of diatom cells, but the Summer blooms do not, because while sunlight is abundant in Summer, silicate becomes scarce (Boyd et al., 1999). As the concentration of silicon dwindles, diatoms are likely to release increasing amounts of dissolved organic carbon, because cell growth decelerates more abruptly than photosynthetic production does (Flynn and Martin-Jezequel, 2000). Consequently, the “export” potential for particulate carbon quite literally dissolves away as Si-limitation sets in. While diatoms use much less Si under iron-replete conditions than under iron-poor conditions (Hutchins and Bruland, 1998), such efficiency might also make the cells lighter and less likely to sink rapidly. In terms of carbon “export”, too much iron can also be limiting.

In contrast to the highly productive, nutrient-replete coastal upwelling areas, most of the world’s ocean is nutrient-poor. However, three perennially under-productive open ocean regions have been identified, where *high* dissolved concentrations of most nutrients occur year-round. It is believed that these three “high-nutrient-low-chlorophyll” (HNLC) zones, which collectively cover about 30% of ocean surface, are lacking in one or more essential ingredients that would allow plankton to utilize the remaining, abundant nutrients. HNLC regions are found in the Eastern Equatorial Pacific, NE Subarctic Pacific and Southern Ocean which surrounds the Antarctic continent.

It is now widely accepted that phytoplankton growth is limited by the availability of iron in the Equatorial Pacific HNLC region (Coale et al., 1996) and in the Southern Ocean (Boyd et al., 2000; Martin et al., 1990), in effect limiting the biological assimilation of other nutrients such as nitrogen and phosphorus. However, the limitation by iron does not preclude simultaneous limitation by other factors. In the NE Subarctic Pacific and the Southern Ocean, primary production is probably co-limited by low levels of light intensity and dissolved iron (Maldonado et al., 1999; Sunda and Huntsman, 1997). Other possible limiting/co-limiting factors for production and growth of phytoplankton in the Southern Ocean are: vertical mixing, temperature, silicate concentrations and zooplankton grazing (Bracher et al., 1999; Sohrin et al., 2000).

“Harmful Algal Blooms” in Ocean Ecosystems

The increasing proliferation of harmful algal¹⁶ blooms (HABs) in coastal areas around the world is suspected to be primarily caused by eutrophication from ever-rising inputs of nitrogen from atmospheric deposition, anthropogenic nitrogen loading of rivers, urban sewage discharges, and now groundwater discharge (Paerl, 1997). Intensification of ship traffic facilitates the introduction of some harmful algal species into coastal waters (Mos, 2001), while ocean currents carry others over long distances (Branca, 1998). Certain algae may lie dormant as cysts for years until brought into more favorable conditions by physical forces (Branca, 1998). Harmful algal

¹⁶ In this context “algae” = phytoplankton

blooms have detrimental effects on the local food webs by inducing toxicity to higher trophic levels, hypoxia or anoxia in the water column, and/or dramatic shifts in species distribution.

Further complications arise from the responses of different species to both concentration and chemical form of nitrogen. As nitrogen concentration rises, the Si:N atomic ratio - an important biological control factor - falls. When the Si:N ratio falls below the threshold “Redfield” values 1:1, the potential for harm (as defined above) increases dramatically (Turner et al., 1998). Dinoflagellates and cyanobacteria are physiologically well adapted to use organic nitrogen {Hans Paerl as cited in (Pelley, 1998)}, and the cyanobacteria show an especially high preference for ammonia (Mulholland and Capone, 1999). Iron fertilization in the ocean typically stimulates the growth of diatoms (de Baar and Boyd, 2000). However, the proliferation of diatoms may have serious negative consequences for the ecosystem as a whole. For example, zooplankton reproduction can be inhibited by bloom diatom species (Miralto, 1999). Some pennate diatom strains belonging to the species *Pseudo-nitzschia* produce a powerful marine biotoxin, called domoic acid. The production of domoic acid appears to be related to iron availability (among other nutrients such as N, P, and Si), perhaps as a metal-binding ligand (Mos, 2001). Domoic acid can travel up the food chain, causing mortality in marine mammals and possibly even humans (Scholin et al., 2000). The production of *Pseudo-nitzschia* should be a real concern for proponents of iron fertilization in the Southern Ocean, because the low light conditions and low temperatures may promote blooms of this diatom (Mos, 2001) with potentially serious consequences for the diverse Antarctic food web.

Export Production and *In Situ* Iron Fertilization Experiments

“New production” is defined as the steady-state fraction of marine primary production that is available for export to the deep ocean (Eppley and Peterson, 1979). It is more properly defined as net community production: That is, the fraction of carbon that is produced in the surface layer of the ocean through primary production, that is not consumed and respired by higher trophic levels and bacteria on contemporary time scales. It is this production that determines the amount of carbon that may be exported from the surface ocean to the deep sea below the thermocline, and which is critical to the biological pump (Falkowski et al., 1998; Sakshaug and Slagstad, 1992).

In the context of carbon sequestration, even all types of new production are not created equal. Nitrate-based new production does not typically generate net carbon export, because the export of carbon from the surface ocean is balanced by an upwelling of CO₂ along with the new nitrate from the deep ocean (Hood et al., 1999a). In other words, nutrients and CO₂ reach the surface together. Hence, the primary production that is fueled by these nutrients draws on the carbon that was upwelled with them, and there will be no net draw down of CO₂ from the atmosphere. In contrast, new production that is driven by limiting factors supplied from *outside* the system (e.g., from the atmosphere) can indeed drive production that results in a net transfer of CO₂ from the atmosphere to the ocean. Indeed, nitrogen gas that is brought into the ocean system from the atmosphere via N-fixation by cyanobacteria, can be a significant source of *net* carbon export from the surface waters. This “true” new production can account for as much as 50% of the nitrogen that actually drives new production in some marine ecosystems (Hood et al., 1999a; Karl et al., 1997; Letelier and Karl, 1996). Likewise, airborne (aeolian) iron-containing dust can

also drive true new production in iron limited ecosystems such as HNLC regions. And since iron limitation can limit N-fixation in the oligotrophic oceans, and atmospheric N₂ is in great abundance, iron is very important to the carbon export budget in these areas (Raven and Falkowski, 1999). Field experiments indicate, however, that when N-fixation is the predominant driver for primary production, an increasing fraction of carbon export occurs as dissolved organic matter relative to particulate organic matter (Karl et al., 1995).

Because aeolian iron is hypothesized to play such an important role in regulating primary production in HNLC areas, four scientific field experiments have been carried so far to examine its effects of iron on primary productivity and other ecosystem properties: IRONEX I (in 1993) and IRONEX II (in 1995) in the Equatorial Pacific Ocean, and SOIREE (in 1999) and EISENEX (in 2000) in the Southern Ocean (Boyd et al., 2000; Coale et al., 1996; Martin et al., 1994; Smetacek, 2000). There are five key observations from the field experiments regarding likely effects of iron fertilization these HNLC ocean regions:

- It is clear that iron limits primary production;
- Phytoplankton biomass can be increased over the short term (weeks) by the addition of iron,
- There is no evidence of increased carbon “export” following fertilization in the time frame of these experiments;
- The composition of the phytoplankton community changes dramatically upon the addition of iron, with diatom biomass increasing preferentially;
- Dimethyl Sulfide (which nucleates cloud formation) production is increased by iron fertilization

Model Analyses of Large Scale Ocean Fertilization Scenarios

The anticipation and results of these mesoscale iron-fertilization experiments stimulated modeling studies of the capacity of the HNLC areas for increased export production and atmospheric CO₂ drawdown, assuming iron limitation was relieved. Ocean ecosystem models were “asked”:

If the phytoplankton had as much iron as they needed, could they convert all of the “unused” nitrogen and phosphorus in these regions into organic carbon and if so, how much atmospheric CO₂ would be transferred to the deep ocean?

Because of the physics and size of the Southern Ocean, this has always been thought to be HNLC region where iron fertilization would have the largest effect for purposes of carbon sequestration, and models supported this belief (Table 3).

But even here, after 100 years of continuous iron fertilization, the carbon sequestration potential corresponds to a 17% reduction in projected CO₂ emissions¹⁷ compared to the projected CO₂ levels for the IPCC’s “business-as-usual” emissions scenario¹⁸ (Sarmiento and Orr, 1991). And this is an upper (and unachievable) limit. The simulation assumes that all of the unused nutrients

¹⁷ This is equivalent to a 9% decrease in projected atmospheric CO₂ levels under a “business-as-usual” scenario.

¹⁸ See Houghton, J., Jenkins, G. and Ephraums, J., 1990. Climate change: The IPCC assessment, IPCC, Cambridge.

are converted to organic carbon, and does not include loss of efficacy due to seasonal and random variations in environmental conditions.

Table 3. Ranked 3-D Ocean Model Estimates for Changes in Average Atmospheric CO₂ Levels and Total New Production (i.e., Carbon Export) for Different Ocean Regions After 100 Years of Continuous Nutrient Depletion in that Ocean Region. The Results are Calculated for a “Business as Usual” Scenario (Sarmiento and Orr, 1991).

Region	Atmospheric pCO ₂ perturbation (ppm)	New Production perturbation (Gt C/yr)
Southern Ocean	-71.8	13.2
North Atlantic	-12.7	1.4
North Pacific	-6.9	0.4
Equatorial Region	-2.8	-0.2

There is remarkable agreement among results of simulations done about a decade ago, describing the carbon sequestration potential of the Southern Ocean fertilization by different research groups (Table 4). (Joos et al., 1991; Kurz and Maier-Reimer, 1993; Peng and Broecker, 1991a; Sarmiento and Orr, 1991). According to these simulations, iron-fertilization in HNLC ocean regions would not “zero out” global CO₂ output under any realistic emissions scenario (Figure 3). Additionally, any atmospheric carbon uptake due to fertilization would be rapidly returned to the atmosphere unless fertilization is sustained for over 50 years (Joos et al., 1991).

Table 4. A Comparison of Simulation Results for Reduction in Atmospheric CO₂ Concentrations due to Sequestration After 100 Years of Complete Nutrient Depletion in the Southern Ocean (Ryan, 1998).

Reference	Business As Usual scenario		Constant Emissions scenario	
	% reduction	ppm reduction	% reduction	ppm reduction
Joos, Sarmiento & Siegenthaler (1991)	14	120	18	90
Peng and Broecker (1991)	10 +/- 5	116	10 +/- 5	90
Sarmiento & Orr (1991)	9	72	12	61
Kurz &Maier-Reimer (1991)	7	50	9	44

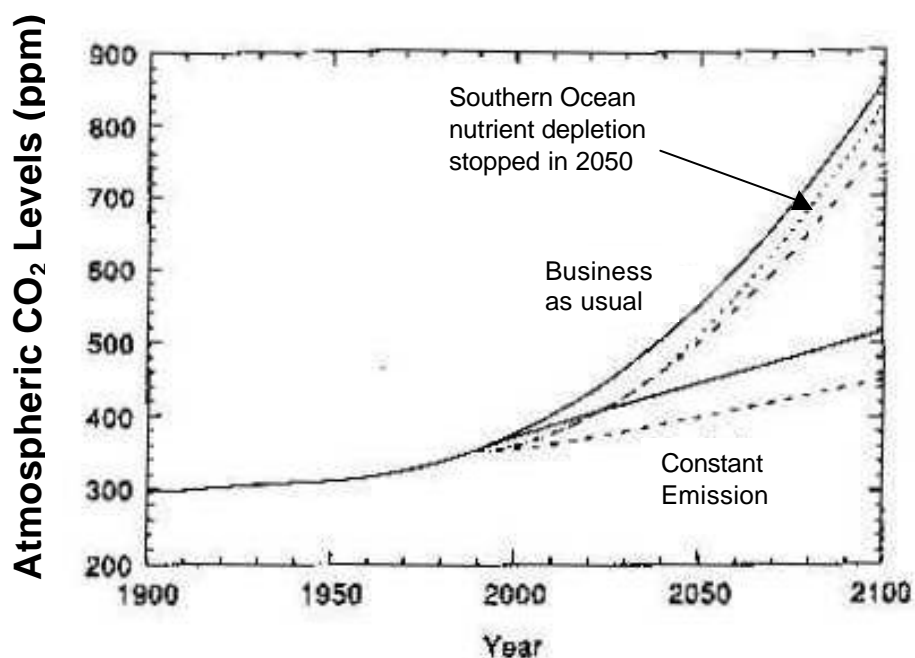


Figure 3. Model results for atmospheric CO₂ levels (units:ppm) in the IPCC business-as-usual and constant emission scenarios (—) as modified by (i) nutrient depletion in the Southern Ocean, with continuous nutrient depletion for 100 yr (- - - -), and (ii) 50 yr of nutrient depletion in the Southern Ocean (·····) followed by 60 yr without depletion. (Sarmiento and Orr, 1991).

Revised modeling estimates (see Table 5), which account for restriction of photosynthetic carbon uptake in the Southern Ocean by phosphorus-limitation, span a wide range - from 50 to 150 Gt C exported after 100 years of continuous iron fertilization (Gnanadesikan et al., 2000; Gnanadesikan et al., 2001). However, since the Southern Ocean is a source for deep waters that re-emerge in the tropics, severe depletion of nutrients in the Southern Ocean could also decrease equatorial primary production by at least 30% and by as much as 70% (see Figure 4) (Gnanadesikan et al., 2000; Gnanadesikan et al., 2001). The loss in tropical productivity may even outstrip the amount of atmospheric carbon that would be captured – a tradeoff that requires very careful assessment. The large range in both effectiveness and ecological impacts of ocean circulation is a function of ocean circulation and also the duration of fertilization.

Table 5. Effect of Ocean Circulation in Simulations of Ocean Fertilization Effectiveness. See also Fig. 4 (Gnanadesikan et al., 2000).

	Strong Upwelling in High Latitudes, Weak Convection in Southern Ocean	Strong Upwelling in Low Latitudes, Strong Convection in Southern Ocean
Uptake of carbon after 100 years Southern Ocean fertilization (Gt C)	67	96
Change in tropical carbon export due to SO nutrient depletion (%)	-71	-29
Uptake of carbon after 100 years of tropical fertilization (Gt C/yr)	10.1	8.5

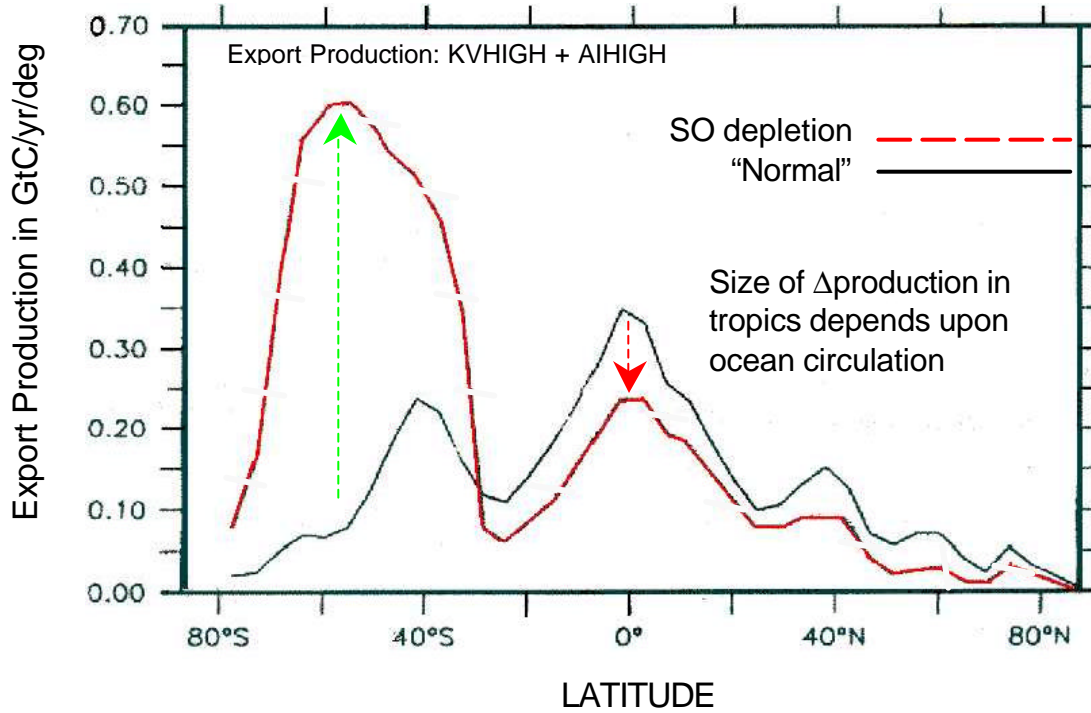


Figure 4. A simulation of change in global export production following complete nutrient depletion in the HNLC Southern Ocean. Carbon export in the Southern Ocean would increase dramatically, while the production in the tropics decreases. The relative changes in export production across latitude are dependent upon ocean circulation. See also Table 5 (Gnanadesikan et al., 2000).

COMMERCIAL PROPOSALS

The idea of nutrient manipulation in marine ocean ecosystems has spawned a variety of proposed applications, from engineering fisheries (Jones and Young, 1997; Markels, 1995) to capturing atmospheric carbon dioxide (Jones and Young, 2000; Markels and Barber, 2000), and it has triggered a cascade of patent applications. Although it is clear that ocean fertilization is not the solution to global warming, it does appear that it could have an influence on atmospheric CO₂ concentrations. The idea has attracted media attention since 1990, less than two years after John Martin first sent ripples through the world oceanographic community with his famous remark, “Give me a half a tanker of iron and I’ll give you an ice age” (Martin, 1990b). Around the same time, high-profile international discussions on the problem of global warming and climate change based on the IPCC findings, and the signing of the UNFCCC in 1990, had generated a worldwide wave of interest and awareness. The appeal of ocean fertilization as a carbon sequestration option has grown during the past decade as the prospect of an international market in carbon credits becomes more of a reality (Ney and Schnoor, 2000).

GreenSea Venture Inc.: “Pulsed” release of iron in HNLC waters

Michael Markels of GreenSea Venture Inc. (GSV; formerly Ocean Farming Inc., Springfield, VA. <http://www.greenseaventure.com>) owns five patents¹⁹ on ocean fertilization. He has, for example, a patent for a reaction mixture comprised of iron-chelate, phosphate, and microorganism²⁰ and inert delivery system²¹ for the explicit purpose of increasing seafood production in the “barren ocean” (Markels, 1998a). More recently, however, he has shifted his focus to carbon sequestration²². To date, Markels has received five patents on different versions of the iron fertilization idea (see Appendix A for summary of patents) and has filed a new patent application with yet another twist to the same formula.

Markels has claimed that it is possible to “zero out” the equivalent of *global* annual anthropogenic CO₂ emissions by continuous fertilization with 8.1 million tons of iron in HNLC waters spanning area of 16,000,000 square miles (i.e., about 11% of global ocean surface) and capturing 8 Gt CO₂ per year in the deep ocean profitably for less than \$2/t CO₂ (i.e., \$7.50/t C)²³ (Graeber, 2000). However, simulations of ocean fertilization effectiveness strongly challenge the such claims (see Tables 3, 4 and 5). In particular, the effect of fertilization in the Equatorial Pacific Ocean on the accumulation of CO₂ in the atmosphere would be practically irrelevant

¹⁹ A sixth patent was filed in January 2001, but has not yet been issued. See Appendix A for details.

²⁰ “...wherein at least one microorganism that fixes nitrogen, is applied with at least one of said fertilizers” and “...said microorganism comprises at least one member selected from the group consisting of blue green algae and phytoplankton.” (from United States Patent 5,967,087 issued to Markels, Jr. on October 19, 1999. See also United States Patent 5,433,173 issued to Markles, Jr. on July 18, 1995.)

²¹ “...in the form of pellets, and said pellets comprise a float material selected from gas bubbles or low density materials, and said pellets further comprise a binder selected from plastic, wax, high molecular weight starch, or a combination thereof.” (from United States Patent 5,967,087 issued to Markels, Jr on October 19, 1999.)

²² Markels fourth patent (P/N 5,967,087 issued on October 19, 1999) shifted the focus from increasing commercial fish catch by iron fertilization to increasing phytoplankton production and “limiting zooplankton and seafood growth...by applying (iron) in pulses”. In the latest patent (P/N 6,200,530 issued on March 13, 2001), the idea is extended to include the release of iron in a spiral pattern.

²³ Markels evidently prefers to use British Imperial units. However, this need not cause any confusion for the purposes of comparing costs of different methods, because the inherent uncertainties in all relevant values are so high that the conversion of units (1 ton = approx. 0.9 metric tons) is effectively rendered superfluous.

from the perspective of mitigating global warming (Gnanadesikan et al., 2000; Gnanadesikan et al., 2001; Sarmiento and Orr, 1991).

Table 6. Fertilization Methods Proposed by Commercial Interests.

Organization	GreenSea Venture, Inc. (formerly OFI) www.greenseaventure.com	Ocean Technology Group (U. of Sydney, Australia) www.otg.usyd.edu.au	Ocean Carbon Science, Inc. (Formerly Carboncorp USA) www.rsrch.com/carboncorp
Principal	Michael Markels, Jr.	Ian S.F. Jones	Russ George/ Robert Falls
Fertilizer	Fe-chelate (lignic acid sulphate)	NH ₃ solution in seawater	Proprietary nutrient supplements, Fe + ?
Approach	<ul style="list-style-type: none"> - Fertilizer released along a "spiral fertilization" path - Small, floating nutrient pellets 	<ul style="list-style-type: none"> - Atmospheric nitrogen fixed as ammonia (NH₃) via industrial process (using fossil fuels) - Ammonia pumped from a land- or ocean-based (i.e., floating) facility for release into the surface ocean near the edge of the continental shelf - Ammonia discharged via multiple "diffuser points" 	<ul style="list-style-type: none"> - Retrofit commercial ocean liners for releasing mix into the propeller wash at an "appropriate" time(s) during a voyage - Algal response monitored by satellite imaging and shipboard instrumentation
Ocean Area(s) Targeted for Fertilization	Equatorial Pacific Ocean (for demonstration experiment)	<ul style="list-style-type: none"> - Chilean coastal upwelling zone (Pearce, 2000) - Coastal waters of "Low income food deficient" nations 	- "Plankton domains" along major shipping lanes
Claimed Efficacy	0.6-2 Mt CO ₂ sequestered over 5,000 sq. mi. of HNLC ocean in 20 days	1 Gt N/yr sequesters about 5 Gt C/yr (Jones and Young, 1997)	Not specified
Claimed Cost	\$7 to \$7.5 /t C (at "commercial scale")	Approx. \$30 /t C	Not available
Source	(Markels and Barber, 2000)	(Jones and Young, 2000), unless noted otherwise	Text of the now defunct Carboncorp website

GSV claims to have conducted two experiments in the Gulf of Mexico in 1998 and has reported a temporary quadrupling of the initial diatom population due to fertilization (Markels, 1998b). The procedures and results of GSV's fertilization experiments were never subjected to standard scientific peer-review, which might have legitimized their claims. GSV has now proposed a 5,000 square mile "technology demonstration" claiming that its technology can permanently sequester 120-400 t CO₂ / square mile²⁴ over a duration of 20 days in the Equatorial Pacific Ocean (Markels and Barber, 2000). Further more, it is claimed in GSV's latest patent application (see summary in Appendix A) that over one year, each square mile of "deep tropical ocean" fertilized with about one half ton of iron fertilizer would yield more than 2000 t CO₂ that would remain sequestered for well over a millennium.

In order to garner support for its proposal for a 5,000 square miles in the tropical Pacific Ocean, GSV has built alliances with prestigious research centers and universities, including the Monterey Bay Aquarium Research Institute (MBARI), Moss Landing Marine Lab, University of Hawaii and Duke University (GreenSea Venture, 2001). GSV has proposed the creation of a foundation in the name of the late John Martin²⁵ (GreenSea Venture, 2001). GSV would manage public relations, governmental lobbying and fund-raising on behalf of the Dr. John Martin Foundation in order to generate support for a large-scale (5,000 square miles) iron fertilization experiment proposed for 2002. In return, GSV would claim exclusive rights to commercial applications of any scientific findings that might emerge from the experiments (GreenSea Venture, 2001).

"Ocean Nourishment": Supplementing Nutrient Upwelling with Ammonia

The Ocean Technology Group (OTG, <http://www.otg.usyd.edu.au>) is located in the University of Sydney, Australia and is involved in studying and promoting its "Photosynthetic Greenhouse Gas Mitigation" approach, also referred to as "ocean nourishment", under the leadership of Ian S.F. Jones. The group is interested in the prospects of fertilization to induce a phytoplankton blooms that could be manipulated for engineering a large-scale fishery or for carbon sequestration (Jones and Otaegui, 1997; Jones and Young, 1997). OTG is also involved with the Earth Ocean & Space Pty Ltd, a company that develops greenhouse gas mitigation technology. OTG has recently approached offshore oil and gas companies, proposing the use "stranded" natural gas reserves and a possibly floating industrial facility to manufacture and pump ammonia fertilizer for carbon sequestration via "ocean nourishment" (Jones and Young, 2000). The cost estimate for sequestration, including capital expenses, was \$7/t CO₂ avoided²⁶ (i.e., \$30/t C).

Building on the hypothesis that nitrogen is usually the most important limiting factor in most Southern hemisphere marine ecosystems, Jones' group has designed a system to deliver "reactive nitrogen" (ammonia) to surface ocean zones to boost biological productivity (Jones and Otaegui, 1997). The patented (see Appendix A for patent number) technological set up (see Figure 5) proposed by OTG includes a terrestrial facility that pumps an aqueous solution containing

²⁴ This corresponds to 600,000 – 2,000,000 t CO₂.

²⁵ John Martin is the father of the Iron Hypothesis that was tested by the IRONEX, SOIREE and EISENEX experiments in the years after his death.

²⁶ Given the large uncertainties, we do not distinguish between CO₂ (or carbon) "avoided" and CO₂ sequestered. In general, the quantity of carbon emissions "avoided" is typically less than the amount of carbon "captured", because the quantity of CO₂ avoided accounts for additional emissions during capture.

dissolved ammonia through a pipeline extending out to the edge of the continental shelf (Jones and Otaegui, 1997). Satellite monitoring of productivity in fertilized areas is an important component of OTG's "ocean nourishment" system, using color imaging to detect chlorophyll-a, presumably as an indicator of carbon "export". OTG has claimed that the nitrogen can be supplied with a 70% uptake efficiency and - using the Redfield ratio - that 1 t N, supplied as ammonia fertilizer could increase "new production" by 5 t C with potential benefits for fisheries and carbon sequestration (Jones and Young, 1997).

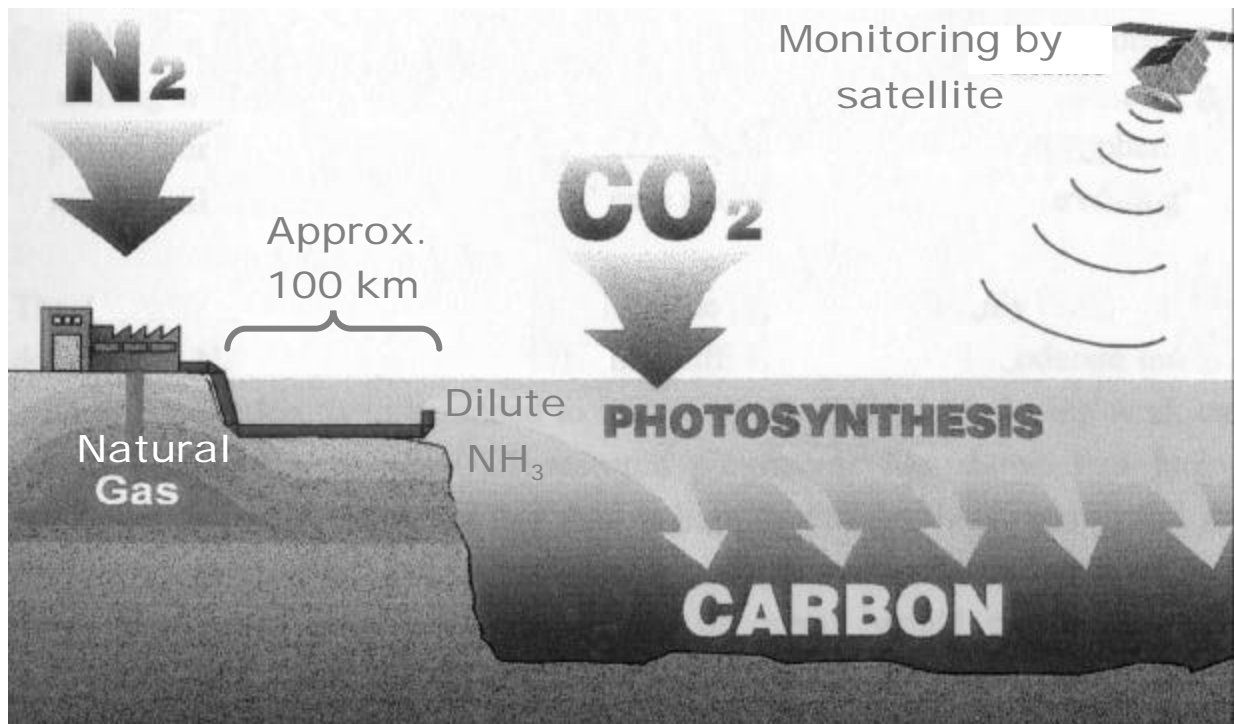


Figure 5. Schematic of the OTG "ocean nourishment" system {modified from (Heddle, 1999)}. Atmospheric nitrogen gas is converted to ammonia through an energy intensive industrial process, and pumped into coastal waters for the purpose of increasing productivity.

In 2000, a report describing plans of "nourishing" upwelling waters²⁷ off the coast of Chile drew media attention, and sharp criticism, to the activities of the OTG (Pearce, 2000). Jones' stated objective was to earn saleable carbon credits for the Chilean government under some emissions trading regime by removing carbon from the surface waters as the sinking wastes and remains of fish and plankton. However, continuous fertilization with ammonia does not mimic upwelling systems well, despite the claim of OTG to the contrary (Jones and Young, 2000). As discussed earlier, upwelling systems typically receive "pulsed" nutrient inputs from the deep ocean in Redfield ratios that match the proportion in which phytoplankton blooms use nutrients on average (Chisholm, 1995). This explains why primary production per unit area is up to 6 times higher in upwelling regions than that in the open sea (Table 7) and about 3 times higher than in typical coastal water (Ryther, 1969), which also tend to be nitrogen-rich due to inputs from

²⁷ Upwelling zones that receive nutrient-rich, deep-ocean waters occur off the coasts of 1) California 2) Peru and Chile 3) NW Africa 4) SW Africa and 5) land masses in the Arabian Sea.

runoff, precipitation and anthropogenic effluents. Even if coastal upwelling regions are limited by nitrogen, if N is supplied they will soon be limited by phosphorus. Hence, it is likely that further nitrogen enrichment, as proposed by OTG for the nutrient-rich Chilean upwelling zone (Pearce, 2000), would mostly likely yield only marginal increase in new production. Similarly, in the sub-tropical gyres, where primary production is usually nitrogen-limited²⁸, fertilization with only nitrogen addition is unlikely to be effective, because the stocks of phosphorus and iron would be quickly consumed following fertilization. Moreover, ammonia can increase the alkalinity of seawater, thus shifting the carbonate equilibrium against CO₂ dissolution further reducing the carbon uptake efficiency²⁹ of such fertilization (Mearns, 1999).

Table 7. Average Values of Gross Primary Productivity for Different Parts of the World Ocean {Data from Smith and Hollibaugh (1993) as cited in Duxbury et al (2000)}.

Area	Average Productivity (gC/m ² /yr)	World Ocean Area (% of total area)
Upwelling Zones	640 +/- 150	0.1
Coastal Ocean	160 +/- 40	15
Open Oceans	130 +/- 35	85
All Ocean Areas	135	100

The continuous supply of nitrogen proposed in Jones' method more closely resembles nitrogen inputs into coastal waters from ground water or atmospheric deposition, which bypass the estuarine filters (Paerl, 1997), than it does coastal upwelling. Increasing productivity, driven by external nitrogen inputs and nitrogen recycling in shallow waters, and high organic matter sedimentation rates in shelf seas (similar to the North Sea) or over continental slopes (similar to that off the North Carolina coast) will likely be accompanied by correspondingly high levels of denitrification (Hydes et al., 1999). The processes of nitrification, denitrification and nitrate uptake, all produce nitrous oxide (N₂O) as a by-product. Not only is an N₂O molecule 250 times more potent a greenhouse gas than a CO₂ molecule, but it also attacks the stratospheric ozone layer (IPCC, 1994). In the event of hypoxia, similar to the infamous, annual "dead zone" in the Gulf of Mexico and elsewhere around the world³⁰, denitrification would intensify and possibly be exacerbated by the production of methane (CH₄), 20 times more potent a greenhouse than CO₂ (IPCC, 1994), from the anaerobic microbial degradation of organic matter (Fuhrman and Capone, 1991). Denitrification is likely to increase even if the bottom waters have near-saturation levels of dissolved oxygen (Jahnke and Jahnke, 2000). Nutrient discharges and other pollution continue to dramatically alter coastal microbial communities around the world (Paerl, 1998). Similarly, it is likely that populations of marine denitrifying bacteria would respond to a sustained increase in the supply of nitrogen, to eventually diminish any benefits of fertilization that could be observed. Model predictions suggest that the marine fluxes of key elements such

²⁸ Although nitrogen-fixation can be a large source of N in the North Pacific (Karl, et al., 1997).

²⁹ Defined as the change in carbon uptake per unit change in macronutrient concentration.

³⁰ Similar problems of low dissolved oxygen and harmful algal blooms have occurred in Chesapeake Bay, the Baltic and Black Seas, and coastal oceans off Japan, Australia and New Zealand (Duxbury, 2000).

as nitrogen and carbon would not revert to their “pre-fertilization” states for several centuries following the termination of a century-long macronutrient fertilization program (Matear, 1999).

Jones would like to promote the “nourishment” approach for use by “Low Income Food Deficient” countries with a “suitable coastline” as a means to alleviate food deficiency (Jones and Young, 2000). However, excessive nutrient inputs into the upwelling ecosystem may change it fundamentally, potentially destroying the economic value derived by local populations. For example, Chile’s economy is highly dependent upon coastal fisheries (CIA, 1999) and it would be especially unfortunate if Jones’ proposed “nourishment” activities (Pearce, 2000) were to induce blooms of toxic algae or hypoxia in that productive ecosystem.

Ocean Carbon Science: Distributed Fertilization

Ocean Carbon Science, Inc. (OCS; formerly Carboncorp; <http://www.rsrch.com/carboncorp/>) is a company led by Russ George and Robert Falls³¹ promoting the concept of releasing small amounts of limiting nutrients, such as iron and/or a combined fertilizer, from commercial ocean liners that routinely traverse shipping lanes on the high seas³². The main selling point is the prospect of canceling out most or all of a ship’s emissions producing a “bankable carbon offset credit”, while achieving economies of scope and scale by eliminating the high cost of centralized distribution of nutrients. The grand vision of an OCS set-up includes centralized, automated, satellite-linked operation of the numerous ship-mounted sensors and nutrient-discharge modules. The release of nutrients would be activated from OCS headquarters when a ship’s position intersected with a “plankton domain”, stimulating an “immediate plankton bloom” in the ships’ wakes. Following the discussion of this climate-change mitigation approach at a scientific meeting in March 1999 (Cullen and Chisholm, 2000), the company’s web site was closed to all but approved users. From a reading of the general introduction text, the fertilizer would most likely be a micronutrient mixture containing iron³³. Whereas OCS claims that “scientific oceanographic teams” would “document and certify” the carbon credits, it would be virtually impossible to assign verifiable OCS “credit” for carbon sequestration to any single iron discharge, especially along busy shipping lanes, because field experiments have shown that the rate and intensity of marine phytoplankton response to nutrient addition in the open ocean is dependent upon highly variable environmental conditions.

The duPont Method: Gradual Release of Nutrients from Synthetic Substrates

In 1999, scientists at E. I. du Pont de Nemours and Co. (Edward Howard Jr. and colleagues) were awarded a patent for a delivery mechanism, primarily for iron as a nutrient, to stimulate marine phytoplankton growth (See Appendix A for patent number). Specifically, the patent is for encasing transition metals such as iron, cobalt, manganese and zinc into a floating matrix made up on polymeric foam, hollow glass or cellulose. The nutrient mixture would be attached to the “float” with a water-soluble adhesive to affect a gradual release of the nutrients for the explicit purpose of “increasing oceanic plankton biomass and / or decreasing atmospheric carbon

³¹ We were unable to elicit a response from either R. George or R. Falls regarding the status of Carboncorp and their exact roles with respect to that company.

³² The high seas are comprised of ocean areas that lie outside any national territorial jurisdiction (UNCLOS 1994).

³³ In its now defunct website, Carboncorp had claimed a patented nutrient supplement to stimulate plankton blooms. As of May 2001, no such patent information was found in the US Patent and Trademark Office database.

dioxide”. The du Pont process entails the application of a “very large” amount of material by blowing it off a barge or dropping it from a cargo plane.

There is no discussion of potential ecological effects, which could be substantial, of the tiny irregularly shaped residual “substrate”. Additionally, local, national or international anti-dumping laws may preclude the large-scale use of such floating materials.

UNRESOLVED SCIENTIFIC ISSUES

The challenges facing us in evaluating commercial ocean fertilization for carbon sequestration fall under three main categories:

1. *Extrapolation of Results*: Commercial fertilization proposals must extrapolate results from short-term (days-weeks), small (about 100 km² or smaller) field experiments to long-term (centuries), large (greater than 100,000 km²) operations. Or they must try to evaluate the cumulative effects of many small fertilization implementations.
2. *Verification of Carbon Sequestration*: Measurement and prediction of the amount of carbon exported to ocean depths as a result of fertilization with any degree of certainty is at present impossible even in field experiments, let alone over vast expanses of ocean.
3. *Ecological Monitoring*: It is not yet possible to measure subtle but potentially damaging changes in ecosystem states in either a precise manner or in real time. Long-term manipulation of marine ecosystems may fundamentally and permanently alter the cycling of nutrients and functioning of food webs.

Extrapolation of Results

The dramatic results from the IRONEX-II experiment in 1995 established the power of iron-addition to stimulate phytoplankton blooms (Coale et al., 1996). Furthermore, it was found that—at least in the short term - iron addition also altered the planktonic species composition preferentially, stimulating growth of large-celled phytoplankton (> 10 micrometer), which are more likely to sink to the ocean bottom (Cavender-Bares et al., 1999). Increased photosynthetic activity (due to higher chlorophyll content overall) increased the fixation of carbon by the phytoplankton. Phytoplankton responded very quickly to iron addition, with increases in growth rate and chlorophyll concentration occurring within 24 to 48 hours (Cavender-Bares et al., 1999; Coale et al., 1996; Flynn and Hipkin, 1999). The effects of fertilization were undetectable several weeks after the conclusion of the IRONEX experiments, but it cannot be guaranteed that conditions would simply and quickly revert to their original states immediately following the termination of a large-scale, long-term fertilization program³⁴. For example, a lingering decline in production may (or may not) persist several months following the end of fertilization (Gnanadesikan et al., 2001).

Moreover, field experiment results cannot be extrapolated to predict the ecosystem responses, including carbon export, for large-scale implementations, or for the cumulative impact of many small-scale implementations. The field experiments done to date were designed to examine a specific process, i.e., effect of iron on phytoplankton in a small patch of nutrient rich water. The duration of the experiment was very short and it is not possible to make reliable predictions on the long-term effects of iron fertilization. As proponents of large-scale demonstration

³⁴ Markels quoted in the article by Graeber (2000): ‘... (if) anything goes wrong, he'll simply pull the plug. Without his iron pills, the phytoplankton bloom would “shut down in 20 days.”’

experiments correctly point out, these experiments provide no insights into carbon export following the fertilization of a vast area wherein multiple key variables are acting upon the system simultaneously. However, even if the desired response, i.e., carbon export were to be fully quantified in a large-scale experiment (e.g., thousands of sq. km), the results still would not be scalable. They would be specific to the prevailing conditions during that experiment and could not be generalized for carbon export under all conditions (Huston, 1999). When one is dealing with a complex self-organizing system such as the ocean ecosystem, there are always certain things that are unpredictable, no matter how much one knows about how the system works at any point in time on a local scale.

An additional layer of complexity is added by the fact that the Greenhouse Effect is warming the ocean (Barnett et al., 2001; Levitus et al., 2001), which will change patterns of precipitation. Greater precipitation in the high latitudes will make the polar waters less salty and, hence, less likely to sink (Manabe and Stouffer, 1994; Sarmiento et al., 1998). If stratification between the upper ocean and deep water intensifies, the vertical exchange of CO₂ and other nutrients would decrease. Thus, ocean stratification would not only strand more CO₂ emissions in the atmosphere, reinforcing the Greenhouse Effect, but also change nutrient cycling with unpredictable consequences to the biological pump, and the ecology of the surface oceans.

The Problem of Verification

It is extremely important to note that carbon *uptake* is not same as carbon *export*. The amount of carbon “exported” (or sequestered) per ton of added fertilizer would be *much lower* than that estimated from C:fertilizer ratios because:

1. Losses of iron-fertilizer occur due to subduction by water masses and the sinking of aggregated colloidal particles (Martin et al., 1994).
2. Variable light conditions are common on the high seas and Fe requirement for phytoplankton increases under low light conditions (Maldonado et al., 1999; Sunda and Huntsman, 1997).
3. Bacterial populations in HNLC waters also suffer from iron-deficiency and could consume a significant fraction of the fertilizer (Maldonado and Price, 1999; Schmidt and Hutchins, 1999).
4. Grazing pressure from predatory heterotrophs will increase rapidly in response to the increased prey density (Cavender-Bares et al., 1999; Denman and Pena, 1999; Lancelot et al., 2000; Leonard et al., 1999). Therefore, most of the carbon taken up by phytoplankton is released back into the surface waters as zooplankton feed on the phytoplankton.
5. Whereas blooms of large diatoms (>10 micrometers) are not usually controlled by zooplankton grazing (Arrigo et al., 2000; Cavender-Bares et al., 1999; de Baar and Boyd, 2000; Hutchins et al., 1999), the sinking of large diatom aggregates from the surface shrinks the phytoplankton population. Hence, absolute rates of nutrient uptake will be limited by first order phytoplankton growth rates (Martin et al., 1994), while the fraction of dissolved iron lost to colloidal aggregation (see above) would increase with time.

There is no direct evidence indicating increased carbon export occurs following the stimulation of primary production by iron fertilization (Charette and Buesseler, 2000; Ridgwell, 2000). Quite to the contrary, during the SOIREE experiment, the rate of carbon export within the iron-

fertilized area was lower than that outside (Boyd et al., 2000). The extent of CO₂ uptake from the atmosphere would depend upon vertical mixing rates in the ocean, which can be significant in the HNLC Southern Ocean. The rates of decomposition, transformation and recycling of particulate and dissolved organic matter in the approx. 100-1000 meter depth zone are other critical unknowns regarding the biological pump (Karl et al., 2000).

Drawdown of dissolved CO₂ in surface waters by a phytoplankton bloom may be largely replaced by the equilibration of dissolved CO₂ between the fertilized area and adjoining water masses (Orr and Sarmiento, 1992; Peng and Broecker, 1991a). In other words, the impact on atmospheric CO₂ could be small even if fertilization results in substantial export of carbon. Another factor that might reduce the sequestration benefits of fertilization is the stimulation of certain phytoplankton that produce calcium carbonate (Matear, 1999). Greater export of carbonate would shift the equilibrium of CO₂ in water against the dissolution of atmospheric CO₂.

For all these reasons, it is imperative that life cycle GHG assessments are conducted to establish the net GHG benefits (or losses) that might result from the implementation of commercial proposals. There are other arguments for considering a “systems view” of ocean fertilization:

The dissolved oxygen in ocean water is, on average, just sufficient for the decomposition of the resulting organic matter (Lenton and Watson, 2000). Hence, intense plankton blooms due to sustained, large-scale ocean fertilization could induce hypoxia large regions of the ocean as aerobic bacteria in the underlying water column continuously decompose the sinking dissolved and particulate organic compounds (Sarmiento and Orr, 1991). Anoxic conditions may suffocate or displace other marine life, altering large ecosystems profoundly. Moreover, as discussed earlier, low oxygen conditions in nitrogen rich areas would facilitate the evolution of potent greenhouse gases such as methane and nitrous oxide³⁵ that would counteract the carbon sequestration benefits of fertilization (AFP, 2001; Fuhrman and Capone, 1991).

In contrast, as primary production increases, the evolution of dimethyl sulfide (DMS) by phytoplankton may be promoted (Turner et al., 1996; Yang et al., 2000). It is argued that DMS may serve to mitigate the greenhouse effect by promoting the production of cloud-forming aerosols (Lovelock, 1990), thus representing a potential bonus of fertilization.

Ecological Monitoring

In the Southern Ocean, diatoms may contribute more than 90% of primary production during ice-edge blooms (Nelson and Smith, 1986). New evidence from the Ross Sea in the Southern Ocean shows efficient and significant carbon export also by other kinds of phytoplankton in the event of structural shifts in the phytoplankton community away from diatom dominance (DiTullio et al., 2000). Phytoplankton communities exhibit a range of regular and irregular variability in bloom dynamics and species distributions at various times scales. It has been hypothesized that it is not only the multiplicity of simultaneously active factors in the pelagic zone, but also site-specific,

³⁵ Global warming potentials of CH₄ and N₂O are about 25 and 250 times greater than that of CO₂, respectively (IPCC 1994). In other words, one kilogram of these CH₄ and N₂O causes 25 and 250 times more global warming than a kilogram of CO₂ over a period of 100 years.

annual shifts in dominance among those factors that renders the quantification of variability a truly daunting task (Smayda, 1998). Therefore, it is difficult to distinguish specific effects of anthropogenic influences in the pelagic zone from the erratic “baseline” to assign causality.

Transitions between ecosystem states occur naturally and reversibly. For example, the influx of nutrients in coastal upwelling regions can catapult stable, “recycling” plankton communities dominated by smaller phytoplankton into a “bloom and export” state that is dominated by larger cells (de Baar and Boyd, 2000). However, once their inherent resilience is overwhelmed, ecosystems tend to shift to a new “stable state”, with fundamentally different distribution of species, processes and responses relative to the original ecosystem state³⁶ (Gunderson, 2000). Precise knowledge of ecological thresholds is currently scarce, making it impossible to exert robust control over even small ecosystems.

Although applications of new techniques in molecular biology are allowing us to describe the diversity of plankton communities in a way that was never possible before, we still cannot culture 99% of the species that comprise the plankton in the ocean, and we do not know what regulates their relative abundances. More importantly, we do not understand the relationship between the *structure* of the community -- that is the species composition -- and its *function* in the biogeochemical cycles of the oceans. We do know that when we change the structure, as we do when we fertilize, we will change the function in unknown ways. We have to accept that as a given if we embark on large-scale ocean fertilization. We can't change the carbon cycle without changing all of the cycles that are coupled to it, and some of these changes could be very undesirable in terms of climate mitigation.

Key Topics for Future Research

Current challenges in marine biogeochemical modeling, which are critical to understanding the ocean carbon cycle, include continuing improvements in the understanding of multi-element cycling and community structure, large-scale physical circulation, mesoscale space and time variability, and mass exchange between marine, terrestrial and atmospheric reservoirs (Doney, 1999). In setting research priorities for future fertilization research it is useful to first identify the key scientific issues that would influence policy decisions on this topic. Table 8 summarizes some of the policy-relevant uncertainties that were discussed in preceding chapters and are categorized here according to relative degrees of confidence. *It is important to note, however, that the uncertainties identified here for assessing the impacts of ocean fertilization represent fundamental uncertainties in our understanding of ecosystem dynamics, and the role of the oceans in the global carbon cycle. Advances in both of these basic research areas are critical to understanding past, present, and future climate regulation, and should be fostered regardless of whether or not we think we should try to mitigate climate change through ocean fertilization.*

³⁶ Gunderson writes: “In 1973, C. S. Holling (defined ecological resilience) as the amount of disturbance that an ecosystem could withstand without changing self-organized processes and structures (defined as alternative stable states). Other authors consider resilience as a return time to a stable state following a perturbation. ... Two definitions recognize the presence of multiple stable states (or stability domains), and hence resilience is the property that mediates transition among these states.”

Table 8. Qualitative ranking of some policy-relevant uncertainties regarding ocean fertilization.
NOTE: Where the fertilizing nutrient– iron or nitrogen– is specified, the scientific results or uncertainties are applicable only for iron fertilization or ammonia fertilization, respectively.

ALMOST CERTAIN	MORE LIKELY THAN NOT	HIGHLY UNCERTAIN
<p>Higher rate of overall primary production – i.e., the rate at which CO₂ is converted into biomass -- following iron fertilization in HNLC areas ^a. Accompanied by increased abundance of large-celled phytoplankton species, most probably diatoms ^b, leading to...</p>	<p>Iron fertilization in the Equatorial Pacific would not yield substantial net “export” of organic carbon. ^{g,h}</p>	<p>Claim that iron fertilization in Southern Ocean could sequester 50 to 150 Gt C over 100 years (i.e., less than 17% of emissions under an IPCC "business as usual" scenario). ^{g,h}</p>
<p>Changes in phytoplankton species composition, which would change the food-web structure (i.e., fish, birds and whale species) ^c, leading to...</p>	<p>Iron fertilization in Southern Ocean might cause a 30 to 70% reduction in tropical marine primary production. ^h</p>	<p>Fate of atmospheric CO₂ uptake by the ocean. ^k (Note: “carbon uptake” by phytoplankton is not the same as “carbon export”. All CO₂ that is taken up could be returned to the atmosphere in a short time.)</p>
<p>Decreased biodiversity compared to the “natural” state, with rare species becoming dominant. ^d</p>	<p>Hypoxia/anoxia in the mid- to deep ocean as DOC/POC is decomposed downstream. ^{g,i}</p>	<p>Changes in the transformation of POM/DOM in the mid- to deep ocean and its effect on residence time of sinking carbon. ^l</p>
<p>Dependence of diatom growth rate not only upon availability of Si and other nutrients (e.g., N and P) at certain minimum concentrations and in specific, “Redfield” ratios, but also a favorable light/mixing regime. ^e</p>	<p>A change in net flux of greenhouse gases (i.e., CO₂, DMS, CH₄ and N₂O) between ocean and atmosphere due to fertilization. ⁱ Increased inventory of organic carbon and/or nitrogen would change the structure of the microbial communities that produce these gases. ^j</p>	<p>Trophic cascades and ecosystem resilience: the magnitude and permanency of impact upon the “food web” and other ecosystem processes.</p>
<p>Changes in the nitrogen cycle and increased evolution of N₂O (a byproduct of denitrification), following the discharge of industrially fixed NH₃ into the ocean. ^f</p>	<p>Ammonia toxicity may occur if nitrogen fertilizer is discharged into coastal upwelling zones (according to the OTG proposal).</p>	<p>The timing and effect of global warming on ocean circulation and nature of marine ecosystem response(s) to ocean fertilization.</p>

References for Table 8:

a Martin et al., 1994; Coale et al, 1996; Boyd, et al., 2000; Smetacek 2000. **b** de Baar, 2000. **c** Cavender-Bares et al., 1999. **d** Dodson et al., 2000. **e** Redfield, 1934; Dugdale & Wilkerson, 1998; Turner et al., 1998; Pondaven et al., 1999; Lanceot et al., 2000. **f** Hydes et al., 1999; Jahnke & Jahnke, 2000. **g** Sarmiento & Orr, 1991. **h** Gnanadesikan et al., 2000; Gnanadesikan et al., 2001. **i** Fuhrman & Capone, 1991. **j** Paerl, 1998. **k** Charette & Buesseller, 2000; Ridgwell, 2000. **l** Karl et al., 2000.

The OCTET³⁷ (Ocean Carbon Transport, Exchanges and Transformations) report summarizes the proceedings of the OCTET Workshop held at Airlie House, Warrenton, VA, in March, 2000. The workshop groups identified key areas for research and recommended approaches to improve scientific understanding of the ocean carbon cycle — past, present and future. From that report, we have excerpted research questions that are especially important to policy-making on the issue of ocean fertilization as a carbon sequestration option.

Some specific areas for improvement with respect to carbon cycling include (Emerson et al., 2000):

1. the rates and mechanisms of particulate and dissolved organic matter degradation, including the differing rates of remineralization of micronutrients (e.g., Fe) and macronutrients (e.g., P, N, and C);
2. the rates and mechanisms of particulate inorganic carbon (PIC) production and dissolution;
3. rates of mixing and subduction in the upper ocean

Unanswered questions regarding the biological pump include, (Ducklow et al., 2000, Karl et al., 2000):

1. What is the strength of the biological pump and how does it differ between biogeographical provinces? How do we most accurately measure its strength?
2. How does the structure and composition of the biological pump change in space and time? How might community structure affect it, and what is the importance of selected functional groups (e.g., nitrifiers, calcifiers, large grazers)? What are the relative roles of the microbial and zooplankton communities?
3. What is the sensitivity of the biological pump to perturbations in forcing (upwelling, dust and Fe deposition, North Atlantic Oscillation, El Niño)? How do we quantify this variability (e.g., time series).
4. How will the biota respond to warming, chemical changes (DIC, pH), and physical changes to the habitat such as enhanced stratification?
5. What are the important processes (N₂ fixation, Fe limitation, etc.) that prevent a simple relationship between net or total production of ecosystems and the nutrient concentrations of the ambient waters?
6. What are the time and space varying processes in the mesopelagic zone (100 to 1000 meters) that control the recycling and gravitational flux of carbon?
7. Would changes in vertical mixing result in changes in primary and export production via changes in N and P delivery or in light supply? What fraction of the total export is delivered from the spring bloom and will it change?
8. How will changes in total and export production be reflected in partitioning among DOC, DON, DOP and their particulate counterparts?

³⁷ OCTET is a planning initiative to promote research on the global carbon cycle, with a focus on ocean carbon dynamics. For more information see <http://alpha1.msrc.sunysb.edu/octet>.

9. How is export production related to the balance of various biological processes (nitrogen fixation, denitrification, and calcification), and how will the relationship change?
10. How do changes in mixing and stratification result in changes in plankton community structure during and following the spring bloom (e.g., dominance shift from diatoms to picoplankton and from large crustacean grazers to microzooplankton)?

Some key modeling issues include (Doney and al., 2000):

1. What are the tradeoffs between measurements of extensive (e.g., satellite chlorophyll) and intensive (e.g., size class structure; grazing rates) properties?
2. How best can one define the dynamic relationships among the ecosystem variables such that assimilation of one observable quantity (e.g., chlorophyll) projects onto other, unobserved ecosystem compartments (e.g., bacterial and zooplankton biomass)?
3. How can results of small process-oriented studies be extrapolated to larger scales?

These basic questions regarding the role of the oceans in the global carbon cycle should give us pause as we consider large-scale fertilization. It is clear that we have just begun to scratch the surface in understanding this system. If we go forward with large-scale manipulation of the system, we will have to do so blindly.

THE POLICY CHALLENGE

Decision-makers involved in formulating an appropriate policy response to the emergence of fertilization as a carbon sequestration option should consider not only the scientific uncertainties, but also matters of national and international law. Given the economic and cultural importance of healthy marine ecosystems and the long-term nature of potential consequences of large-scale fertilization it is essential that policy analysts weave the overarching principles of sustainable development into their policy recommendations. Here we discuss some pertinent legal and ethical considerations.

International Agreements on Marine Conservation and Protection

Whereas the growing problem of coastal eutrophication has prompted various national laws and international agreements to control the deliberate efflux of nutrients into coastal seas, there are no direct legal precedents for ocean fertilization in the open ocean. It is possible to divide the relevant treaties into two general categories: those that generally promote further research and development into the exploitation the ocean through the use of fertilization, and those that may serve to regulate the deployment of these technologies. The various Fisheries Conventions, overseen by different UN agencies, and the UNFCCC belong generally to the former category; while UNCLOS, the London Convention (especially the 1996 protocol amendment) (UN, 1972), the Multilateral Environmental Agreements for the Antarctic (UN, 1980; UN, 1991), the Convention on Biological Diversity (UN, 1992b) and the Kyoto Protocol fall generally into the latter category.

At the international level, the United Nations Organization (UNO) has served as an important forum for addressing environmental problems of global scope. The United Nations Division for Ocean Affairs and the Law of the Sea (DOALOS) is a focal point for international dialogue relating to stewardship of the oceans. The International Marine Organization (IMO) administers the London Convention on illegal dumping at sea and deals with global problems of vessel-source pollution. Therefore, it appears that the IMO would be also a suitable candidate for an organization that would safeguard the integrity of commonly held property rights over the high seas.

The UNFCCC urges nations to seek ways to mitigate the effects of global climate change expeditiously and inexpensively— without dallying to develop the most scientifically sound solution -- and allows the classification of the oceans as a potential sink for CO₂ to be developed as such. The now imperiled Kyoto Protocol to the UNFCCC, however, does not include the oceans in its list of permitted carbon sinks. It is not clear if the exclusion of the ocean as a sink would make it more expensive for some countries to reduce future GHG emissions. It also remains to be established if and what role the 1972 London (Anti-dumping) Convention and 1996 Protocol to the London Convention may have in regulating carbon sequestration. Specifically, two open questions regarding the legal definition of “wastes” are:

1. Would fertilizer packaging substrates (such as that being developed by GSV and duPont) be classified as a pollutant under the London Convention?

2. Would anthropogenic carbon dioxide be classified a “waste”, since it is derived substantially from an atmosphere “polluted” with anthropogenic emissions? And if so would the process of fertilization to sequester CO₂ be considered “dumping”?

It is of the highest importance that a coherent set of science policy guidelines be established to govern the deployment of the proposed technologies. An analysis of the effectiveness of prior treaties yields some important principles that may reinforce the likelihood of success of future treaties aimed at the protection of marine ecosystem integrity {based upon arguments presented in (Birnie, 1996; Lyster, 1996)}:

1. The rights of governance should be vested in an international body over (1) all living resources in the high seas (e.g., building on the precedent of the International Whaling Commission) and over pollution from operations on the high seas (e.g., by expanding the scope of the International Seabed Authority under UNCLOS).
2. Issues of jurisdiction and sovereignty are often hurdles to enforcement of international agreements on the high seas³⁸. One approach to improve enforcement is the adoption of “private law” provisions allowing private organizations of signatory states to be held financially liable for ecological damage. Alternatively, “public law” provisions³⁹ may be adopted to allow individual states to act directly against ships registered under foreign flags.
3. A full-time, well-funded secretariat is essential to the successful implementation of any treaty, because it provides a “neutral” forum for coordinating stakeholder interactions, and overseeing the collection and evaluation of relevant scientific data critical to decision-making and enforcement (e.g., the services provided by IMO to States, NGOs and international shipping companies.)
4. Selection of an appropriate voting procedure is the key to efficiency in formulating effective multilateral agreements within international organizations. Consensus building as a means for decision-making in many large international bodies often results in the dilution of the effectiveness of proposed measures⁴⁰. In contrast the use of “tacit amendment procedures”, which have been standard procedure for IMO conventions since 1972, require explicit *dissent* to stop automatic approval. Thus, the procedure penalizes diplomatic foot-dragging and provides clear incentives for timely and meaningful participation by stakeholders.
5. Treaties for the conservation of marine resources and coastal habitat should emphasize preservation of ecological integrity of marine habitat, rather than on banning all human exploitation of living resources⁴¹. The wise use of ecological goods and services can keep stakeholders connected to shared resources.

³⁸ E.g., the failure of 1980 UN Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) to curb over exploitation of fisheries.

³⁹ Such as those in certain International Marine Organization (IMO) agreements.

⁴⁰ E.g., the failure of the Convention on Conservation of Antarctic Marine Living Resources (UN, 1980) to regulate excessive fishing in the Antarctic.

⁴¹ E.g., the 1971 Ramsar Convention on “wise use” of wetlands.

An Intergenerational View of the Oceans

There is some worry that the legal vacuum regarding the rights on the high seas and historically weak enforcement could lead to a “carbon-rush”, with various entrepreneurs commandeering vast patches of ocean water for implementing their patented fertilization methods. The unregulated proliferation of large-scale fertilization schemes could ultimately lead to a situation analogous to the “Tragedy of the Commons” scenario (Hardin, 1968), wherein the chemistry and biology of marine ecoregions are altered significantly from their current state, ultimately leading to detrimental consequences for all stakeholders.

Most scientists believe that large-scale fertilization projects in the open ocean are neither ecologically acceptable, nor likely to be economically rewarding in the long run (Chisholm, 2000; Sarmiento, 1996). If returns on investment in large-scale ocean fertilization appear attractive, it is often only due to the externalized costs borne by the greater environment -- the ocean Commons. It is commonly observed that heavy subsidy of energy and materials may be required to sustain large, managed ecosystems (Christensen et al., 1996) such as those proposed by the proponents of ocean fertilization.

In its report on ecosystem management, the Ecological Society of America (Christensen et al., 1996) provides a framework for the following consideration of ethical issues with respect to intergenerational sustainability and the future use of oceans (See Box 1 below).

Box 1. Guidelines for Decisions Regarding Ocean Ecosystem Management {Modified from Ecological Society of America Report (Christensen et al., 1996)}:

1. Long-term sustainability as a fundamental value.
2. Clear, operational goals stated in terms of desirable “states” of ecosystem components.
3. Sound ecological models and understanding of relevant processes and functions.
4. Appreciation of essential complexity and interconnectedness.
5. Recognition of the dynamic character of ecosystems.
6. Attention to context, scale and stakeholders.
7. Acknowledgment of humans as ecosystem components.
8. Commitment to adaptability and accountability informed by effective monitoring programs.

True sustainable development is not achievable without the harmonization of human activity with the assimilative and regenerative cycles of the ecosystems upon which the sustainable development of human existence depends. By nature of their processes, goods and services (Box 2), marine ecosystems represent a true economic value greater than the sum of their structural components alone (Constanza et al., 1997). Biological diversity and structural complexity of ecosystems are critical to such processes as primary production and nutrient cycling and the natural dynamics of ecosystems play out at rates that preserve complexity and diversity. Complexity and diversity also impart resistance to and resilience from disturbance, and provide

the genetic resources necessary to adapt to long-term environmental change (Christensen et al., 1996).

Box 2. Marine Ecosystem Goods and Services⁴². {Adapted from (Christensen et al., 1996)}

Ecosystem processes include:

- Hydrologic flux and storage
- Biological productivity
- Biogeochemical cycling and storage
- Decomposition
- Maintenance of biological diversity

Ecosystem "goods" include:

- Food
- Medicinal plants
- Wild genes for domestic plants and animals
- Tourism and recreation

Ecosystem "services" include:

- Maintaining hydrological cycles
- Regulating climate
- Cleansing water and air
- Maintaining the gaseous composition of the atmosphere
- Pollinating crops and other important plants
- Generating and maintaining soils
- Storing and cycling essential nutrients
- Absorbing and detoxifying pollutants
- Providing beauty, inspiration, and research

Since uncertainty is inherent to complex natural systems, manipulations aimed at fundamentally altering the structure and function of biogeochemical cycling in marine ecosystems should be undertaken only with the greatest precaution (Huisman and Weissing, 1999). Indeed, the uncertainty with respect to the outcomes of ocean fertilization may actually increase as the scale and extent of fertilization is increased. For example, there is evidence that sustained fertilization increases ecosystem variability, and decreases predictability, in experimentally fertilized lakes (Cottingham et al., 2000). This implies that fertilization could not only destabilize ocean ecosystems, but also impair our ability to predict the consequences of global change.

⁴² Here, goods refer to items given monetary value in the market place, whereas the services from ecosystems are valued, but rarely bought or sold.

CONCLUDING REMARKS

There is no doubt that the problems of global warming must be addressed promptly and effectively, because to do nothing may be no more prudent than “leaping without looking” by choosing geoengineering solutions such as ocean fertilization. Policy makers should consider all options available for achieving the international goals embodied in the UNFCCC. There are legitimate concerns regarding likely effectiveness of the proposed fertilization approaches for capturing significant amounts of carbon dioxide from the atmosphere. More importantly, there are valid concerns regarding the unintended side effects of this procedure. Carbon sequestration in the ocean will involve large-scale and long-term manipulation of marine ecosystems.

Whereas environmental change and successional changes within ecosystems are inevitable, these cannot be used as arguments for arbitrary and capricious manipulation of the marine environment. Indeed, many of the formidable environmental problems confronting humanity are the result of moving substances between the geologic, atmospheric and hydrospheric reservoirs at ever-increasing rates over the past century. In this light, decision-makers should carefully consider the wisdom of supporting the proposed geoengineering approaches discussed in this paper. Many leading marine scientists support the position that, given the current lack of detailed mechanistic understanding of the biological pump, it is not appropriate to use empirical models, no matter how statistically sound it may appear, to make future predictions for large-scale manipulations of marine ecosystems (Karl et al., 2000).

Although one can easily make a compelling argument that ocean fertilization has no place in any responsible carbon mitigation strategy, it appears that the idea has enough momentum that arguments based on the precautionary principle may not prevail if global warming reaches levels sufficient to sound stronger alarms. Thus an argument can be made that parallels that of the US Department of Energy’s commitment to “science-based sequestration approaches” and to rigorously assessing their “environmental acceptability”. Concerns regarding the technical efficacy and ecological impacts of fertilization should be resolved first by a more thorough synthesis of disciplinary knowledge in the aquatic sciences, including input from ecologists and limnologists. Then, if the arguments are still not persuasive enough for sound decision-making *limited, scientific* testing of carbon sequestration methods may be justified. It should be noted that while issues of “science-based” policy making regarding fertilization may be pursued with greater success in developed countries, such arguments are harder to sustain for poorer nations. Lesser-developed coastal countries may be much more susceptible to experimenting with ocean fertilization methods in the hopes of boosting fish catches or acquiring a means to reduce the global warming impact of “dirty”, domestic industrial growth. Examples of such behavior are seen in the ocean fertilization agreement entered into by the government of the Marshall Islands (Markels, 1998a), and the proposal to “nourish” Chilean territorial waters (Pearce, 2000). It is important for scientists at leading research institutions in developed countries to initiate or intensify dialogue with their peers in the developing world regarding the ecological and economic implications of fertilization.

Carbon sequestration by any means should be recognized for what it is: nothing more than a partial, stopgap measure. “Partial”, because the amounts of CO₂ captured by fertilization (or other approaches) will not be sufficient to mitigate the potential for climate change. “Stopgap”, because the CO₂ that goes down into the ocean will eventually re-surface, though the timing will

depend upon ocean circulation and the duration of the fertilization program. Even if the “quick-fixes” for atmospheric GHG reduction such as ocean fertilization emerge as technically and economically viable options, there is a need for renewed political commitments to promote the adoption of “cleaner” energy systems, many of which have been studied intensively for over a generation now. If used appropriately, carbon sequestration may buy human societies a little time to help them make the necessary technological and cultural transition to a sustainable system of development, but sequestration is not a sustainable solution to the global warming problem.

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APPENDIX A: US PATENTS ISSUED FOR METHODS OF OCEAN FERTILIZATION

(Based on information freely available from www.uspto.gov)

PATENT NUMBER	<i>INVENTOR NAME</i>	TITLE	YEAR ISSUED
Application # 20010002983	Markels	Method of sequestering carbon dioxide with a fertilizer comprising chelated iron	Not yet issued
6,200,530	Markels	Method of sequestering carbon dioxide with spiral fertilization	2001
6,056,919	Markels	Method of sequestering carbon dioxide	2000
5,992,089	Jones, et al.	Process for sequestering into the ocean the atmospheric greenhouse gas carbon dioxide by means of supplementing the ocean with ammonia or salts thereof	1999
5,967,087	Markels	Method of increasing seafood production in the barren ocean	1999
5,965,117	Howard, et al.	Water-bouyant particulate materials containing micronutrients for phytoplankton	1999
5,535,701	Markels	Method for increasing seafood production in the ocean	1996
5,433,173	Markels	Method of increasing production of seafood	1995

Title: Method of sequestering carbon dioxide with a fertilizer comprising chelated iron.
Assignee: Markels, Michael JR. **Year:** Application filed in 2001
US Patent Application Number: 20010002983

Abstract: A method of sequestering carbon dioxide (CO₂) in an ocean comprises testing an area of the surface of a deep open ocean in order to determine both the nutrients that are missing and the diffusion coefficient, applying to the area in a spiral pattern a first fertilizer that comprises a missing nutrient, and measuring the amount of carbon dioxide that has been sequestered. The fertilizer preferably comprises an iron chelate that prevents the iron from precipitating to any significant extent. The preferred chelates include lignin, and particularly lignin acid sulfonate. The method may further comprise applying additional fertilizers, and reporting the amount of carbon dioxide sequestered. The method preferably includes applying a fertilizer in pulses. Each fertilizer releases each nutrient over time in the photic zone and in a form that does not precipitate.

Title: Method of sequestering carbon dioxide with spiral fertilization.
Assignee: Markels, Jr. **Year:** 2001
US Patent Number: 6,200,530

Abstract: A method of sequestering carbon dioxide (CO₂) in an ocean comprises testing an area of the surface of a deep open ocean in order to determine both the nutrients that are missing and the diffusion coefficient, applying to the area in a spiral pattern a first fertilizer that comprises a missing nutrient, and measuring the amount of carbon dioxide that has been sequestered. The application of the first fertilizer in a spiral pattern results in a patch of fertilizer where the concentration of the fertilizer does not vary by more than about 50% within two days of the local application. The concentration of the fertilizer at the center of the patch does not decrease through diffusion by more than about 5% during a time period of about 20 days after the application of the patch of fertilizer. The method may further comprise applying additional fertilizers, and reporting the amount of carbon dioxide sequestered. The method preferably includes applying a fertilizer in pulses. Each fertilizer releases each nutrient over time in the photic zone and in a form that does not precipitate.

Title: Method of sequestering carbon dioxide.
Assignee: Markels, Jr. **Year:** 2000
US Patent Number: 6,056,919

Abstract: A method of sequestering carbon dioxide (CO₂) in an ocean comprises testing an area of the surface of a deep open ocean in order to determine the nutrients that are missing, applying to the area a first fertilizer that comprises an iron chelate, and measuring the amount of carbon dioxide that has been sequestered. The method may further comprise applying additional fertilizers, and reporting the amount of carbon dioxide sequestered. The

method preferably includes applying a fertilizer in pulses. Each fertilizer releases each nutrient over time in the photic zone and in a form that does not precipitate.

Title: Process for sequestering into the ocean the atmospheric greenhouse gas carbon dioxide by means of supplementing the ocean with ammonia or salts thereof.

Assignee: Jones, et al. **Year:** 1999

US Patent Number: 5,992,089

Abstract: The present invention provides a method for removing CO₂ from the atmosphere. The method comprises the step of delivering a source of nitrogen to the mixed layer of the ocean to cause an increase in the number of phytoplankton in the mixed layer and thereby increase the amount of photosynthesis carried out by the phytoplankton. The source of nitrogen is delivered to the mixed layer at a location where an ocean current will carry the source of nitrogen and phytoplankton over a region of the ocean having a depth sufficient to allow dead phytoplankton and organic material derived from the phytoplankton to fall from the mixed layer and enable carbon originating from the CO₂ to be sequestered from the atmosphere.

Title: Method of increasing seafood production in the barren ocean.

Assignee: Markels, Jr. **Year:** 1999

US Patent Number: 5,967,087

Abstract: A method of increasing seafood production in the oceans comprises testing the water at the surface of the ocean in order to determine the nutrients that are missing, applying to the surface of the ocean a first fertilizer that comprises an iron chelate, and harvesting the increased production of seafood that results. The method may further comprise applying a microorganism that fixes nitrogen such as phytoplankton, applying additional fertilizers, and seeding the ocean with fish. Each fertilizer releases the nutrient(s) over time in the photic zone and in a form that does not precipitate before use by the phytoplankton.

Title: Water-bouyant particulate materials containing micronutrients for phytoplankton.

Assignee: Howard, Jr. et al. **Year:** 1999

US Patent Number: 5,965,117

Abstract: Water-buoyant compositions comprising a source of micronutrients for photosynthetic phytoplankton growth are useful for stimulating photosynthetic phytoplankton growth in ocean areas devoid of such growth when deployed on ocean surfaces as floating particles. Iron is the preferred micronutrient.

Title: Method of increasing seafood production in the ocean.

Assignee: Markels, Jr. **Year:** 1996

US Patent Number: 5,535,701

Abstract: A method of increasing seafood production in the oceans comprises (1) testing the water at the surface of the ocean in order to determine the nutrients that are missing, (2) applying to the ocean water a fertilizer that comprises a microorganism that fixes nitrogen and sufficient nutrients to cause the microorganism to fix nitrogen (if the ocean water is missing nitrates), and the other missing nutrients, and (3) harvesting the increased production of seafood that results from the fertilization.

Title: Method of increasing seafood production.

Assignee: Markels, Jr. **Year:** 1995

US Patent Number: 5,433,173

Abstract: A method of improved production of seafood comprises (1) testing the water at the surface of the ocean in order to determine the nutrients that are missing, (2) applying a fertilizer that contains the missing nutrients, to fertilize the surface of the ocean, and (3) harvesting the increased production of seafood that results from the fertilization.

APPENDIX B: ANNOTATED BIBLIOGRAPHY

The following is a comprehensive- though, not exhaustive- compilation of annotated references on ocean fertilization covering topics that may be useful for readers unfamiliar with the underlying historical context and the relevant science.

The Iron Theory

Martin, J.H. and S.E. Fitzwater (1988) **Iron deficiency limits phytoplankton growth in north-east Pacific subarctic**. *Nature*, 331: 342-243. [Addition of iron to incubated algal suspensions from the northeast Pacific subarctic yields dramatic increases in chlorophyll concentrations and decreased nitrate and phosphate relative to control bottles.]

Martin, J. H. (1990) **Glacial-interglacial change: The iron hypothesis**. *Paleoceanography*, 5: 1-13. [Enter: the iron hypothesis. Martin suggests that increased supplies of iron to the HNLC Southern Ocean during the last glacial maximum stimulated the biological pump and contributed to atmospheric CO₂ drawdown, reducing concentrations to 200ppm. See also Martin, J.H. *et al.* (1990) **Iron in Antarctic waters**. *Nature*, 345: 156-158.]

Chisholm, S.W. and F.M.M. Morel (1991) **What controls phytoplankton production in nutrient-rich areas of the open sea?** *Limnology and Oceanography*, 36 (8): Preface. [Recounts the birth and rise of John Martin's 'iron hypothesis'. The discussion highlights important uncertainties and reflects on the philosophical dilemmas posed by the issue of ocean fertilization.]

Chisholm, S.W. (1995) **The iron hypothesis: Basic research meets environmental policy**. *Reviews of Geophysics, Supplement* 1277-1286. [The story and the science behind the first IRONEX experiment. Also online at <http://earth.agu.org/revgeophys/chisho00/chisho00.html>]

Iron Fertilization Field Experiments

Martin, J.H. *et al.* (1994) **Testing the iron hypothesis in ecosystems of the equatorial Pacific**. *Nature*, 371:156-158. [The first IRONEX experiment showed that iron limits phytoplankton growth in the tropical HNLC ocean, but left questions of other controls on primary production unclear. For example the role of grazing and the fate of iron remained unclear.]

Coale, K.H. *et al.* (1996) **A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific ocean**. *Nature*, 383: 495-501. [Results from IRONEX-II: (i) Phytoplankton response to iron-fertilization was immediate and sustained, (ii) phytoplankton abundance increased 20-fold, (iii) Diatoms showed the largest increase in abundance- 85-fold- and were not controlled by zooplankton grazing.]

Behrenfeld, M.J. *et al.* (1996) **Confirmation of iron limitation of phytoplankton photosynthesis in the equatorial Pacific ocean**. *Nature*, 383: 508-510. [Iron enrichment

during IRONEX-II triggered biophysical alterations of the phytoplankton's photosynthetic apparatus, resulting in increased photosynthetic capacities throughout the experiment and, hence, the observed bloom.]

Cooper, D.J. *et al.* (1996) **Large decrease in ocean-surface CO₂ fugacity in response to *in situ* iron fertilization.** *Nature*, 383: 511-513. [During IRONEX-II, the induced phytoplankton bloom caused a 60% decrease in the "natural" ocean-to-atmosphere CO₂ flux in the upwelling zone of the HNLC Equatorial Pacific Ocean.]

Turner, S.M. *et al.* (1996) **Increased dimethyl sulphide concentrations in seawater from *in situ* iron enrichment.** *Nature*, 383:513-517. [During IRONEX-II, iron addition increased the amount of DMS evolution by a factor of 3.5]

Boyd P.W., *et al.* (2000) **A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization.** *Nature*, 407, 695-702. [Results from the Southern Ocean Iron Release Experiment (SOIREE) iron fertilization experiment in the Southern Ocean. Almost 5 days elapsed before any observable biogeochemical change. Primary production increased gradually (four fold increase in Chl a, corresponding to 50% increase in POC) over two weeks following iron fertilization, but no evidence of significant carbon export was obtained. See also the official SOIREE website at (<http://tracer.env.uea.ac.uk/soiree/index.html>)]

Watson, A.J. *et al.* (2000) **Implications of a Southern Ocean iron fertilization experiment for past and future atmospheric CO₂.** *Nature*, 407, 730-733. [SOIREE results were fed into a model. Conclusion: "modest sequestration of atmospheric CO₂ by artificial additions of iron to the Southern Ocean is in principle possible, although the period and geographical extent over which the sequestration would be effective remain poorly known."]

Chisholm, S.W. (2000) **Stirring times in the Southern Ocean.** *Nature*, 407: 685-687. [This is the News and Views article prefacing the SOIREE papers, voicing the 'Commons concern' and questioning the sustainability of ocean fertilization.]

Charette, M.A. and K.O. Buesseler (2000) **Does iron fertilization lead to rapid carbon export in the Southern Ocean?**, *Geochemistry Geophysics Geosystems*, 1 (Research Letter), [During SOIREE, the biological response was delayed and negligible particulate carbon export occurred over 14 days. This result may be attributed to colder water temperatures that promote slower cell metabolism in phytoplankton and hence slower secondary responses of herbivores and particle aggregation. (<http://146.201.254.53/publicationsfinal/researchletters/2000GC000069/fs2000GC000069.html>)]

Ridgwell, A.J. (2000) **Climatic effect of Southern Ocean Fe fertilization: Is the jury still out?** *Geochemistry, Geophysics, Geosystems* (an online journal), [There is a gap in scientific understanding of the fate of carbon taken up by photosynthetic organisms following iron fertilization. Persistent ambiguity regarding the transport of organic matter to the deep ocean might weaken John Martin's iron hypothesis for glacial times. Anticipated results from new

Southern Ocean experiments, one in 2000 (EISENEX) and another planned for 2002 (SOFEX), might serve to reduce the uncertainty.
(<http://146.201.254.53/publicationsfinal/forum/2000GC000120/fs2000GC000120.html>)

Modeling the Potential Effectiveness of Ocean Fertilization

[The following four modeling papers assumed *continuous* ocean fertilization from 50 to 100 years and all agreed on two main points:

1. Iron fertilization is – at best – a partial solution to global warming (10 +/- 5 % reduction in atmospheric CO₂, depending on model and emissions scenario).
2. The Southern Ocean is the only suitable target area for significant climate mitigation by iron fertilization.]

Sarmiento, J.L. and J.C. Orr (1991) **3-dimensional simulations of the impact of the southern ocean nutrient depletion on atmospheric CO₂ and ocean chemistry**. *Limnology and Oceanography*, 36:1928-1950.

Peng T.-H. and Broecker, W.S. (1991) **Dynamic limitations on the Antarctic iron fertilization strategy**. *Nature*, 349: 227-229.

Joos F. *et al.* (1991) **Estimates of the effect of Southern-Ocean iron fertilization on atmospheric CO₂ concentrations**. *Nature*, 349: 772-775.

Kurz, K.D. and E. Maier-Reimer (1993) **Iron fertilization of the Austral Ocean – the Hamburg model assessment**. *Global Biogeochemical Cycles*, 7:229-244.

Gnanadesikan, A. *et al.* (2000) **Potential Limits on the Efficiency of Ocean Fertilization as a Sequestration Strategy: The Importance of Circulation**. *Invited talk, Session: Science of Carbon Sequestration-I, American Geophysical Union 2000 Fall Meeting*. San Francisco, December 15-19, 2000. [Modeling results reiterate the much larger carbon sequestration capacity of the Southern Ocean (65 to 100 GtC over 100 years) relative to the Equatorial Pacific HNLC waters for iron fertilization (~ 10 GtC over 100 years). Ocean circulation is critical in modeling the amount of carbon sequestered and the negative impact of Southern Ocean fertilization on "downstream", tropical new productivity (30 to 70% decrease).]

Gnanadesikan, A. *et al.* (2001) **Ocean Fertilization and Biological Productivity**. *1st National Conference on Carbon Sequestration, National Energy Technology Lab, US DOE*. Washington, DC. May 14 – 17, 2001. [Emphasizes earlier findings by same authors that micronutrient (iron) fertilization in HNLC waters could diminish biological production in surrounding areas and remote locations. On a century scale, the reduction in global carbon export may far exceed the amount of atmospheric CO₂ that could be captured by fertilization. Moreover, after-effects of fertilization, such as lowered biological production in the fertilized area may linger for some time after termination of fertilization. Full text online at http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/6b3.pdf]

On Ecosystem Response to Ocean Fertilization

Fuhrman J.A. and D.G. Capone (1991) **Possible biogeochemical consequences of ocean fertilization.** *Limnology and Oceanography*, 36 1951-1959. [Impacts may extend beyond mere increase in primary production. Other possible outcomes include anoxia and, hence, production of GHGs such as CH₄ and N₂O. Production of such powerful GHGs might negate the benefits from fertilization. Anoxia may also result in Fe mobilization resulting in "self-fertilization", prolonging the effects of fertilization.]

Downing, J.A. *et al.* (1999) **Meta-analysis of marine nutrient-enrichment experiments: Variation in the magnitude of nutrient limitation.** *Ecology*, 80: (4) 1157-1167. [Nutrient bioassay experiments in many marine and estuarine environments around the world have yielded mixed results, despite relatively uniform protocols, implicating N, P, Si, Fe and other elements as factors limiting phytoplankton growth, depending upon the nutrient fluxes in the ocean region. Experiments lasting a day or less suffer from time lags in the numerical response of phytoplankton to nutrient addition, while experiments lasting >7 days confounded nutrient limitation with processes such as increased grazing or depletion of other nutrients.]

Cavender-Bares, K.K. *et al.* (1999) **Differential response of equatorial Pacific phytoplankton to iron fertiization.** *Limnology and Oceanography*, 44: 237-246. [Analyses of biological response from the IRONEX-II experiment showed that overall increase of chlorophyll a in the patch was due in part to increases in chlorophyll content per cell and in part to increases in cell numbers of specific groups. In terms of net cell growth, however, the phytoplankton groups responded very differently. Within 1 week, this differential response led to a dramatic change in the local phytoplankton community structure, from one dominated by picoplankton to one dominated by large diatoms. It is not known whether this shift would be sustained over extended periods of fertilization, a response that would ultimately change the structure of the food web.]

Micheli, F. (1999) **Eutrophication, fisheries, and consumer-resource dynamics in marine global fisheries.** *Science*, 285: 1396-1398. [Nutrients generally enhance phytoplankton biomass. However, weak coupling between primary producers and herbivores prevents the propagation of "cascades" up or down through marine pelagic food webs. In coastal waters anthropogenic N loading (e.g., as proposed by Ian Jones and OTG for the Chilean upwelling zone; see Pearce (2000) below) is unlikely to increase fish biomass. Moreover, the fate of "new" carbon is difficult to predict.]

Barber, R.T. **Using modeling to design and evaluate transient open ocean iron enrichment for carbon sequestration.** *1st National Conference on Carbon Sequestration, National Energy Technology Laboratory, US DOE.* May 14-17, Washington DC. [Announces an existing, validated ecosystem model (in press) that may serve as an alternative means to test many of the engineering aspects of ocean fertilization in the Equatorial Pacific Ocean. Thus,

fewer *in situ* experiments would be required to demonstrate efficacy and environmental safety. See http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/6b4.pdf

Reviews of Carbon Sequestration Technology

De Baar, H.J.W. et al. (1992) **Confining and abating CO₂ from fossil fuel burning – a feasible option?** Report prepared for the *TNO Institute of Environmental and Energy Technology*, The Netherlands. [Although it predates the IRONEX experiments, this is still a useful scientific review of the oceanic carbon cycle and the two main carbon sequestration approaches. The author questions the scientific basis for, and ethics of, large-scale ocean fertilization. Conclusion: carbon sequestration will not by itself solve the GHG emissions problem and capturing carbon, in any case, amounts to "only buying time".]

Ormerod, W and M. Angel (1998) **Ocean fertilisation as a CO₂ sequestration option.** *International Energy Agency Greenhouse Gas R&D Programme Report*, United Kingdom. [Includes discussions on Japanese, Norwegian, American and Australian micro-, macro-nutrient ocean fertilization proposals. Analyses the practical requirement for Southern Ocean fertilization. Agrees with modeling results from Sarmiento & Orr (1991) and others. Concludes that while carbon sequestration and fish production are not compatible objectives for ocean fertilization, the concept of ocean fertilization becomes more attractive if uptake of CO₂ from the atmosphere is presented as a benefit supplementary to other goals.]

Johnston, P., et al (1999) **Ocean Disposal/Sequestration of Carbon Dioxide from Fossil Fuel Production and Use: An Overview of Rationale, Techniques and Implications.** Technical Note 01/99, *Greenpeace Research Laboratories*, UK. (Full text at <http://www.greenpeace.org/politics/co2/co2dump.pdf>) [A good technical review of the different ocean fertilization and direct injection approaches. Also reviews international treaties, specifically the London Convention and the Kyoto Protocol.]

Brewer, P.G. (1999) **Contemplating action: Storing carbon dioxide in the ocean.** *National Academy of Sciences*, The First Roger Revelle Commemorative Lecture, Washington, D.C. November 9, 1999. (Full text at <http://www.mbari.org/ghgases/revelle/text.htm>) [Discusses the underlying science and the feasibility of both direct injection and ocean fertilization against the backdrop of the 1996 IPCC report and Kyoto Protocol. Advises a cautious, but committed approach toward developing carbon sequestration options.]

US Department of Energy's Carbon Sequestration Website (http://www.fe.doe.gov/coal_power/sequestration) [Predicting that fossil fuels will remain the mainstay of energy production in the 21st century, DOE concludes that it will be necessary to deploy carbon sequestration in some form in order to reduce greenhouse gas emissions. This page links to various research program areas (e.g., ocean sequestration, geologic sequestration, etc.), to the comprehensive R&D roadmap report and a recent PNNL report on "advanced" technological options.]

"Annex B: Sequestration of carbon dioxide by ocean fertilisation." From the February 2000 report of the British Government Panel on Sustainable Development on "Sequestration of Carbon Dioxide." (<http://www.sd-commission.gov.uk/panel-sd/position/co2/annb.htm>). [A thorough review of the state of science and modeling discussing sequestration potential and environmental impacts of micro- and macro-nutrient fertilization. Concludes that too little is known to implement large-scale ocean fertilization and specifies research needs. See also *The Government Response to the Sixth Annual Report of the Government Panel on Sustainable Development*. Government officials comment that "in terms of environmental sustainability, (there is) a strong presumption against attempting to solve an imbalance due to human intervention in one part of the global carbon cycle by manipulating another part". Concerns are expressed regarding uncertainties and whether this approach would be legal. The government supports further research into efficacy and costs and "urges immense caution meanwhile". See full text of the U.K. government's deliberations on carbon sequestration at (<http://www.defra.gov.uk/environment/sustainable/sdpanel/response6/02.htm>)]

Climate Engineering: A critical review of proposals, their scientific and political context, and possible impacts by Ben Matthews, PhD (formerly of the School of Environmental Sciences, Univ. of East Anglia, UK). [This source is presented without review, for now, regarding the accuracy of the facts and quality of analysis. The site contains a comprehensive listing of various carbon sequestration approaches. (<http://chooseclimate.org/cleng>)]

Ocean Fertilization – Policy Analysis

Ryan, A.C. (1998) **Should we fertilize the ocean?** *MS Thesis, Dept. of Civil & Env. Engg. and Technology & Policy Program, MIT*. [The author concludes: No and makes strong cases against some commercial ocean fertilization proposals. The document provides a plain-language review of important scientific concepts followed by an in-depth scientific and economic analysis of commercial ocean fertilization proposals. Also contains an informative review and analysis of relevant international environmental and marine laws.]

Adhiya, J. (2001) **Is Ocean fertilization a good carbon sequestration option?** *MS Thesis, Technology & Policy Program, MIT*. [The author emphasizes the need for full consideration of scientific uncertainties and issues of international law in the evaluation of ocean fertilization proposals by policy makers. A comprehensive review of scientific uncertainties is presented. A preliminary decision-analytic framework for evaluating possible outcomes of fertilization policy decisions is also developed.]

Some Papers from Limnology

Dodson, S.I. *et al.* (2000) **The relationship in lake communities between primary productivity and species richness.** *Ecology*, 81: (10) 2662-2679. [For average lake size, the highest biodiversity tended to occur in lakes with relatively low primary productivity. In whole lake experiments, nutrient enhancement produced unpredictable and varied responses

in species richness, probably due to transient dynamics and time lags, but species richness of most taxa would likely decline as lakes become eutrophic.]

Cottingham K.L. *et al.* (2000) Increased ecosystem variability and reduced predictability following fertilisation: Evidence from palaeolimnology. *Ecology Letters*, 3: (4) 340-348. [Inter-annual variability in algal communities increases, whereas predictability of change in ecosystem state decreases, in nutrient enriched lakes. Anthropogenic eutrophication of ecosystems may destabilize lakes, and obscure impacts of global change.]

Papers/ Presentations by Proponents of Commercial Ocean Fertilization

Jones, Ian S.F. and D. Otaegui (1997) **Photosynthetic Greenhouse Gas Mitigation by Ocean Nourishment**. *Energy Conversion & Management*, 38, S367-S372. [Describes the process and plant design for 'ocean nourishment' with ammonia along with other technical and cost specifications. Claims costs of approx.\$7.5/ton of CO₂ captured. Also available online at <http://www.otg.usyd.edu.au/papers/jo96a.htm>. See also other online papers on the OTG website.]

Markels Jr, M. (1998) **Ocean Farming: An Update**. *Regulation*, 21(2): 9-10. [Refers to the purchase from Marshall Islands government of an option to fertilize 800,000 sq. miles of open (coastal) ocean. Focus was still on enhancing fish production by iron fertilization, at this point. Also available online at <http://www.cato.org/pubs/regulation/regv21n2/pers2-98.pdf>]

Jones, I.S. and Young, H.E. (2000) **Reducing greenhouse gas by ocean nourishment**. *Offshore Technology Conference*, Houston, Texas (May 1-4, 2000). [Discusses the use of floating platforms to utilize "stranded" natural gas for fertilizer production. Estimates a cost of \$7/ t CO₂ avoided Includes reference to "low income food deficient (coastal) countries" as potential clients.]

Markels Jr. M and Barber R.T. (2000) **The sequestration of carbon to the deep ocean by fertilization**. *ACS Symposium on CO₂ Capture, Utilization, and Sequestration*. August 20-24, 2000. [Proposes a demonstration experiment over 13000 sq. km in the Equatorial Pacific, and contains a discussion of never-published results of privately funded field tests in the Gulf of Mexico. Claims costs of \$1-2/ton of CO₂ captured. References are included for patents and the pending "spiral fertilization" patent application. See also, the company's upcoming website: GreenSea Venture, Inc. (<http://www.greenseaventure.com>)]

Markels Jr. M and Barber R.T. (2001) **Sequestration of CO₂ by fertilization**. *Poster Presentation, 1st National Conference on Carbon Sequestration, National Energy Technology Laboratory, US DOE*. May 14-17, Washington DC. [An updated version of the paper presented at ACS in 2000, in which Markels and Barber ratchet up the sales pitch a notch for ocean fertilization. This draft incorporates results from Hansell et al. (*Nature*, v386, p240-243, 1997), projecting a carbon sequestration fraction of 53% of primary

production, comparable to that in the upwelling zone off Peru. Full text online at http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/p25.pdf

Jones, I.S.F. (2001) **The Global Impact of Ocean Nourishment**. *1st National Conference on Carbon Sequestration, National Energy Technology Laboratory, US DOE*. May 14-17, Washington DC. [Jones reverts to food production as his primary rationale for “ocean nourishment” with liquid ammonia. Argues for a doubling in nitrogen fertilizer production over the next 50 years. Claims the potential for “permanent sequestration” of gigaton scale carbon sequestration at a cost of \$5 to 15 per ton of carbon avoided *minus* value of fish produced. See http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/6b2.pdf]

Jones, I.S.F. and Young, H. E. (2001) **The Short and Long Term Role of the Ocean in Greenhouse Gas Mitigation**. *Poster Presentation, 1st National Conference on Carbon Sequestration, National Energy Technology Laboratory, US DOE*,. May 14-17, Washington DC. [The authors once again take the grow-more-food-for-the-poor angle to promote fertilization, while also maintaining the need to use the ocean as a carbon sink. Vehement arguments are presented that the potential benefits justify taking the risks. Authors claim that while “(e)xtensive ocean nourishment will change both the physical and biological nature of the ocean”, thus enhancing depleted commercial fish stocks, “the strategy does not encourage a monoculture” and “aims not to disrupt the biodiversity of the ocean.” Argues that “nourishment” is not “dumping” under the 1972 London Convention. Memorable sentence: “At present the amount of upwelled water is not under human control.” Full text online at http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/p44.pdf]

Recent Ocean Fertilization Patents (From www.uspto.gov)

Markels, Jr., M., 1995, P/N 5433173, *Method of improving production of seafood*.

Markels, Jr., M., 1996, P/N 5535701, *Method of increasing seafood production in the ocean*.

Markels, Jr., M., 1999, P/N 5967087, *Method of increasing seafood production in the barren ocean*.

Jones, Ian S. F. et al., 1999, P/N 5992089, *Process for sequestering into the ocean the atmospheric greenhouse gas carbon dioxide by means of supplementing the ocean with ammonia or salts thereof*. [Patent for the Ocean Technology Group at the University of Sydney, Australia. Includes a schematic for the ‘nourishment’ process.]

Howard Jr., E.G. and O’Brien, T.C. (assignee: E.I. du Pont de Nemours and Company), 1999, P/N 5965117, *Water buoyant particulate materials containing micronutrients for phytoplankton*. [Du Pont’s variant on Markels’ patented idea of floating pellets with embedded iron fertilizer. Specifies a wide range of compounds for making pellets with.]

Markels, Jr., M., 2000, P/N 6056919, *Method of sequestering carbon dioxide*. [Markels’ first patent emphasizing carbon sequestration. Markels’ previous patents were focused upon fish

production by fertilization, although the potential for carbon dioxide capture was also mentioned in the patents (see below).]

Markels, Jr., M., 2001, P/N 6200530, *Method of sequestering carbon dioxide with spiral fertilization*. [Note the incremental, almost annual "improvements" being made to the patented technology. This is the fifth patent application for Markels; see four patents below.]

Markels, Jr., M., Filed in 2001, A/N 20010002983, *Method of sequestering carbon dioxide with a fertilizer comprising chelated iron*.

Some Important Research Programs

DOE Center for Research on Ocean Carbon Sequestration) [DOCS was established by DOE to "conduct, focus, and advance the research necessary to evaluate and improve the feasibility, effectiveness and environmental acceptability of ocean carbon sequestration." The site offers concise overviews of the ocean fertilization and direct injection options for carbon sequestration and outlines important research and modeling issues. (<http://www-esd.lbl.gov/DOCS/>)]

Ecological Determinants of Ocean Carbon Cycling (<http://picasso.oce.orst.edu/ORSOO/EDOCC>). [The website is an initiative supported by the National Science Foundation and focuses on improving comprehension of the role that marine ecosystems play in atmospheric carbon sequestration and burial. There is a downloadable report on state of science and research priorities. Also contains useful links to other research program sites.]

Woods Hole Oceanographic Institution 1999 Annual Report [Comments from Ken Buessler, Associate Scientist at WHOI, on the contrasting results obtained from IRONEX-II and SOIREE iron fertilization experiments. Biological productivity increase dramatically during IRONEX, but not during SOIREE. Additionally, carbon uptake: export ratios were higher during IRONEX. Plans for future experiments in the Southern Ocean in 2002 are briefly outlined. Dr. Buessler also feels that pressure to try something on an industrial scale will soon culminate in a large-scale experiment with or without scientific input as entrepreneurs gather the necessary permits, patents and funding (<http://cafethorium.whoi.edu/Fe/1999-Annualreport.html>).]

OCTET-Ocean Carbon Transport, Exchanges and Transformations [This is a new research planning initiative involving top-tier scientists focussed on addressing key uncertainties in ocean carbon cycling that are relevant to understanding anthropogenic global change. The March 2000 workshop report outlines these uncertainties in detail (<http://alpha1.msrc.sunysb.edu/octet>).]

The IEA Greenhouse Gas R&D Programme [An introduction to climate change problem as well as evaluations of possible technical solutions. Of special interest are the technical reports and online conference proceedings that collectively provide status updates, useful numbers for

the potentials and costs for a range of carbon sequestration options. The focus of "practical research" is primarily on carbon capture from point sources (power plants) for injection into geologic or marine reservoirs. (<http://www.ieagreen.org.uk>)]

National Energy Technology Laboratory's Carbon Sequestration Website [Contains a wealth of information on various types of carbon sequestration approaches. Also a good source of up-to-date information on governmental policy on sequestration and for news regarding sequestration research. (<http://www.netl.doe.gov/products/sequestration/index-b.html>)]

Some Education-Focussed Websites

"Is Iron Fertilization Good for the Sea?" Case teaching notes prepared by LeLeng To Department of Biological Sciences, Goucher College. [The commercial iron fertilization controversy is presented a case study for students. This website gives a general summary of the results of IRONEX I and II and some useful background information on global warming as well. The impressive bibliography is divided into categories for easy navigation. (http://ublib.buffalo.edu/libraries/projects/cases/iron_case/geritol_notes.html)]

Perturbation to the Carbon Cycle by Enhancing Plankton Growth, Final Report - Glen Romine, University of Oklahoma's Earth System Science Education Web Site. [The report includes a modeling exercise to calculate how much carbon fertilizing 20% of the world's ocean (i.e. the HNLC regions) with iron would capture. The author concludes that atmospheric CO₂ would be lowered by 38ppm (76.4 GtC). The paper concludes with a balanced discussion of uncertainties and implications. (<http://www.esse.ou.edu/~gromine/iron.html>)]

The Effect of Iron on Plankton Use of CO₂ - Dept. of Chemistry, Michigan State University. [Another course website, providing a useful summary of the IRONEX results. (<http://www.cem.msu.edu/~cem181h/projects/96/iron/cem.html>)]

EPA's Global Warming Site (<http://www.epa.gov/globalwarming>) [A very good overview of the scientific evidence for global warming and its potential impacts. The materials include numerical estimates for domestic and global greenhouse gas emissions. (<http://www.epa.gov/globalwarming>)]

Ocean Fertilization Articles in News Media and Magazines

Nadis, S. (1998) **Fertilizing the Sea**. *Scientific American*, (Apr. 1998). [Markels versus Chisholm and others. Online at <http://www.sciam.com/1998/0498issue/0498scicit5.html>]

Schueller, G. (1999) **Testing the Waters**. *New Scientist* (Oct. 2). [One of several print-duels pitching Professor Chisholm's ecological insights against Michael Markels' dreams of green seas.]

Graeber, C. (2000) **Dumping Iron**. *Wired Magazine* (November). [A light-hearted and somewhat lop-sided account of the ocean fertilization controversy. Obviously fascinated

with Markels, the author dedicates a lion's share of ink to Markels' world view and the pitch for a "technology demonstration experiment" of his patented ocean fertilization method in a marine "Desolate Zone". The article touches on Markels' claim of capturing carbon for \$2 per ton and also the association with Dick Barber. "Eco-experts" Chisholm, Cullen, Bishop and Carter are allowed rebuttals. Memorable sentence: "Markels is well outside the atmospheric science mainstream, but he's no crackpot." Full text online at <http://www.wired.com/wired/archive/8.11/ecohacking.html>]

Pearce, F. (2000) **A cool trick: how Chile could help save the world and get credits for it.** *New Scientist* (April 8), pp. 18. [This article broke the story on the proposal by the Australian OTG scientists (along with their Japanese collaborators) to "nourish" the already nutrient-rich, upwelled waters off the Chilean coast in order to capture atmospheric carbon for \$5-\$15.]

New Scientist Editorial (2000), **Keep it simple, stupid.** *New Scientist* (April 8). [Appearing in the same issue as the above story about pumping ammonia into Chilean coastal waters, this editorial categorizes the idea as "madcap scheme."]

[The following are some of the articles that appeared in the mainstream newsmedia during October 2000, following the publication of the SOIREE papers in the October 12th issue of the journal *Nature*.]

Ball, P. (2000) **Blooming marvellous.** *Nature Science Update* (online, October 12). [Nature's plain language summary of the SOIREE articles, with historical overview. Conclusion: plant growth in the Southern Ocean can be fertilized with iron, soaking up carbon dioxide. But this is no panacea for the problems of global warming See <http://helix.nature.com/nsu/001012/001012-10.html>.]

Onion, A. (2000) **Just Add Iron - Some Suggest Dumping Iron in Oceans May Be Global Warming Fix.** *ABC News.com*. [Has quotes from SOIREE scientists expressing their surprise at the duration of the lingering phytoplankton bloom following iron addition. Also has comments regarding implications of the uncertain results from Prof. Chisholm. Interestingly, this article broke the story of the failure of the bid by Markels to secure ocean fertilization rights in the Marshall Islands' territorial waters and also records his intention to pursue private funding for a 5,000 sq. mi. experiment off the Galapagos Islands. See full story at <http://www.abcnews.go.com/sections/science/DailyNews/ironoceans001012.html>]

The Washington Post Online (2000) **Iron in the ocean's diet.** (October 16). [A short news piece emphasizing that the fate of the stimulated carbon uptake by phytoplankton was unknown. See also <http://www.washingtonpost.com/wp-dyn/articles/A13842-2000Oct15.html>]

On Carbon Emissions Trading

Edmonds, J. et al. (1999) **International Emissions Trading & Global Climate Change: Impacts on the Cost of Greenhouse Gas Mitigation.** [This report prepared for the *Pew Center on Global Climate Change* proposes the idea that "international trade holds the

potential of reducing costs of controlling world emissions of greenhouse gases (GHGs), because the nations of the world experience very different costs for achieving emissions reductions on their own. However, the potential gains from trade, like the costs of compliance themselves, may be very unevenly distributed across the world's participants. Available online at http://www.pewclimate.org/projects/econ_emissions.cfm]

Ney, RA and Schoor, JL. (2000) **What course for carbon trading?**, *Environmental Science & Technology: News and Research Notes*, 2000, 34 (7), p177A- 182A [Reports the emergence of a carbon and GHG trading market in the United States, despite the Senate's failure to ratify the Kyoto Climate Convention and without formal legislation to mandate its enforcement. Lists some key related legislation before Congress and some international developments to encourage GHG trading.]

Haites, E. and Aslam, M.A. (2000) **The Kyoto Mechanisms and Global Climate: Change Coordination Issues and Domestic Policies**. [This report prepared for the *Pew Center on Global Climate Change* explore the potential benefits and pitfalls of the three Kyoto Mechanisms: international emissions trading, joint implementation (JI) and the clean development mechanism. Emphasizes the need for domestic cap-and-trade systems and strong enforcement as keys to the successful application of the Mechanisms. Available online at http://www.pewclimate.org/projects/kyoto_mechanisms.cfm]

International Laws on Climate Change and Use of the Ocean

UNFCCC Climate Change Information Kit: **The Kyoto Protocol** [An excellent resource with easy to read summaries of the climate change problem and the United Nations' policy response. (<http://www.unfccc.int/text/resource/iuckit/index.html>)]

United Nations website on the **Law of the Sea** [The UN Convention on the Law of the Seas (UNCLOS) came into force in 1994 and "lays down a comprehensive regime of law and order in the world's oceans ... establishing rules governing all uses of the oceans and their resources. ... The Convention also provides the framework for further development of specific areas of the law of the sea." More information is online at <http://www.un.org/Depts/los/losconv1.htm>.]

Text and discussion of the **London Convention** [In force since 1975, the London Convention is a powerful treaty regulating the disposal (or dumping) of terrestrial materials or wastes at sea. The 1996 protocol to the Convention strongly applies the "precautionary principle" and would be a stringent replacement for the London Convention if and when it enters into force. More information at <http://www.londonconvention.org>.]

APPENDIX C: TABLE OF CARBON SEQUESTRATION OPTIONS ⁱ

Carbon Capture Option	Approx. Global Capacity (GtC)	Cost ⁱⁱ (\$/tC)	Residence Time (years)	Sequestration Rate (GtC/yr)	Ecological Risks	Other Benefits	Deployment Status
Southern Ocean Iron Fertilization	50 – 150 ^{iii,iv} (after 100 years continuous fertilization)	1 - 15 ^v 85 ^{vi}	Varies with duration of ocean fertilization ⁱⁱⁱ .	Declines rapidly to 1–2, from 11-12 in first year ^{iv} .	30 to 70% decrease in tropical primary production ⁱⁱⁱ . Hypoxia, change in species composition ^{vii} .	Could increase local fish production.	Demonstration experiments being discussed in the Equatorial Pacific.
Deep Ocean Injection or Diffusion	> 1,000 ^{viii}	110 - 180 ^{ix} (4.1) ^x	100 - 1000 (“leakage” varies with site & depth) ^{xi} .	Optimal rate to be determined.	Ecosystem disruption due to CO ₂ acidity ^{ix} .	None	DOE Testing off Kona Island in 2001-2002 ^{ix} .
Ocean Saline Aquifers	> 220 ^{xii}	(4.7) ^{xi}	Site specific.	> 0.001 ^{xiii} (not yet maximized.)	Groundwater impact, leakage to benthic zone ⁱ .	None	Commercial pilot at Sleipner in North Sea ^{xiii} .
Depleted Oil & Gas Reservoirs	180 ^{xiii,xv}	(8.2) ^{xi}	Site specific.	Site specific.	Groundwater impact, land absidence, or subsidence ⁱ .	Extends value of reservoir site.	No commercial applications.
Agro-forestry	50 – 100 ^{xiv} (About 290 Mha suitable globally for this practice)	16 - 76 ^{xv}	> 100 (Depends on management strategy)	0.94 - 1.27 ^{xv} (Global average of approx. 3.2 tC/ha-yr)	Introduction of alien species, monoculturing, land/water use conflicts.	Biofuels, habitat, watershed management.	JI project in Scolel Te, Mexico . Farm & soil management in USA ^{xv} .
Enhanced Oil Recovery	65 ^{xv}	40-60 ^{xv}	Site specific.	0.4 ^{xv}	Groundwater impact, land absidence, subsidence ⁱ .	Increased oil recovery.	Pilot study in North sea and commercial use in West Texas ^{xv} .
Coal-bed CH ₄	(a) 1.4 - 4.1 (b) 16.4 (c) 40 ^{xvi}	(a) - 55 (!) (b) < 185 (c)350-440 ^{xvii}	Site specific.	Site specific.	Low risk.	Recovery of methane.	Commercial pilots in New Mexico and Australia ^{xvii} .

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- ⁱ All industrial CO₂ capture options suffer from the following: mass CO₂ escape following fracture of transmission pipeline, pipelaying disruptions (e.g. to ecosystems) and worker exposure to CO₂ capture solvents. These and most other scenarios listed above discussed in H. Audus, P. Freund and A. Smith (1995). *Global Warming Damage and the Benefits of Mitigation*. IEA Greenhouse Gas R&D Programme. [www.ieagreen.org.uk/sr5p.htm]
- ⁱⁱ Cost figures in brackets are estimated “injection” costs only.
- ⁱⁱⁱ Gnanadesikan, A., Sarmiento, J. and Slater, R., 2000. *Potential limits on the efficiency of ocean fertilization as a carbon sequestration strategy: The importance of circulation.*, American Geophysical Union 2000 Fall Meeting, San Francisco.
- ^{iv} Sarmiento JL, Orr JC (1991) *Three dimensional simulations of the impact of Southern Ocean nutrient depletion on atmospheric CO₂ and ocean chemistry*. *Limnology and Oceanography*, 36, 1928-1950.
- ^v NAS (1992) “Policy implications of greenhouse warming”, National Academy Press.
- ^{vi} Ryan AC (1998) “Should we fertilize the ocean?”, Master’s degree thesis, Civil&Env. Engg., MIT
- ^{vii} Fuhrman J.A. & Capone D.G. (1991) *Possible biogeochemical consequences of ocean fertilization*. *Limnology & Oceanography*, 36, 1951-1959.
- ^{viii} Herzog, H., K. Caldeira, and E. Adams (2000) *Carbon Sequestration via Direct Injection*. Preprint for the Encyclopedia of Ocean Sciences. [<http://web.mit.edu/energylab/www/hjherzog/publications.html#co2>]
- ^{ix} W. Ormerod, P. Freund and A. Smith (1999), *Ocean Storage of CO₂*. IEA Greenhouse Gas R&D Programme. [www.ieagreen.org.uk/ocean.htm]
- ^x Riemer, P. (1995) *Greenhouse Gas Mitigation Technologies, an Overview of the CO₂ Capture, Storage and Future Activities of the IEA Greenhouse Gas R&D Programme*. IEA Greenhouse Gas R&D Programme. [www.ieagreen.org.uk/paper2.htm]
- ^{xi} Orr, J. C. et al. (2001) *Ocean CO₂ Sequestration Efficiency from 3-D Ocean Model Comparison*. presented at the 5th International Conference on Greenhouse Gas Control Technologies (GHGT-5) held in August 2000 at Cairns, Queensland, Australia. [www.ieagreen.org.uk/ghgt5-15.pdf]
- ^{xii} Torp, TA (1998) *Capture and reinjection of CO₂ in a saline aquifer at Sleipner Field and the future potential of this technology*. [<http://www.ieagreen.org.uk/reinject.pdf>]
- ^{xiii} D. Adams, W. Ormerod, P. Riemer and A. Smith (1994). *Carbon dioxide disposal from power stations*. IEA Greenhouse Gas R&D Programme. [www.ieagreen.org.uk/sr3p.htm]
- ^{xiv} W. Ormerod, P. Riemer and A. Smith (1995), *Carbon Dioxide Utilisation*. IEA Greenhouse Gas R&D Programme. [www.ieagreen.org.uk/sr4p.htm]
- ^{xv} *Technologies for Activities Implemented Jointly - Highlights of the Vancouver Conference, 1997*. [www.ieagreen.org.uk/aijsumm.htm]
- ^{xvi} Stevens, S.H.; Kuuskraa, V.A.; Spector, D.; Riemer, P. (1998), *CO₂ Sequestration in Deep Coal Seams: Pilot Results and Worldwide Potential*, IEA Greenhouse Gas R&D Programme. [www.ieagreen.org.uk/pwrghgt4.htm]