Should we fertilize the oceans?
Examining the science, economics and policy of the iron hypothesis & ocean fertilization

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Abstract
John Martin's 'iron hypothesis' (Martin, 1990), and the subsequent ground-breaking IRONEX experiments (Martin 1994, Coale 1996) have stimulated wide spread speculation about the concept of fertilizing the oceans. It has been suggested that adding nutrients to the open oceans will stimulate primary production, increasing the sequestration of carbon dioxide and enhancing potential fish harvest. Ocean fertilization has thus been heralded as a possible cure for global climate change and world food shortages.

Despite considerable scientific effort, private investment, and public interest in this field there has been limited evaluation of the feasibility of ocean fertilization. This thesis attempts to fill this void by addressing not only the scientific, but also the economic and policy dimensions of ocean fertilization. It starts by reviewing current research proposals and implementation activities in the field of ocean fertilization. It identifies potential environmental impacts and biogeochemical consequences of ocean fertilization, highlighting the outstanding scientific unknowns associated with this field. The study reviews cost estimates compiled by the private sector, and examines likely practical obstacles to implementation. Legal, political and public response to fertilization proposals is also explored. Finally, some of the ethical concerns relating to fertilizing the oceans are discussed, and recommendations on future research directions and initiatives to manage this rapidly growing field are provided.

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Ocean Fertilization

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INTRODUCTION
In 1988, John Martin - a respected oceanographer at the Moss Landings Laboratories - stood up at a gathering of his colleagues at the Woods Hole Oceanographic Institution, and boldly claimed 'give me half a tanker of iron, and I will give you the next ice age' (Martin 1990b). With these now infamous words, Martin revitalized a theory that has become known as the 'iron hypothesis' (Chisholm 1995).

The iron hypothesis suggests that iron availability limits phytoplankton growth in nutrient rich seas. Since Martin’s words, conclusive proof has been gathered in support of the iron hypothesis. Field experiments have shown that iron additions stimulate phytoplankton growth in regions of the equatorial Pacific. (Banse 1995; Behrenfeld et al. 1996; Coale et al. 1996; Cooper et al. 1996; DeBaar et al. 1995; Frost 1996; Martin et al. 1994; Turner et al. 1996; Watson 1997).

The implications of this theory has been the subject of public debate and scientific controversy (Blakeslee 1990; Broad 1996; Broecker 1990; Kaiser 1995; Martin 1990a; Martin et al. 1990; Nadis 1998; Sarmiento 1991; Warsh 1996; Wells 1994). One of the developments to emerge from this speculation is now a rapidly growing field referred to as ocean fertilization. This field includes many alternate proposals to enhance marine biological production through the addition of ‘nutrients’ to the oceans (Hoell 1994; Jones 1996a; Jones 1996b; Markels 1997c). By enhancing primary productivity in the oceans, it is hoped that ocean fertilization will sequester
carbon dioxide, and stimulate fish production, thereby presenting a ‘solution’ to the global problems of climate change and world food shortages.

The aim of this thesis is to evaluate the potential of ocean fertilization. It examines the scientific, economic and policy dimensions of this emerging technology. The thesis compiles and reviews current information on this potentially earth changing science, asking the fundamental question - ‘Should we fertilize the oceans?’

BACKGROUND
As early as the 1930’s, scientists deduced that iron may be a limiting factor regulating the productivity of the oceans (Gran 1931; Harvey 1938). But it took years of careful observation of dissolved iron concentrations in the sea before Martin and his colleagues were able to confidently reintroduce this theory. Through bottle experiments the Moss Landing team clearly showed that small additions of iron dramatically increased both primary productivity and phytoplankton\(^1\) abundance (Martin et al. 1990).

Subsequent measurements of dissolved iron in the high nutrient, low chlorophyll (HNLC) regions of the ocean\(^2\) indicated that concentrations of iron in these regions were very low. The Moss Landing team concluded that this trace element was limiting the full biological utilization of nutrients, and thus growth in these regions (Martin et al. 1990). Martin suggested that increased supplies of iron to the Southern Ocean during the last glacial maximum, enhanced phytoplankton activity and contributed to a drawdown of atmospheric carbon dioxide (CO\(_2\)) levels (Martin 1990a). He linked this theory to research which showed that variations in atmospheric CO\(_2\) concentration may have played a role in the changing temperatures during the

---

\(^1\) Phytoplankton are the ‘plants’ of the ocean. Through photosynthesis they capture and convert carbon dioxide (CO\(_2\)) to carbon and form the base of the marine food web. ‘Primary productivity’ refers to the rate at which carbon is fixed by phytoplankton, per square meter of sea surface, per unit of time (gC/m\(^2\)/yr). For further discussion of these organisms refer to chapter 2. Other definitions are provided in the attached glossary.

\(^2\) In some regions of the oceans, low chlorophyll (and primary productivity) are observed despite high surface water concentrations of nutrients. These HNLC anomalies are found in the Equatorial Pacific and in the Southern Ocean and could not be explained until Martin introduced his iron hypothesis (Martin 1992).
interglacial/glacial transition (Shafter 1989). This phenomena is supported by Antarctic ice-core records, which indicate that CO₂ levels were indeed reduced during this period (Martin 1992).

Martin reasoned that if the primary productivity in these HNLC regions of the ocean could be enhanced by iron addition, the amount of CO₂ sequestration by phytoplankton could also be increased. Martin calculated that fertilizing the Southern Ocean with 300,000 tons of iron could remove 2 billions tons of CO₂, from the atmosphere (Martin 1990b). This would be sufficient to substantially reduce rising atmospheric concentrations of CO₂ which is thought to be inducing global warming (Houghton et al. 1995).

Needless to say, Martin’s theory, and brazen statement, evoked much controversy amongst the marine scientific community. Indeed, a symposium of scientists was called to assess both the validity and consequences of these claims (Chisholm and Morel 1991). The Press also showed much interest in Martin’s statements, promoting his work as a potential solution for growing climate change concerns³ (Blakeslee 1990; Roberts 1991). Martin eventually obtained approval and funding to conduct a series of small-scale experiments to test his hypothesis that iron limited growth in the HNLC Equatorial Pacific. The ‘IRONEX’ experiments were conducted in 1993, and again in 1995, generating compelling evidence for Martin’s theory⁴ (Coale et al. 1996; Martin et al. 1994).

Data is still being analyzed from these two experiments (Cavender-Bares et al. 1997; Landry and al. 1997). But since the first reported success of the IRONEX experiments, interest has grown in the concept of ‘iron fertilization’ (Kaiser 1995; Monastersky 1995; Wells 1994). The original theory of fertilizing the oceans with iron has now been expanded to include all forms of nutrient addition - and this field has come to be known as ‘ocean fertilization’. Current ocean fertilization proposals range from balanced addition of nutrients in ‘natural proportions’ (Hoell et

³ It was speculated that iron-enhanced primary productivity would increase photosynthesis and result in the sequestering of CO₂ into the oceans. Chapter 2 provides more details of this biological mechanism.
⁴ A comprehensive and interesting recount of the history of Martin’s work and the subsequent IRONEX experiments is provided in (Chisholm and Morel 1991) and (Chisholm 1995).
al. 1995), to nitrogen addition (Jones 1996a) to more complex nutrient/chemical mixes (Markels 1996).

Ocean fertilization no longer remains simply a climate mitigation science and is now being seriously examined by parties as a potential means of enhancing fish production (Hoell et al. 1995; Jones 1996b; Markels 1997c). Thus, the broad spectrum of ocean fertilization practices are being propounded as a potential geoengineering solution to climate change, as well as a viable means of addressing future world food shortages.

So what does this all mean? This thesis is an attempt to provide a first overview of the fledgling field of ocean fertilization, and to seriously and objectively evaluate its future application. When initially delving into this field it became abundantly clear that the immediate challenge was to compile all the available information not yet consolidated in open literature. Although substantial amounts of research has been completed on ocean fertilization, this research has been disparate, involving many disciplines and interests. The rapid pace of development in this field has also prevented scientists, and the public at large, from keeping abreast of recent advances. Thus, this thesis is a badly-needed, long overdue attempt to consolidate what we know; what we are doing; and what we should be doing about the potentially ‘earth-changing’ science of ocean fertilization. It poses the one question asked all too softly to date - SHOULD we fertilize the oceans?

**THESIS OUTLINE**

Because of the complex nature and consequences of ocean fertilization this thesis must incorporate a vast range of issues. In order to assist the reader in navigating its contents an explanation of the thesis layout is provided.

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5 It is now being reasoned that fertilizer-induced primary productivity in the open oceans can be channeled up the food web and utilized to produce fish. For further details of this biological mechanism refer to chapter 2.
For those less familiar with oceanography and biological sciences, chapter 2 commences by introducing some fundamental ocean concepts. These will provide the necessary foundation for later discussions.

The proper evaluation of ocean fertilization then commences in chapter 3. Here we start by examining current activities in the rapidly growing field of ocean fertilization. Chapter 3 summarizes the major events, research and projects in ocean fertilization being undertaken around the world.

In chapter 4 the capacity of ocean fertilization to achieve stated climate mitigation goals is assessed by comparing numerous ocean circulation models (Joos et al. 1991; Kurz and Maier-Reimer 1993; Peng and Broecker 1991; Sarmiento and Orr 1991). Unfortunately, the fish production potential of ocean fertilization has tended to be less well studied. In lieu, proposals (including estimates) by a variety of commercial proposals have been assessed (Jones 1996b; Jones and Otaegui 1997; Jones and Young 1997; Markels 1995; Markels 1997a; Markels 1997b; Markels 1997c).

The next natural question is whether ocean fertilization is truly practicable. Implementation issues for both climate mitigation and fish production have therefore been discussed. According to claims, fertilizing the oceans is an inexpensive means of sequestering CO₂ and producing fish (Hoell 1994; Jones 1996b; Markels 1997c; Martin 1992). To date, many of these cost estimates have not been verified. Chapter 4 therefore assesses these numbers by comparing them with reworked estimates.

Chapter 5 provides an overview of the potential environmental impacts, biogeochemical consequences, and scientific unknowns associated with ocean fertilization. In the absence of large scale, long term, field data; and because of the limited time that has been available for
thorough scientific investigation⁶, many of the suggested impacts and problems must remain speculative in nature. It is an interesting exercise however, to consolidate and compile current thought, thereby gaining a more complete appreciation of the likely risks of ocean fertilization proposals.

No evaluation of ocean fertilization would be complete without considering likely legislative, public and political issues that may arise during research and full scale implementation. Law, the public, and politics are likely to play an important, if not dominant, role in any decision making process relating to the implementation of ocean fertilization for either fish production or climate mitigation goals. Chapter 6 reviews these complex issues.

Now well-versed in the primary constraints, impacts and uncertainties associated with ocean fertilization, it is hoped that the reader has sufficient grasp of the practical issues to make their own decision about ocean fertilization, and it’s appropriate future. Nevertheless, chapter 7 introduces some further thoughts on fertilizing the oceans. The objective evaluation is clear and can stand alone. It alone will tell us whether we can fertilize the oceans in a practical, continuous, and economic manner that will adequately address climate change and food supply concerns. But the question ‘SHOULD we fertilize the oceans?’ has a much more significant meaning. Chapter 7 starts by re-examining climate mitigation and food production issues, to assess whether ocean fertilization adequately and cost effectively addresses these global goals. It then explores some fundamental, deep-seated ethical reasons why we should think carefully before fertilizing the oceans.

In chapter 8 the primary conclusions of the thesis are summarized. What then follows are recommendations on what we should be thinking, and doing, about ocean fertilization; to ensure that this fascinating concept is appropriately controlled and investigated in the future.

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⁶ Ocean fertilization began to be seriously considered only in the early 1990s (Hoell et al. 1993). The iron hypothesis was only conclusively proven as late as 1995 (Coale et al. 1996). Much data awaits to be analyzed and further research is proposed to attempt to quantify impacts (Coale 1997).
REFERENCES


Chapter 2
An Introduction to the Oceans

INTRODUCTION

FUNDAMENTAL CONCEPTS

Phytoplankton
Other Plankton
Phytoplankton and Primary Production
Limiting Factors
  Light
  Physics
  Nutrients
  Macro and Micronutrients
  'Top-down' control
New and Regenerated Production
  Regenerated Production
  New Production
Global Patterns of Productivity

THE OCEAN CARBON CYCLE

Air-sea exchange
Biological Pump
Solubility Pump
  Thermohaline circulation
Significance of biological and solubility pumps
Ocean Anomalies - the HNLC Southern Ocean

OCEAN PRODUCTION

Marine Ecosystems
Production and the 'matter cycle'
Energy Transfer in Marine Food Webs

CONCLUSION

REFERENCE
INTRODUCTION
The oceans occupy over two thirds of the surface of the earth. They account for almost half of the planet’s total annual primary production, and play an important role in the modulation of the climate and the atmosphere. Until recently, mankind has had negligible influence or control over this vast and mighty force. Large scale implementation of ocean fertilization has the potential to change this status quo - and so must be considered carefully. But before embarking on an evaluation of the potential of ocean fertilization, it is essential to understand a number of underlying oceanic principles. This chapter outlines some of the fundamental biological and physical processes which characterize the oceans, providing the reader with background for later discussions.

FUNDAMENTAL CONCEPTS

Phytoplankton
Just about all that takes place biologically in the oceans is based on the activity of microscopic phytoplankton\(^1\). These microscopic, unicellular, plants are fundamental to all life in the oceans. Harnessing the energy of the sun, plus carbon dioxide (CO\(_2\)) and other essential elements, they undertake a process called photosynthesis to produce organic matter which fuels all the higher organisms of the oceans. Although globally, the total amount of photosynthesis undertaken by phytoplankton in any year is approximately equal to that of terrestrial plants and trees, their total biomass is only 0.2% of terrestrial plants. Their extraordinary capacity is achieved by their rapid growth and reproduction rate. Although doubling rates of marine phytoplankton vary widely, they are estimated to achieve between 1 to 5 doubling per day (Furnas 1990). This is remarkable when compared to land based plants (which take months to years to double their biomass), and helps to explain the high rates of photosynthetic production achieved by phytoplankton.

There are thousands of different species of phytoplankton, ranging in size from 0.6 to 500 microns in diameter. They most often occur as single cells, although some species form chains

22
and colonies. Four dominant phytoplankton groups, of interest to the discussion of ocean fertilization are outlined below:

1. **Diatoms** (*Bacillariophyceae*): Typically ubiquitous in marine waters this group of large (typically 10 to 200 microns) single celled algae comprise many different species. Diatoms are distinguished by their rigid and often complex structured cell walls comprised of silica. They occur floating in the water column or attached to surfaces, singly or as chains of cells. They are the major contributors to photosynthetic production and are the only phytoplankton species which require the macronutrient silica for growth.

2. **Dinoflagellates**: The dinoflagellates are also widely distributed in marine environments, and are major contributors to photosynthetic production. They mostly occur as single cells, and are typically smaller than diatoms, ranging in size from 1 to 100 microns. Most species are motile, using a paired set of flagella for propulsion.

3. **Cyanobacteria**: Also known as blue-green algae, certain species of this group can fix atmospheric nitrogen gas to fulfill their nitrogen nutrient requirements. They occur as single cells or as bundles of longer filaments. Small marine cyanobacteria - *Prochlorococcus* and *Synechococcus* - are tiny organisms (~1 micron) who’s cells are so small that they have been unrecognizable until epifluorescence microscopy became available. They are now thought to dominate the seas in terms of numerical abundance but are not known to fix nitrogen.

4. **Coccolithophores**: These phytoplankton occur as single cells and are protected by ornate calcareous plates (coccoliths). Coccolithophores contribute to the biogeochemical carbonate pump in the oceans\(^2\).

**Other Plankton**

Although formally classified in the broader category of plankton, marine bacteria include a diverse group of microscopic unicellular organisms that thrive free-floating throughout the sea

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1 *Plankton* include all free-floating surface dwelling organisms. Those plankton that undertake photosynthesis are referred to as *phytoplankton*.

2 Refer later discussion in this chapter under 'THE OCEAN CARBON CYCLE: Biological Pump'.
and on the surface of just about everything including dead organic matter, living organisms and sediment grains. Bacteria play an important role in the ocean, recycling elements and organic materials back into the food chain.

Cell size is an important feature of marine plankton. Diameters of cells can vary over several orders of magnitude and so it is often used as a convenient method of subdividing and classifying plankton. Plankton less than 2 micron in size are called *picoplankton* - this group comprises mainly bacteria, cyanobacteria, and small eukaryotic phytoplankton. *Nanoplankton* is the term applied to small plankton between 2 and 20 micron in diameter - including diatoms and some other species. Cells in the size range 20-200 micron are *microplankton* - diatoms and dinoflagellates are common in this size class.

**Phytoplankton and Primary Production**

Phytoplankton are responsible for converting and storing solar energy in chemical form through the process of photosynthesis. This life-supporting process is described in the following equation:

\[
\begin{align*}
\text{PHOTOSYNTHESIS} \\
\text{chlorophyll & sunlight} \\
6\text{CO}_2 + 12\text{H}_2\text{O} & \rightleftharpoons 6\text{O}_2 + C_6\text{H}_{12}\text{O}_6 + 6\text{H}_2\text{O} \\
\text{carbon dioxide} & \quad \text{water} & \quad \text{oxygen} & \quad \text{glucose (sugar)} & \quad \text{water} \\
\text{RESPIRATION}
\end{align*}
\]

Equation 2-1: Photosynthesis and Respiration. *Photosynthesis* is the source of energy for nearly all life on earth, and is undertaken by phytoplankton and plants. The net reaction is shown above. The reverse of this reaction is *respiration*, carried out by all organisms, that live in aerobic environments. Energy is released and converted to high-energy intermediates during respiration. These are used to drive the biochemical processes of the cells.

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3 For fuller explanation of this process, refer to later discussion in this chapter under 'FUNDAMENTAL CONCEPTS: New and Regenerated production.'
Photosynthesis occurs when the reaction is driven to the right\(^4\). Energy is stored and carbon incorporated into living material (glucose). The reverse of this reaction is \emph{aerobic respiration}. In this process, energy is released for use by the cells when carbon is oxidized.

There are a number of terms typically used to quantify photosynthesis and biological production, which should be defined before proceeding.

The total fixation of energy by photosynthesis in a particular region is referred to as the \emph{Gross Primary Production (GPP)}. It is measured by the amount of inorganic carbon converted to organic carbon through photosynthesis and is denoted in units of mgC/m\(^2\). Gross primary production varies significantly across the earth’s waters.

\emph{Net Primary Production (NPP)} measures the amount of carbon fixed by photosynthesis in excess of the respiration demands of the phytoplankton. It is a measure of the extent to which the photosynthesis reaction proceeds to the right; the amount of net energy stored, and thus the amount available for growth. NPP decreases to zero at the base of the euphotic zone as photosynthetic activity is reduced.

A final term often referred to in evaluating ecosystem production is \emph{Net Community Production (NCP)}. This quantity is the total net carbon fixed by an ecosystem. It is equivalent to the net primary production minus the amount of carbon respired by all animals which comprise the community in any given region of the ocean.

\textbf{Limiting Factors}

Light and nutrients are the primary limiting factors regulating phytoplankton growth and thus primary productivity. Physics also plays an important role in this highly balanced biological system.

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\(^4\) Chemosynthesis is an alternative reaction to photosynthesis, depicted by the same equation. It is typically undertaken under light limited conditions by bacteria that use energy from chemical oxidation rather than sunlight to produce organic compounds from inorganic nutrients.
Light
Incident sunlight at the ocean surface is absorbed and scattered as it passes through the water column. Consequently, light intensity attenuates rapidly with water depth, penetrating to a maximum depth of about 200m in the open ocean. Thus, only a tiny 5% fraction of the total ocean volume is illuminated. This region of illumination, where primary production can occur, is referred to as the euphotic zone and extends to depths where light intensity is less than 0.1% of full sunlight (Fig 2-1). Phytoplankton rely on this euphotic zone for their survival.

Physics
Solar heating of the ocean’s surface layer gives rise to a physical phenomena which conveniently maintains the otherwise ‘slow sinking’ phytoplankton community in the life-sustaining euphotic zone. As surface waters heat, a temperature gradient referred to as a thermostcline is generated, which combines with salinity gradients to effectively separate the wind-mixed surface layers from the thousands of meters below (Fig 2-1).

The depth of the thermocline varies with season and location. As temperature decreases, and wind shear increases, the thermocline can be eroded and tends to deepen. Under these conditions phytoplankton can become light limited. Thermocline depth also effects the availability of nutrients in the surface waters.

Nutrients
Phytoplankton demand a steady supply of essential nutrients to sustain primary production. During photosynthesis these inorganic nutrients, together with CO₂, are converted to organic compounds in the surface layer of the ocean. Some carbon is immediately re-released during respiration. The remaining carbon and nutrients contribute to growth and reproduction (Eqn 2-1). Small marine animals graze on the multiplying plants and in turn respire or decay, releasing some CO₂ back into the surface waters, or serve as food for higher order organisms. When marine organisms die or excrete, they sink with gravity. Some of this organic matter is immediately recycled in the process of photosynthesis. Those that fall below the permanent thermocline take with them captured carbon and the nutrients vital for growth. Most of the
Figure 2-1: Light, Physics, and Primary Production (modified from Chisholm, 1992). Light intensity declines exponentially with depth. Phytoplankton photosynthesis also decreases with light and therefore depth, however, respiration remains constant. The euphotic zone continues to a depth at which light levels are 0.1% of its surface intensity. It is separated from the deep waters below by a sharp density gradient established by the thermocline.
organic carbon which arrives in the deep sea is ultimately assimilated by bacteria which then regenerate it to CO₂ and inorganic nutrients.

This mechanism, which results in the net conversion of inorganic carbon and nutrients in the surface waters, and then re-releases inorganic compounds at depth is commonly referred to as the biological pump. The biological pump depletes nutrients and carbon from the surface waters. The thermocline then acts as a partial barrier to mixing, hindering the return flux of these nutrients to the surface and concentrating them at depth. Over the time scale of centuries this can create a sharp nutrient concentration gradient from the surface waters to the ocean bottom (Fig. 2-2).

**Macro and Micronutrients**

A number of essential nutrients are critical to sustain phytoplankton production and growth. Macronutrients⁵ include nitrogen, phosphorus and silicon. Traditionally it has been understood that it is these nutrients that regionally limit phytoplankton growth. In addition, certain micronutrients⁶, although required in only low concentrations are indispensable to phytoplankton growth. The list of micronutrients is varied but includes trace elements such as iron, copper, manganese, zinc, and cobalt. Iron, in particular has been shown to locally limit phytoplankton growth (DeBaar et al. 1995), and speculation indicates it may even have regional influences (Falkowski 1997; Johnson et al. 1997; Martin et al. 1990a).

A tight coupling of phytoplankton and dissolved nutrient distributions has arisen over three billion years of co-evolution. Unlike common seawater ions, the concentration of nutrients in the oceans varies from location to location, indicating the important role of biota in the chemistry of the oceans. This observation drew the attention of Alfred Redfield at Harvard University earlier this century. By examining the uptake of nutrients by phytoplankton, Redfield discovered that these organisms invariably extract carbon, nitrogen and phosphorus from seawater roughly in the

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⁵ 'Macronutrients' are those nutrients required by organisms in relatively large quantities in order to grow and reproduce.
Figure 2-2: Schematic diagram of the biological pump (modified from Chisholm, 1995). Refer to detailed description of this mechanism in this chapter under *The Ocean Carbon Cycle*.

6 *Micronutrients* are nutrients typically required by organisms in relatively small quantities in order to grow and reproduce.
molar proportions of 106C:16N:1P (Redfield 1934; Redfield 1958). This ratio has become known as the ‘Redfield’ ratio. Although the amounts of dissolved carbon, nitrogen and phosphorus are known to vary enormously across locations, they vary approximately in this constant proportion and are also remarkably similar to the ratios of these elements observed in the phytoplankton themselves.

This observation provides some useful insights into the nutrient dynamics of the oceans. From a cursory examination of the Redfield ratio one might presume that carbon, which is required in large relative quantities, might be the limiting macronutrient. However, this is not the case. The ocean bicarbonate system stores 3900 GtC of dissolved carbon, more than 50 times the atmospheric levels (750GtC) (Holmen 1992). This would appear to be more than enough to sustain unheralded levels of primary production. Thus, in terms of final biomass yield, or ‘carrying capacity’, CO₂ seems unlikely to be a problem, however there is some debate that CO₂ may limit the rate of growth of some phytoplankton species (Raven 1993; Raven and Johnston 1991; Riebesell et al. 1993).

Typically, the nature of nutrient limitation tends to relate to the ‘availability’ of a nutrient relative to the biological demand. Thus, even micronutrients required in very small quantities can become limiting if present in concentrations too low to satisfy biological requirements.

The nutrient which tends to be central in the discussion of production limitation in marine systems is nitrogen. As early as 1971, Ryther and Dunstan (1971) demonstrated that it was the addition of nitrogen that stimulated growth of phytoplankton in marine environments. Although this conclusion cannot be considered universal, many nutrient limitation studies conducted since confirm that in the marine environment nitrogen tends to be the primary limiting nutrient,

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7 Silica is also included as one of these macronutrients. It is estimated to be required in the molar proportions of 106C:50Si:16N:1P.
although phosphorus does provide secondary limitation\(^8\) in many locations (Graneli et al. 1990; Ryther and Dunstan 1971).

It is believed that nitrogen assumes the limiting role in the ocean because of the scarcity of nitrogen-fixing blue-green algae (and hence rates of nitrogen fixation)\(^9\) in marine environments. The reason for the low proportions of these organisms in the oceans remains a matter of speculation, although Falkowski (1997) has recently presented new data which indicates iron may be responsible for limiting the growth of these marine organisms (Falkowski 1997)\(^10\).

Silicon may also become limiting for diatoms who require large amounts of dissolved silicon to form their intricate shells (Dugdale and Wilkerson 1998; Round et al. 1990; Smetacek 1998). Diatoms, due to their large cell size, make a significant contribution to fish yield and carbon export (Ryther 1969). Also, these are the organisms that have been shown to be preferentially enhanced during iron fertilization experiments (Coale et al. 1996).

Scientific interest has recently been drawn to the significance of micronutrients, such as trace metals, in limiting phytoplankton growth. Iron is one of these trace elements, and has attracted much interest. The phenomena of iron limitation has already been explained in chapter one. It has particular significance because of the low quantities of iron required by biota - meaning that the addition of small amounts of iron has the capacity to generate large increases in productivity. The ‘revised’ Redfield molar ratio, which incorporates iron, can be approximated as follows:

\(^8\) When inputs of a primary limiting nutrient occur in excess of the Redfield ratio, the ecosystem is no longer constrained and productivity is enhanced to levels at which a second nutrient may become limiting - the ecosystem is then said to be subject to secondary limitation

\(^9\) As opposed to freshwater aquatic environments which are characterized by high abundance of blue green algae making these systems phosphorus limited.

\(^10\) Refer chapter 3, under ‘CLIMATE RESEARCH AND EXPERIMENTS’ for discussion of this new twist to iron limitation theory.
Equation 2-2: Revised Redfield Ratio. Median C:Fe molar ratio deduced from average values obtained in cultures. These typically range from between ~ 10,000 and ~400,000, (e.g., Anderson and Morel, 1982; Laurel and Hudson, 1985; Sunda, 1991) (obtained from Sarmiento and Orr 1991)

‘Top-down’ control
Nutrient limitation offers what is commonly referred to as ‘bottom-up’ control of marine ecosystem production. An alternative mechanism which may control phytoplankton growth is ‘top-down’ control whereby the grazing of herbivorous plankton also keep the phytoplankton population in check, preventing if from achieving maximum production. In practice, however it is likely that a number of factors combine to limit the rate of photosynthesis - seldom is one factor singularly limiting over time (Brandini 1993; Riley 1946; Riley 1947).

New and Regenerated Production
Nutrients are cycled through the oceans by biological and physical processes, and are utilized by phytoplankton to generate primary production. A large portion of this primary production is recycled, giving rise to ‘regenerative production’. The remaining primary production is referred to as ‘new production’. This amount may be lost to sedimentation, or alternately consumed and transferred up the food web.

Regenerated Production
Regenerated production is driven by nutrients recycled within the surface waters of the ocean. Inorganic nutrients are taken up by phytoplankton in the euphotic zone and transformed to organic material, promoting growth and reproduction. Surface dwelling bacteria and microzooplankton then complete this ‘microbial loop’. By decomposing the dead tissue of phytoplankton and grazers, bacteria re-release essential inorganic nutrients into the surface water where it is once again available to phytoplankton (Fig 2-3).
Figure 2-3: Simplified diagram of the microbial loop. Inorganic nutrients and CO₂ are taken up by phytoplankton in the euphotic zone and transformed to organic material, promoting growth and reproduction of grazers. Surface dwelling bacteria and microzooplankton complete this loop decomposing some of the dead tissue of phytoplankton and grazers, and re-releasing essential inorganic nutrients into the surface waters where it is once again available to phytoplankton. This portion of primary production is referred to as ‘regenerated production.’ Not all dead organic matter is taken up by bacteria. Instead, some is sedimented, sinking below the euphotic zone, completing the action of the biological pump (refer to Figure 2-2).
Without the efficient microbial loop, nutrients would remain chemically bound in the tissue of animals and plants and be lost in the sinking or 'sedimentation' process. But instead this regenerated production maintains the surface biota in a tightly balanced and highly efficient cycle of production and consumption in the euphotic zone. It is estimated that 90% of the open ocean production is consumed and recycled within the upper 100m of the water column in this manner (Holmen 1992b; Murray 1992). Recycled or regenerated production does not contribute to net community production. Although it is the fundamental process which sustains phytoplankton in the ocean, it does not add to carbon export to the deep sea, or result in net production.

**New Production**

Only the introduction of 'new' nutrients from deep waters can create *new production*. Inorganic nutrients and carbon introduced to the euphotic zone are transformed to organic matter by phytoplankton and ultimately sedimented, respired or consumed and stored in the food web. Thus it is new production - and not the combined total of new and regenerative production, or 'total primary production' - that sets an upper limit for the production of harvestable ocean resources (Sakshaug and Slagstad 1992). Actual harvest however, is unlikely to reach these new production levels in practice, because of the competing processes of sedimentation and respiration.

Three major oceanic mechanisms replenish surface waters with nutrients from depth, and generate new production.

1. **Diffusion:** Some nutrient replenishment arises from a slow process of diffusion across the thermocline
2. **Seasonal Mixing:** Seasonal variations in wind shear, light intensity, and temperature can deepen the thermocline and entrain nutrients from below. This gives rise to seasonal cycles of production.
3. **Upwelling:** Prevailing winds and diverging surface currents can induce upwelling bringing nutrient laden waters to the surface. This regional phenomena is witnessed along the western
edge of some continents. Upwelling is also observed as a result of thermohaline circulation\textsuperscript{11}. This effect produces some of the world's most productive oceanic regions and coincides with the world's greatest fisheries.

**Global Patterns of Productivity**

Nutrient fluxes vary significantly across the oceans according to the prevalence of diffusion, seasonal mixing and upwelling. This gives rise to distinct patterns of global primary production. Table 2-1 presents estimates of total and new primary production in different oceanic zones.

Table 2-1: Estimates of Total and New Primary Production from (Knauer 1993)

<table>
<thead>
<tr>
<th>Eco-System Type</th>
<th>Area (% ocean)</th>
<th>Mean Prod (gC/m\textsuperscript{2}yr)</th>
<th>New Prod. (gC/m\textsuperscript{2}yr)</th>
<th>New Prod. (%)</th>
<th>Total Global Prod. (10\textsuperscript{15} gC/yr)</th>
<th>Global New Prod. (10\textsuperscript{15} gC/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>open ocean</td>
<td>90</td>
<td>130</td>
<td>18</td>
<td>14</td>
<td>42</td>
<td>5.9</td>
</tr>
<tr>
<td>Coastal zone</td>
<td>9.9</td>
<td>250</td>
<td>42</td>
<td>17</td>
<td>9.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Upwelling area</td>
<td>0.1</td>
<td>420</td>
<td>85</td>
<td>20</td>
<td>0.15</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>51</strong></td>
<td><strong>7.4</strong></td>
</tr>
</tbody>
</table>

The vast central regions of the ocean circulation gyres (or open oceans) have low phytoplankton biomass\textsuperscript{12}. Downwelling waters in these regions carry nutrients away from the euphotic zone, limiting growth. Water in the center of these gyres is also highly stratified, because the intense sunlight creates a permanent thermocline. These stable waters prevent overturning so deep nutrient-rich water is prevented from reaching the euphotic zone. In these regions nutrient supply relies on slow diffusive mechanisms.

Coastal zones and continental shelves are characterized by moderate rates of primary production. This is due to inputs of dissolved nutrients from rivers and anthropogenic sources. The shallow

\textsuperscript{11} For further explanation of the processes that cause thermohaline circulation refer to discussion later in the chapter under 'THE OCEAN CARBON CYCLE: Thermohaline circulation'.

\textsuperscript{12} The central gyres are often described as the 'ocean deserts' as a result of this absence of life.
depths of these regions also means they tend to be well mixed by wave activity and tides. In the mid latitudes seasonal mixing can stimulate blooms of primary production in these regions.

In the polar sea and along the equatorial upwelling belt, the surface water is kept fertile by thermohaline circulation which slowly raises relatively nutrient rich water from below. These regions are moderately productive.

The most fertile areas are coastal upwelling regions. These are stimulated by prevailing winds and currents and are typically located along western edges of landmasses in the low to middle latitudes. Perhaps the most notable of these is the waters adjacent to Peru, Canary Islands, and Benguela in South West Africa - the homes of some of the world’s largest fisheries.

As nutrients are cycled through the marine environment, CO$_2$ is converted to organic carbon and regenerated back to CO$_2$. A more detailed description of the mechanisms that sequester carbon and generate biological production in the oceans follows.

**THE OCEAN CARBON CYCLE**

The oceans contain approximately 90% of the biosphere’s total actively circulating carbon (Siegenthaler and Sarmiento 1993) (Fig 2-4). As well as being the largest single reservoir of circulating carbon, the oceans serve two other significant functions.

(i) The large, and relatively easily exchangeable reserves of dissolved inorganic carbon found in the surface waters of the oceans are thought to play a major role in controlling atmospheric CO$_2$ levels (Summerhayes et al. 1995); and

(ii) The oceans play a primary role in the formation of sediments, which is the process by which carbon, including atmospheric carbon dioxide is removed from active circulation.

(iii) For these reasons, the oceans play a fundamental role in the global carbon cycle. Carbon enters the marine component of the global carbon cycle -or ‘ocean carbon cycle’- predominantly through air-sea exchange.
Figure 2-4: Box model of the global carbon cycle, reservoirs and fluxes (modified from Siegenthaler and Sarmiento, 1993). The ocean carbon cycle comprises the surface ocean and its biota, dead organic matter and the deep waters. Together they constitute approximately 90% of the biosphere's actively circulating carbon.


**Air-sea exchange**

Atmospheric CO₂ readily enters the ocean by diffusing across the air-sea interface and dissolving in the surface waters. The rate and direction of the flux of CO₂ is directly dependent on the difference in gas concentrations between the atmosphere and the surface waters, and is a function of water temperatures, wind velocity and sea condition. The amount of CO₂ absorbed by the oceans is thus highly variable. Indeed, there are some regions of the oceans, such as the equatorial Pacific where these factors combine to cause a net flux of CO₂ *out of* the ocean and *into* the atmosphere. Upwelling of carbon-rich waters into the warm equatorial regions results in a high saturation of CO₂ in the ocean waters and the release of CO₂ into the atmosphere. As a global average however, it is estimated that 2GtC/yr is uptaken by the oceans through air sea exchange (Sarmiento and Sundquist 1992).

Within the surface waters only a small amount of the CO₂ gas remains in dissolved form. Instead, most of it tends to dissociate forming the following equilibria. (Eqn 2-3)

**Equation 2-3: CO₂ Carbonate System**

\[
\text{H}_2\text{O} + \text{CO}_2(\text{g}) \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{HCO}_3^- + \text{H}^+ \leftrightarrow 2\text{H}^+ + \text{CO}_3^{2-}
\]

Under typical conditions, around ninety percent of the inorganic carbon in the sea occurs as bicarbonate ions (\text{HCO}_3^-), an estimated ten per cent forms carbonate ions (\text{CO}_3^{2-}) and less than one per cent occurs as CO₂. The exact concentration of dissolved CO₂ in the seawater depends on a number of factors, including temperature, total concentration of organic carbon and alkalinity (Holmen 1992). Typically, the solubility of CO₂ increases with increasing organic carbon concentration, increasing alkalinity and decreasing temperature.

A notable aspect of the CO₂ carbonate system is it’s buffering capacity. An increase in the partial pressure of CO₂(\text{g}) generates a proportional increase in the concentration of carbonic acid
(H$_2$CO$_3$). The ionic forms (i.e. HCO$_3^-$, CO$_3^{2-}$) of this carbonate system however, change little, due to acid-base equilibria (Holmen 1992). This buffering phenomena has significance for the CO$_2$ uptake capacity of the ocean. When sea water absorbs additional CO$_2$, the equilibria between the carbon species (CO$_2$, HCO$_3^-$ and CO$_3^{2-}$) shift, lowering the pH (and increasing the alkalinity) of the water and thus reducing the solubility of CO$_2$. As a consequence, the ocean cannot achieve it’s theoretical storage capacity. In reality, carbon storage is reduced tenfold from 65 times the quantity of carbon in the pre-industrial atmosphere, to a factor of 6.5 at equilibrium. And even this reduced capacity can only theoretically be achieved when CO$_2$ is diffused throughout the water column so that the entire ocean is equilibrated with the new atmospheric CO$_2$ concentration. This process would take in the order of 1000 years$^{13}$ (Siegenthaler and Sarmiento 1993). The current rate of increase in atmospheric CO$_2$ concentrations prevents this steady state from being achieved.

The dynamics of the oceanic uptake of CO$_2$ is strongly determined by the rate at which carbon is transferred from the surface waters to the deep ocean where it can then be isolated for centuries. Two major processes influence the rate at which CO$_2$ is removed from the atmosphere. These are commonly referred to as the ‘biological pump’ and the ‘solubility pump’.

**Biological Pump**

The biological pump has been introduced in earlier discussion. It comprises phytoplankton, their animal predators and bacteria whose actions generate two discrete and opposing mechanisms - the ‘carbon pump’ and the ‘carbonate pump’.

Phytoplankton uptake CO$_2$ from the atmosphere as well as surface water nutrients converting them to organic carbon through photosynthesis and light energy (Eqn 2-1). The organic carbon generated is then either consumed and used to fuel biological production at higher trophic levels; is recycled; or is sedimented as waste and deposited in the deep sea. This highly balanced process is sometimes referred to as the *carbon pump*.

$^{13}$ 500-1000 years is the approximate turnover rate of the deep ocean, and the time required for the deep ocean to
The net effect of the carbon pump is that carbon is delivered from the surface waters to the deep sea according to the elemental proportions of the Redfield ratio (106C:16N:1P). About 106 atoms of carbon is delivered to the depths of the ocean for every 16 atoms of nitrogen and 1 atom of phosphorus extracted from the surface waters. This reduces the partial pressure of CO$_2$ in the surface waters driving additional air-sea exchange of CO$_2$ into the ocean, and thereby reducing the levels of CO$_2$ in the atmosphere.

The *carbonate pump* is another component of this biological pump. Phytoplankton, particularly coccolithophores$^{14}$, and other calcified surface organisms, utilize bicarbonate ions to produce their hard CaCO$_3$ shells as they grow.

\[
\text{Ca}^{2+} + 2\text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} + \text{CO}_2
\]

Equation 2-4: The Carbonate Pump

During this process CO$_2$ is re-released into surface waters retarding the CO$_2$ gas exchange across the air-sea interface into the oceans. Typically, the carbon pump is the dominant biological mechanism, resulting in a net export of carbon to depth. However, the ratio of production of calcite to the production of organic carbon - termed the *rain ratio* - remains very important in determining the sequestration capacity of the biological pump (Broecker and Peng 1982; Heinze and Maier-Reimer 1991; Yamanaka and Tajika 1996)

**Solubility Pump**

Superimposed on the biological pump is a *solubility pump* which also has the net effect of concentrating dissolved inorganic carbon in the deep ocean.

equilibrare with the atmosphere.

$^{14}$ Recall from earlier discussion this chapter, that coccolithophores are a species of phytoplankton characterized by calcereous plates
The solubility pump is a physically-driven process generated by variations in CO₂ solubility with temperature and salinity. Carbon dioxide becomes more soluble at lower temperatures and lower salinity. This serves to drive dissolved CO₂ into the colder waters in the deep ocean which have higher solubility and greater storage capacity. This general movement of CO₂ deeper into the water column leaves a CO₂ deficit in the surface waters, increasing the partial pressure differences between the atmosphere and the shallow ocean waters, and forcing further CO₂ exchange into the sea.

This process is very slow. Although surface sea water is typically capable of reaching equilibrium with atmospheric CO₂ concentrations within one year (Siegenthaler and Sarmiento 1993) it takes many centuries for the CO₂ to reach the large reservoirs of the deep sea by this process alone.

**Thermohaline circulation**

In some high latitude regions of the ocean, cold water forms near the surface, absorbs high levels of CO₂, and sinks as a result of salt and temperature-induced density differences. This process of mass water convection is called thermohaline circulation and enhances the effects of the solubility pump. Saline, cold, carbon-laden waters of the polar regions sink and become the bottom waters throughout the marine environment. This bottom water spreads from the poles and enters a continuous circulation that connects the earth’s ocean basins, upwelling from the deep at regions such as the equatorial Pacific. This continuous cycle is often metaphorically compared to a ‘conveyor belt’. It is a long and slow process. It may take thousands of years for a single parcel of water to complete it’s circular journey (Mann and Lazier 1991).

**Significance of biological and solubility pumps**

The net result of the biological and solubility pumps is that carbon, along with essential nutrients are converted according to approximate molar Redfield proportions of 106C: 16N: 1P: 0.001 Fe and recycled in the surface waters many times, before eventually being exported to the deep sea as particles and aggregates. Most of this particulate organic matter is remineralized by living species in the deep oceans. A small proportion is permanently sequestered in the sea floor
sediments. However, the majority of remineralized product is stored in a massive reservoir of concentrated carbon dioxide until it is eventually recycled back into contact with the atmosphere, driven to the surface by thermohaline circulation in 500-1000 years. A number of recent modeling exercises have examined the relative importance of the solubility and biological pumps in this process (Table 2-2).

Table 2-2: Box Model Scenarios of Atmospheric CO₂ concentration
Results below summarize findings from various ocean model simulations. Full operation of the biological pump was modeled by assuming complete removal of surface water nutrients. Partial operation of the biological pump describes the present situation without anthropogenic CO₂ perturbation. (From Sarmiento and Orr (1991))

<table>
<thead>
<tr>
<th>Solubility Pump</th>
<th>Biological Pump</th>
<th>Pre-industrial pCO₂ (ppm)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>no</td>
<td>720</td>
<td>Volk and Hoffert (1985)</td>
</tr>
<tr>
<td>Yes</td>
<td>no</td>
<td>450, 530</td>
<td>Wenk (1985); Bacastow and Maier-Reimer 1990; Baes and Killough 1986.</td>
</tr>
<tr>
<td>Yes</td>
<td>full</td>
<td>165</td>
<td>Sarmuento and Toggweiler (1984)</td>
</tr>
<tr>
<td>Yes</td>
<td>partial</td>
<td>280</td>
<td>Neftel et al. 1985</td>
</tr>
</tbody>
</table>

These results suggest that the biological pump is responsible for about 40% of the carbon export to depth. The models indicate that if the solubility and biological pump had not functioned, pre-industrial levels of CO₂ would have reached 720 ppm. With only the solubility pump in operation, the pre-industrial concentration of CO₂ in the atmosphere was predicted to reach 450 ppm. Assuming full utilization of nutrients, and the combined actions of the solubility and biological pumps, the models forecast a pre-industrial atmospheric CO₂ value of 165 ppm. This result can be compared with measurements taken from gas bubbles in ice-cores, that indicate pre-industrial levels of CO₂ in the atmosphere was actually 280 ppm. This would seem to indicate that either our estimates of the global carbon cycle are wrong, or the biological pump is not currently achieving it’s full potential.
The hypothesis that the biological pump is currently only partially functioning is supported by anomalies witnessed in high nutrient low chlorophyll (HNLC) regions of the Southern Ocean and areas of the Equatorial Pacific (Gran 1931). In these regions, Redfield’s ratio are not precisely obeyed. Primary productivity levels remain low despite a surplus of dissolved nutrients in surface waters and the tight coupling of nutrients to phytoplankton appear to have broken down (Martin 1990a; Martin 1992; Martin et al. 1994; Martin et al. 1990a; Martin et al. 1993; Martin and Gordon 1988; Martin et al. 1990b; Martin 1990b).

Ocean Anomalies - the HNLC Southern Ocean
The high nutrient, low chlorophyll (HNLC) regions of the Southern Ocean have special importance in the global carbon cycle. Comprising a little over 10% of the earth’s ocean surface, this body of water, surrounding the Antarctic continent, represents the single largest reservoir of unutilized nutrients in the surface waters of the sea. Even more significantly, it is only one of three regions where surface waters sink, offering a highly efficient mechanism for sequestration of CO₂. Indeed, a leading theory suggests that changes in productivity in the Southern Ocean played a key role in glacial/interglacial transitions in atmospheric CO₂ (Knox and McElroy 1984; Martin 1990a; Sarmiento and Toggweiler 1984; Siegenthaler and Wenk 1984).

Low temperatures and seasonal light provide scientists with inadequate explanation for the high stock of nutrients found in the waters of the Southern Oceans. Despite much speculation, this apparent anomaly could only recently be satisfactorily explained. In the late 1980’s a new hypothesis was put forward by the late John Martin. From field observation and bottle experiments he deduced that the trace element iron was the factor limiting production in the Southern Ocean and other nutrient rich areas such as the equatorial and subarctic Pacific (Martin 1990a). In a pair of revolutionary mesoscale fertilization experiments Martin and colleagues successfully tested his hypothesis in the equatorial Pacific, first in 1993 and again in 1995 (Behrenfeld et al. 1996; Coale et al. 1996; Cooper et al. 1996; Frost 1996).

---

15 Zones where primary production (and chlorophyll levels) are low despite an abundant supply of nutrients are
Trial fertilization experiments to verify the iron limitation theory in the HNLC regions of the Southern Ocean are now proposed for early next year (Coale 1997)\textsuperscript{16}. If successful, the abundant nitrogen and phosphorus nutrient supplies could be completely converted to organic matter in the surface waters. Unlike other HNLC regions of the ocean\textsuperscript{17}, surface waters in the Southern Ocean sink due to thermohaline circulation, capturing CO\textsubscript{2} and significantly increasing the amounts of carbon delivered and isolated in the deep sea. Fertilization in this unique region would thus benefit from the combined action of biological and mass physical subduction processes, ensuring CO\textsubscript{2} is isolated from the atmosphere for many hundreds of years.

**OCEAN PRODUCTION**

Discussion thus far has focused on the role of the oceans in the global carbon cycle. An equally important dimension of marine biological activity is the means through which it cycles and transfers energy and matter to produce food for consumption by animals, and ultimately humans.

**Marine Ecosystems**

Marine ecosystems are typically organized into a series of ‘trophic levels’ according to the flow of energy and matter. Trophic levels define the position an organism occupies in the food chain and are determined by the number of energy transfer steps to reach a particular level. Trophic levels are commonly arranged into a simple *food chain*, or more complex *food webs* which depict the network of ecosystem members and their food relationships (Fig 2-5).

---

\textsuperscript{16} Further discussion of these proposals can be found in chapter 3.

\textsuperscript{17} Regions of the Equatorial Pacific also exhibit the HNLC anomaly. Iron limitation was confirmed in these regions during the IRONEX experiments. However these zones are less favorable for carbon sequestration because carbon export to the deep relies solely on the biological pump. Thermohaline circulation in the equatorial Pacific also counters the effect of the biological pump, bringing CO\textsubscript{2} rich upwelling water to the surface, and generating a net flux of CO\textsubscript{2} outwards from the ocean.
Figure 2-5: Simple food chain (modified from Pinet, 1998). Trophic levels define the position an organism occupies in the food chain and are determined by the number of energy transfer steps required to reach a particular level. Energy and matter is passed up the food chain from the primary producers to the primary consumers, then secondary consumers, tertiary consumers, and so on.

Figure 2-6: Biomass pyramid. Measurements of grams dry weight/m² for the English Channel from Harvey (1950). Primary Consumers tend to have greater biomass than primary producers in aquatic systems.
Within these community structures phytoplankton are ‘primary producers’ (also referred to as ‘autotrophs’\(^{18}\)) and occupy the first trophic level. Above the primary producers are the consumers (or ‘heterotrophs’\(^{19}\)). Energy and matter is transferred through the ecosystem from primary producers to the ‘primary consumers’. These are herbivores that graze plants at the second trophic level. The primary consumers are then eaten by ‘secondary consumers’, and so on, up the food web. Secondary consumers are carnivores and consume flesh at the third trophic level and above. Top predators such as large animals and humans typically reside at the fifth or sixth trophic level.

**Production and the ‘matter cycle’**

There are a number of additional definitions that are useful in understanding the dynamics of fish production and the marine matter cycle. The ‘bodies’ of the living organisms within a unit area constitute a standing crop of ‘biomass’. Biomass is commonly expressed as grams per unit area (or unit volume). The ‘primary productivity’ of a community is the rate at which biomass is generated by the primary producers per unit area.

In aquatic communities a unique relationship exists between productivity and biomass. Biomass tends to increase in the higher trophic levels even though productivity declines in this direction \(^{20}\). Thus the small highly productive biomass of short-lived phytoplankton supports a larger biomass of long-lived zooplankton, in what can be represented as an inverted biomass pyramid (Fig 2-6). This phenomena is partially explained by the efficiency of phytoplankton organisms, who have no support tissue to maintain. Most importantly, however, this phenomena is due to the rapid turnover of phytoplankton biomass. The annual net primary productivity of an aquatic community is actually produced by a succession of overlapping phytoplankton generations, whilst the standing crop biomass is only the average present at any instant.

---

\(^{18}\) An ‘autotroph’ is defined as any organism that generates its organic material from inorganic sources - it is independent of outside sources for organic food materials.

\(^{19}\) Any organism with a requirement for energy-rich organic molecules is typically referred to as a ‘heterotroph’.

\(^{20}\) In contrast terrestrial systems typically display declining biomass and productivity at higher trophic levels.
Energy Transfer in Marine Food Webs

Energy is passed upward in a step wise fashion through the food web to higher trophic levels. This energy is used by animals to grow and to reproduce. ‘Secondary productivity’ is defined as the rate of production of new biomass by heterotrophic organisms (or the primary consumers). Since secondary productivity relies on primary productivity, a positive relationship should be expected and is indeed, typically observed between the two. However, secondary productivity is generally an order of magnitude less than the primary productivity upon which it is based. This is because in grazer systems the transfer of energy from trophic levels is not efficient.

The losses of energy or productivity through the food chain can be explained by a number of mechanisms. Not all the biomass that is eaten is assimilated, and thus available for incorporation into consumer biomass. Some is assimilated but lost in faeces and this is passed to the decomposers. Finally, not all the energy assimilated is converted to biomass but some is instead lost as respiratory heat, or work. These three energy pathways occur at all trophic levels (Fig 2-7).

It is estimated that on average 90% of the energy which passes from one trophic level to the next in aquatic communities is either lost, not assimilated, expended as kinetic energy, or is used in the manufacturing of non-nutritional tissue, such as shell, bone, chitin, scales, and the like. Only the remaining 10% of the energy from the food is used to increase mass, either by growth of the individual organism or by reproduction (Pauly and Christensen 1995). This relationship exists at each step in the food chain and is called the ‘trophic energy transfer efficiency’.

As a result of these heavy trophic level losses, the longer the food chain (i.e., the more trophic level losses incurred), the greater the amount of required plant productivity to supply the nutritional needs of top predators. To maximize fish biomass production it is advantageous to harvest the lowest possible trophic level (Pauly et al. 1998).
Figure 2-7: Energy pathways at a single trophic level (modified from Begon, Harper and Townsend, 1996). Energy (or productivity) is lost at each trophic level in the food chain to the decomposer system, and in respiratory heat.
In reality, trophic energy transfer efficiencies vary significantly in different regions of the ocean. A compilation of trophic studies from a wide range of freshwater and marine environments completed by Pauly and Christensen (1995) revealed that trophic level energy transfer efficiencies range between about 2 and 24%, with a mean of 10.13% (Pauly and Christensen 1995). A similar earlier compilation also found that, although both mean transfer efficiencies and primary productivity varies throughout the ocean, there is no correlation between the two. Thus, even unproductive offshore systems pass their energy up the food chain as efficiently as productive coastal zones (Pauly and Christensen 1990).

Nevertheless, overall ecosystem efficiency is improved in highly productive waters. In regions that are naturally highly fertilized, organisms are larger and food chains are shorter and more efficient (Ryther 1969). It can be expected that the larger the phytoplankton cell size at the beginning of the food chain, the fewer the trophic levels that are required to convert the organic matter to a useful form, the less energy losses will be incurred in trophic transfers, and the more productive the region will be.

Primary Production is also found to make a greater proportional contribution to the fish food web in highly productive zones. In a recent study Pauly and Christensen (1995) calculated a ‘Primary Production Required (PPR)’ value for different oceanic regions. This value is defined as ‘the primary production required to sustain each group of species’. Using global fish catch and discard statistics, and assuming a 10% trophic energy transfer efficiency, the amount of ocean primary production which is required to maintain the fish food web was estimated [PPR = (dry catch weight) \times 10^{(TL-1)}]. For unproductive open ocean areas, this number was found typically to be about 1.8%. In contrast, in highly productive upwelling zones, the PPR value was found to increase to 25.1% (Table 2-3).
Table 2-3: Global Estimates of Primary Production Required (PPR) to Sustain World Fisheries from Pauly and Christensen (1995).

<table>
<thead>
<tr>
<th>Ecosystem Type</th>
<th>Trophic Level of Catch</th>
<th>Mean PPR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>open ocean</td>
<td>4.0</td>
<td>1.8</td>
</tr>
<tr>
<td>upwellings</td>
<td>2.8</td>
<td>25.1</td>
</tr>
<tr>
<td>tropical shelves</td>
<td>3.3</td>
<td>24.2</td>
</tr>
<tr>
<td>non-tropical shelves</td>
<td>3.5</td>
<td>35.3</td>
</tr>
<tr>
<td>coastal/reef systems</td>
<td>2.5</td>
<td>8.3</td>
</tr>
<tr>
<td>rivers and lakes</td>
<td>3.0</td>
<td>23.6</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2.8</strong></td>
<td><strong>8.0</strong></td>
</tr>
</tbody>
</table>

**CONCLUSION**

This now completes a brief review of the fundamental biological, chemical and physical principles underlying oceanic processes. The oceans occupy a vast expanse of the earth's surface. It's processes play a vital role in the modulation of the climate, and it's life remains one of our last, relatively untouched, living resources. It is therefore not surprising that there is increasing interest in manipulating this large and powerful force for human purposes. We now turn to a discussion of ocean fertilization, commencing with an examination of recent activities in this rapidly emerging field.
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Equipped with the necessary background information, we now turn to a discussion of ocean fertilization schemes. The success of the IRONEX experiments has spawned widespread scientific, political and commercial interest in ocean fertilization (Blakeslee 1990; Institute for Urban Development Research 1994; Kaiser 1995; Nadis 1998; Sorensen 1995; Vovcsko 1997; Warsh 1996; Wells 1994). There are currently a wide sweep of proposals which advocate alternative forms of nutrient enrichment for both climate mitigation and food production goals. Publicity has tended to focus on ocean fertilization as a climate mitigation option and research efforts have been directed towards this end (Chisholm and Morel 1991; DeBaar et al. 1995; Martin et al. 1990; Sarmiento 1991; Watson 1997). In contrast, the private sector have been captivated by ocean fertilization as a potential productivity enhancing and food production technique (Hoell 1994; Jones 1996b; Markels 1995a; Markels 1996). This chapter compiles and reviews current global activity in the field of ocean fertilization. A description of current marine productivity initiatives, climate mitigation research, as well as proposed ocean fertilization projects follow.

MARINE PRODUCTION INITIATIVES

In recent years there has been a great deal of commercial interest in the potential of enhancing marine production (or ‘marine harvest’), by ocean fertilization as well as many other means. A number of research programs, as well as the Ocean Harvest 97 scientific gathering have been funded and directed by private companies who are interested in exploring new ways of exploiting ocean resources. Many of these programs are well-advanced, and several projects progress towards full scale implementation.

Maricult

MARICULT is a Norwegian-led research program, designed to investigate the ‘possibilities and environmental constraints for increased effective production and harvesting of food and raw materials from the sea’ (Hoell and Olsen 1996). It is amongst the first research programs to seriously experiment and develop open ocean fertilization techniques for commercial purposes.
The program was formally initiated in 1996 by international corporation Norsk Hydro, and since this time has been developed in collaboration with the European marine science community, Norwegian Universities, Research Institutes and various government authorities and agencies (Hoell et al. 1993).

The research agenda of Maricult has a dual focus: marine food webs/fisheries and marine macroalgae.

(i) Marine food web research has focused on quantifying how fertilization and restocking of marine systems impact the biological yield of the oceans. Research has examined the effects of marine fertilization on the uptake and retention of CO₂ in the oceans and evaluated associated harmful side effects, in particular eutrophication.

(ii) Marine Macroalgae is also being tested for harvest potential. Large scale experimental macro-algae farms are being planned for open ocean regions in order to quantify relationships between biomass production and nutrient availability.

Generally, Maricult field work has involved small to medium scale fertilization trials in both inland and offshore waters within Europe. Scientists hope to reproduce conditions of naturally occurring productive zones in the oceans by controlled and balanced addition of various fertilizer mixes that mimic natural nutrient replenishment processes (Hoell 1996).

Researchers anticipate that both the quantity and efficiency of fish production will be enhanced by fertilization. They expect the ecosystem to adjust to the elevated nutrient levels, shifting to shorter and more efficient food chains such as those found in the naturally fertilized, highly productive, upwelling zones (Ryther 1969). In these areas the contribution of primary production to fish growth is enhanced (Pauly and Christensen 1995). According to Maricult scientists, there are no undesired side effects from the ‘natural fertilization’ which occurs in these productive zones, and it is suggested that this should be considered convincing illustration of the potential for artificial fertilization (Hoell and Olsen 1996). These claims however, have yet to be experimentally verified, and results from the research program have not been forthcoming.
The Maricult program has suffered from intense criticism from European Non-governmental Organizations (NGOs) and environmental lobby groups, who claim this joint science-industrial effort is an excuse to make profit by destroying the environment. The North Sea Monitor, an environmental newsletter for the North East Atlantic point out that 'Norsk Hydro is the world’s largest manufacturer of artificial fertilisers, terrestrial markets are stagnant, and they stand to reap huge profits from any future ocean fertilizer sales' (Lutter 1996). In short, Norsk Hydro’s motives for ocean fertilization are questioned (SAR 1996).

Concerned NGOs argue that similar anthropogenic influxes of nitrates and phosphates to coastal and inland European waters have been the cause of reduced biodiversity, eutrophication and associated environmental problems. These negative impacts have overridden any the ‘benefits’ of enhanced primary production. NGOs claim that Maricult violates regional conventions such as the 1992 OSPAR ¹ Convention for the Protection of the Marine Environment of the North East Atlantic - an agreement that places specific controls on nutrient discharges (Lutter 1997).

**Marino Forum 21**

MARINO FORUM 21 is perhaps the most well-advanced of the current productivity enhancement initiatives. A joint government/private funded program, Marino Forum 21 was established in Japan in 1987 for the purpose of improving productivity of fisheries and aquaculture in Japan’s Exclusive Economic Zone (EEZ). Major projects undertaken by this group include artificial upwelling and ‘sea’ fertilization.

**Artificial Upwelling**

The lead Marino Forum 21 project - now underway for almost a decade - has been an experiment to artificially create upwelling flow, raising nutrient rich bottom water into the euphotic zone (Morimura 1997). Although avoiding some of the problems of external nutrient addition, this projects reflects the kind of ocean manipulation that is being developed in the search for enhanced marine harvest.

¹ Oslo and Paris Comission (OSPAR). For further discussion of the OSPAR Convention refer to chapter 6.
Commencing in 1987, a series of concrete structures have been constructed at 50m depth to guide tidal currents into upwelling flow in the sea of Uwa off the shore of Ehime prefecture, Shikoku. The completed upwelling structure is 10m high (20% of depth) with a total width of 190m. The mean quantity of upwelling water generated by the system is 278 m$^3$/min under typical tidal velocities of 0.5m/min. Monitoring is reportedly ongoing, but no reports are currently known to be available.

Results reported by Morimura (1997) indicate that dissolved nitrogen has increased 2.6 times in the vicinity of the structure. Wide expanses of high nutrient water have also been observed in the area. Phytoplankton abundance has been enhanced by a factor of 7.5-25 and zooplankton biomass has increased 2.3-2.6 times. Remote aerial sensing reportedly indicates that cold water masses about 1km$^2$ in extent were brought to the surface behind the upwelling structure. These zones correlate with areas of elevated chlorophyll concentrations. Anecdotal evidence from fisherman suggest that the fish harvest has increased by a factor of two in the vicinity. No reports on the environmental impacts of this project could be located. Research data was also unavailable.

The experiment developed under Marino Forum 21 is now reportedly being adopted by private companies. It is understood that commercial applications of this project are currently being presented for public review. The first prototype commenced construction off Matsuura Nagasaki prefecture Kyusyu in 1995. There is limited additional information currently available on this work (Morimura 1997).

**Sea Fertilization**

The Marino Forum 21 program have also conducted sea fertilization trials, but with limited success. A practical field test for the improvement of the productivity of marine plants by fertilization was undertaken in Hookkaid for a 4 year period from 1986 (Morimura 1997). Three tons of fertilizer, comprising predominantly fish dregs, but including 10% pure nitrogen; were added annually to waters on the coast of Syukuzu, Hokkaido. Fertilizer was added in 10 installments in 1987, 2 installments in 1988 and a single addition in 1989. The single
fertilization in 1989 was found to be the most successful. Although it is reported that some varieties of seaweed benefited from fertilization, exhibiting elevated growth rates, the effects could not be sustained beyond 10 days because of rapid diffusion of fertilizer. It was concluded that the production of marine plants as feed for higher trophic level fish was not realistic or efficient, although the technique is now being explored by Marino Forum 21 for the cultivation of plankton feeders such as sardine (Morimura 1997).

**Ocean Harvest 97 Workshop**

Recent interest in ocean productivity enhancement culminated in a gathering of scientists and experts at the Ocean Harvest 97 Workshop in Southampton, U.K last year. This gathering is discussed here, because it represents an interesting initiative by the private sector to get marine productivity enhancement on the scientific agenda.

Initiated and sponsored by Norsk Hydro, the conference brought together biological oceanographers, fisheries biologist, marine biologists, private sector scientists and international bureaucrats to debate 'new concepts to increase the sustainable use of marine biological resources' (Shephard 1997a). Reflecting the increasing commercial interest in oceanic yield, the conference outlined current research and uncovered some interesting experiments in marine production. Plenaries were held on the Maricult Research Program; and the groundbreaking mesoscale experiments undertaken by Marino Forum 21. In addition, the conference addressed alternative means of increasing sustainable marine yields. Amongst these alternate strategies were the establishment of new habitats (e.g. artificial reefs), sea farming, food web manipulation, exploitation of currently non-harvested species and other forms of ocean management (Shephard 1997a).

One of the lasting accomplishments of the Ocean Harvest 97 Workshop however, was to initiate discussion, consolidate opinion and identify future research for marine harvest production. Participant consensus was that marine harvest could play an important role in meeting the protein demands of the world’s growing population (Shepherd 1997b), and scientists were called to
explore ways in which marine production could be increased in a sustainable and environmentally acceptable way (Olsen 1997). Discussion highlighted the urgent need to develop more reliable theory and models about fish populations and ecosystem processes. This lack of data and understanding of biological systems was identified as a fundamental constraint to predicting ecosystem consequences of harvesting marine resources. Due to this lack of knowledge scientists cautioned great care in the implementation of ocean harvest schemes (Underwood 1997).

**CLIMATE RESEARCH AND EXPERIMENTS**
In contrast, scientifically driven interest in ocean fertilization has tended to focus on the role of the oceans in regulating climate. Following the success of IRONEX II substantial laboratory and field research has been undertaken to investigate the role of nutrients in regulating productivity, with some startling discoveries, of considerable significance to the future of ocean fertilization. Scientists have also embarked on efforts to test the carbon sequestration potential of the iron hypothesis in the Southern Antarctic Ocean - where ocean fertilization is thought to have its most powerful effect².

**Southern Ocean Experiments**
It is believed that two experiments to continue IRONEX testing are currently in planning and await funding. The first of these initiatives is led by a team from the United States of America. It is understood that a similar series of experiments are concurrently being planned by a multilateral team of scientists, although no details of this latter proposal are known. Members of the original IRONEX II team and other lead American scientists, headed by Kenneth Coale are currently seeking funding for a proposal to perform *in situ* iron enrichment experiments in the HNLC waters of the Southern Ocean. Tests will be conducted in the nitrate rich silicate poor waters north of the Antarctic Polar Front as well as in the nitrate and silicate rich waters south of this front. The primary focus of these trials will be carbon cycling and climate change. Although phytoplankton and zooplankton response to fertilization in the two distinctive regions will be
observed, testing does not appear to include general or long term ecosystem responses.

Additional information to be gathered include, but are not limited to, taxon specific iron effects, carbonate system parameters, nitrogen cycling, flourescence response, silicate uptake kinetics, and metal complexation. ‘IRONEX III’ field experiments are scheduled to proceed over two austral summer seasons commencing in January/February 1999. In year one tests will be performed to the north of the Antarctic Polar Fronts (APFZ). Identical experiments will then be conducted in year two to the south of the APFZ. A third year will be spent in analysis, data interpretation and documentation (Coale 1997).

**New Twists to Nutrient Limitation**

Scientific research has also recently introduced a fresh dimension to the ocean fertilization debate. Falkowski (1997) presents the hypothesis that iron, which had previously been thought limiting only in HNLC zones, might be regulating productivity throughout large expanses of the oceans because of it’s influence on the ratio of nitrogen fixation to denitrification (Falkowski 1997).

So how does this mechanism work? Nitrogen fixation in the oceans is undertaken by certain cyanobacteria. Traditionally the abundance of cyanobacteria observed in the ocean has been very low, suggesting that their growth has been somewhat limited. Cyanobacteria require relatively large quantities of iron to complete nitrogen fixation, and it is now believed that this element is the primary factor which has limited their abundance (Falkowski 1997).

This new twist in iron limitation theory has broad ramifications for ocean fertilization because it may lead to the ability to apply iron fertilization to areas of the oceans not previously considered. The role of iron in limiting photosynthesis in high nitrate, low chlorophyll regions of the world ocean has been established by direct experimental manipulation of iron concentrations (Coale et al. 1996). If Falkowski’s hypothesis is correct, the larger role of iron in limiting nitrogen fixation in low nutrient, low chlorophyll regions of the subtropical ocean gyres dramatically extends the

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2 Refer previous discussion in chapter 2 under ‘THE OCEAN CARBON CYCLE: Ocean Anomalies - the HNLC
area of application of iron fertilization. Iron fertilization could be conceivably applied to oligotrophic zones to stimulate cyanobacteria, causing an increase in nitrogen fixation, and enhancing the supply of this limiting nutrient to surface waters. This finding dramatically broadens the potential CO₂ sequestration and food production impact of this technology. Another startling but distinct observation, also suggests iron fertilization might have greater areas of application than previously anticipated. Johnson (1997) and IRONEX III colleagues at the Moss Landing Laboratories have recently completed a compilation of measurements of dissolved iron concentrations from around the world’s oceans (Johnson et al. 1997). Low iron concentrations were confirmed as a common feature of HNLC regions such as the Southern Ocean. More surprising however, is that iron was found to be limiting at the base of the euphotic zone, where the bulk of the new production, (and therefore carbon export, and food production) occurs (Coale and Bruland 1987). This finding also indicates that iron limitation may occur throughout the oligotrophic regions of the world’s ocean, which comprises over 90% of it’s surface area (Coale 1997).

**OCEAN FERTILIZATION PROJECTS**

It would be wrong to assume that ocean fertilization remains purely the subject of research. A number of proposals for commercial implementation of ocean fertilization have recently been developed. Fertilization processes have been patented and full scale operations are in planning. Like the private initiatives discussed previously, these commercial fertilization projects tended to initially focus on the fish production potential of fertilization, although they are now seriously adopting climate mitigation goals.

**Ocean Farming Inc.**

A recent commercial ocean fertilization proposal capitalizes on the research undertaken by Falkowski. An experimental ocean farming scheme using iron fertilization to increase nitrogen fixation by cyanobacteria has been proposed by a Virginian based entrepreneur - Dr. Michael

\[\text{Southern Ocean.}^3\]

\[^3\text{Refer previous discussion in this chapter under ‘CLIMATE RESEARCH: New Twists to Nutrient Limitation.’}\]
Markels. A newly formed and dedicated company by the name of ‘Ocean Farming Inc.’ has been established, and start-up capital acquired to develop and commercialize this technology. Markels holds patents for the proposed fertilizer and fertilization process in the United States and in 14 other foreign countries (Markels 1995b; Markels 1996).

Ocean Farming Inc. (OFI) plan to fertilize with a nutrient mix comprised primarily of iron (Fe) and phosphorus (P) in the hope of stimulating diatoms that have endosymbiotic cyanobacteria. It is hoped that this cyanobacteria will fix sufficient atmospheric nitrogen to meet the nitrogen needs of the enhanced production. Some floatation material, seed phytotissue species, and also filter feeding fish may be added. Although primarily to be applied for harvesting fish, OFI are investigating the commercialization of CO₂ sequestration as a by-product of this process (Markels 1997a; Markels 1997c, personal communication).

Preliminary calculations of this process have been compiled by Markels and are reviewed in detail in chapter 4. OFI claim that by spreading five tons of fertilizer over each square mile annually, they will be able to harvest 1,000 tons of fish (Markels 1997c) and sequester 17,000 tons of CO₂ (Markels 1997a) per square mile per year.

An outline of environmental impacts compiled by Markels recognizes primarily positive effects associated with ocean fertilization. He claims fertilization will produce ‘very happy fish’ and ‘greatly increase the amount and diversity of the marine ecosystem’ (Markels 1997b). Although it is noted that shading may produce some potentially harmful effects for coral, it is argued that these effects will be minimized (Markels 1997b). It is assumed that fertilization will be completely reversible and that impacts will vanish with the cessation of fertilization (Markels 1997a). These claims have yet to be verified either scientifically or in the field.

**Current Status**
Ocean Farming Inc. are currently developing their patented technology according to a three phase development program, comprising Fertilizer Development; Fertilizer Evaluation and Refinement; and Full Scale Experimentation:
Phase I: This phase will be laboratory based and involves designing and testing fertilizer materials for density, solution rates and performance. A buoyant fertilizer mix consisting of a combination of limiting nutrients such as iron, phosphate and other trace elements will be designed.

Phase II: During phase II, field experimentation of the developed fertilizer mix will be undertaken in the open ocean. A nine square mile test area in the Gulf of Mexico will be used to perfect the composition, distribution and seeding protocols of the fertilization techniques.

Phase III: A six month period of full scale experimentation over approximately 500 square miles in the Gulf of Mexico is being planned for phase III of the project. This testing will be used to demonstrate the fish production potential of fertilization. The fertilized area will be seeded with filter feeder fish and their growth rate determined (Markels 1997c).

Organizations are currently under contract to complete the three phases of the program. As of the beginning of 1998, Phase I had been completed, and has reportedly resulted in the development of fertilizer pellets that, in anticipated field conditions, will dissolve, float, and slowly release iron over several days (Markels 1997c).

Development phase II was commenced in January 1998 with limited success. Three trial patches, nine square miles in extent were fertilized in the Gulf of Mexico during the evening of January 12-13, 1998. Each patch contained different concentrations of phosphorus as follows:

Patch #1: 238 lbs Fe chelate: 8,450 lbs phosphoric acid (molar ratio 63.5P:1Fe)
Patch #2: 238 lbs Fe chelate: 845 lbs phosphoric acid (molar ratio 6.35P:1Fe)
Patch #3: 238 lbs Fe chelate only

The fertilizer mix was designed to raise surface water iron concentrations to a level that would stimulate primary production throughout the estimated 75-100m depth of the euphotic zone.
Floating iron pellets with a slow release mechanism was expected to enable continuous supply over a period of about five days. Liquid phosphoric acid was used to supply phosphorus requirements.

Although a 400% increase in large diatoms, and a 54% increase in chlorophyll were recorded in patches 2 and 3 (patch 1 could not be located) on the day after fertilization, these effects were not sustained. Chlorophyll concentrations declined after the first day. It is believed that rapid mixing, and a deep thermocline diluted the added fertilizer. Observations were restricted primarily to growth and distribution of diatoms, and to dissolved Fe and P concentrations (Markels 1998).

A redesigned series of tests were subsequently completed in the Gulf of Mexico in late May of this year. It was expected that mixing and weather conditions would be more favorable in the spring compared to the winter conditions of the earlier experiment. However, recent verbal advice from Markels indicates this second series of tests were also not successful. Although no further information has yet been obtained on these experiments, it is understood that field tests will be repeated later this year with a new fertilizer mix comprising greater concentrations of phosphorus (Markels, personal communication). Once these third series of experiments are completed, it is hoped to proceed with Phase III.

**Marshall Islands**

In Phase III development is planned to proceed to full scale implementation in the Equatorial Pacific. In a revolutionary agreement, OFI have purchased an option for private property rights for some, or portions of, the Republic of the Marshall Island’s 800,000 square mile Exclusive Economic Zone. It is expected that this option will be exercised within the next two years for a 100,000 square mile ocean fertilization scheme which is to be used for commercial fish harvest (Markels, personal communication).
Recent Developments
Recently OFI have incorporated CO₂ sequestration into their operations (Markels 1997a). OFI intend to market these services, seeking grants and in-kind contributions or contracts from government agencies, foundations and industry to help complete the development and testing program (Markels, personal communication).

Photosynthetic Greenhouse Gas Mitigation Scheme (PGGM)
Another current ocean fertilization scheme is undergoing development within the Department of Civil Engineering at the University of Sydney in Australia. Jones and colleagues within the Ocean Technology Group, actively support ocean fertilization⁴, and have published numerous papers on it’s potential for both fish harvest and CO₂ sequestration (Jones 1996a; Jones 1996b; Jones and Otaegui 1997; Jones and Young 1997). Jones believes fertilizing with reactive nitrogen, possibly in conjunction with trace nutrients, can be used to increase the production of phytoplankton, enhance photosynthesis, generating a sustainable high yield global fishery (Jones and Young 1997) and sequestering carbon to mitigate greenhouse gas effects (Jones and Otaegui 1997).

Citing a review article by Howarth (1988), Jones argues that nitrogen is the primary limiting nutrient regulating productivity throughout the oceans. There is however, some doubt whether nitrogen limitation can be extrapolated to the entire ocean region in this manner. There is considerable evidence of regional, temporal and species specific variations in production limitation⁵. Nevertheless, by introducing nitrogen to the ‘desert areas’ of the oceans, Jones hopes to boost the growth of phytoplankton, both increasing seafood yields and sequestering carbon (Jones 1996b).

Jones proposes a ‘Photosynthetic Greenhouse Gas Mitigation (PGGM) Process’ which he describes in detail(Jones and Otaegui 1997) and recommends a similar proposal for fish

⁴ Jones refers to fertilization proposals as ‘ocean nourishment’. Although ascribed this different name, his proposals fit the description of ocean fertilization.
⁵ For fuller discussion refer to chapter 2, under ‘FUNDAMENTAL CONCEPTS: Limiting Factors’
production goals (Jones 1996b). It is intended that reactive nitrogen in the form of ammonia is supplied approximately 100km offshore to the upper sunlit region of the deep ocean. Ammonia is expected to be manufactured from natural gas, dissolved in sea water to allow easy pumping and dispersion, and then pumped through a steel pipe laid on the seabed. The pipe will extend to the edge of the continental shelf where depths exceed 200m, from which a vertical riser will disperse the aqueous ammonia into the euphotic zone through a diffuser located at a depth of about 50m. It is planned to monitor stimulated primary productivity from space, enabling a quantitative measure of CO$_2$ sequestration to be made (Jones and Otaegui 1997).

If successful, nitrogen fertilization may be able to be applied to a broader area than iron fertilization. However, an overwhelming disadvantage of nitrogen fertilization lies in the Redfield ratios$^6$. This ratio dictates marine biota’s proportional demand for different nutrients. The carbon: nitrogen requirement for marine ecosystems is significantly lower than the corresponding carbon:iron ratio. As a result, nitrogen additions will have to be a factor of 16,000 greater$^7$ to achieve primary productivity enhancements of a similar magnitude to iron. In addition the possibility of secondary limitation by phosphorus must be explored. Iron is unique in that it has been clearly demonstrated to be the primary limiting factor in HNLC regions of the oceans (Coale et al. 1996), and similar results may not be extrapolated to other nutrients.

**Current Status**

As of this writing, a pilot PGGM plant is in planning (Jones and Young 1997). It is suggested that this plant be located in the Indonesian thoroughflow that sweeps past the island of Timor. The plant will reportedly comprise a nutrient source; nutrient delivery system; photosynthetic process; and monitoring devices to measure carbon uptake and control operations in order to minimize adverse effects on the local environment. Carbon uptake will be restricted to 300mg carbon/m$^2$/day in order to maintain levels below those that naturally occur in coastal regions. It

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$^6$ Redfield (1934) hypothesized that biota utilized nutrients in a fixed proportion - commonly referred to as the Redfield Ratio. The Redfield ratio is estimated to be 106:16:1:0.001 for C:N:P:Fe. Refer to chapter 2 under 'FUNDAMENTAL CONCEPTS: Macro and Micro Nutrients'.

$^7$ For every mole of iron; 16,000 moles of nitrogen would have to be added to achieve the same effect.
is understood that the plant will be tested initially for 3 years at 60% efficiency and refurbished to operate for the economic life of the equipment, if required. (Jones and Otaegui 1997). It is unclear whether financing has been obtained for this project. The primary goal of operations appears to be carbon sequestration.

Jones estimates that he will be able to produce approximately 90 kg of fish (Jones 1996b) and sequester 10.5 tons of CO₂ (Jones and Otaegui 1997) per ton of fertilizer. Models, estimates and further discussion of Jones’ proposal are provided in chapter 4.

**CONCLUSION**

Publicity has tended to focus on ocean fertilization as a climate mitigation option, and scientists have been quick to respond. Considerable research effort has been channeled into micro and meso scale experiments in an attempt to understand climate responses to various fertilization scenarios. Some significant discoveries have arisen from this work and have led us to reconsider classical theorems of nutrient limitation. Future scientifically-driven research continues in much the same direction.

It is clear that the private sector have also been captivated by ocean fertilization. In contrast, however they are interested in this technology as a potential productivity enhancement and food harvesting technique. This has resulted in privately led fertilization initiatives such as the Maricult Research Program; Ocean Farming Inc. and was also responsible for initiating the PGGM proposal. Commercially driven development now proceeds hastily towards full scale implementation of ocean fertilization techniques.

With this dichotomy of scientific and commercial interest there has been little coordination between the two groups. The next two chapters attempt to merge current thought. By compiling current knowledge we assess the feasibility of ocean fertilization - reviewing the science behind the business proposals, and rethinking the business potential of the science.
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INTRODUCTION

The outstanding question with respect to ocean fertilization is - can it work? The ability of ocean fertilization to achieve climate mitigation goals has been the subject of numerous models. There has been far less rigorous analysis of the fish production potential of this technology. Practical implementation issues and the economics of proposed operations also warrant further investigation. This chapter reviews what we do know about the potential of ocean fertilization
by first taking a look at the models, reviewing current claims, operations, and finally, comparing costs.

**CLIMATE MITIGATION MODELS**

Martin's speculation about inducing an ice age¹ (Martin 1990b) stimulated a flurry of numerical modeling experiments to investigate the validity of his scientific claims. Martin's initial estimate was that the annual addition of 430,000 tons of Fe could increase the total new productivity in the Southern Ocean from a current value of approximately 0.07Gt C/yr to 2-3 Gt. C/yr, if all the nitrate were utilized in accordance with a Redfield ratio of 106C:16N:1P:0.005Fe (Martin 1990a). Estimates of the global net primary production at the time ranged from 4 to 8 Gt. C/yr. (Eppley and Peterson 1979; Martin et al. 1987), thus this additional productivity represented a 50 to 100% increase in global net primary productivity, with significant anticipated impact on the global carbon cycle. Martin proposed the 'ultimate enrichment experiment' (Martin 1990a; Martin et al. 1990a), but he does not specify the total area of fertilization, and does not indicate the chemical form of the iron.

Subsequent numerical modeling experiments have been completed by Peng and Broecker (1991); Joos, Sarmiento and Siegenthaler (1991); Sarmiento and Orr (1991); and most recently Kurz and Reimer (1993). Typically these models assume a continuous iron supply for 50 to 100 years. Although the scientists approached the modeling tasks from a variety of perspectives, they obtained remarkably similar predictions of sequestration.

**Peng and Broecker, 1991**

Peng and Broecker (1991) deployed a box model of the ocean and atmosphere to examine dynamical limitations to the removal of CO₂ from the Antarctic ocean via iron fertilization. They reasoned that in order to maintain the flow of atmospheric CO₂ into the oceans, the CO₂ saturated surface waters would have to be replenished regularly from the deep. The success of fertilization techniques was therefore constrained by the rate of vertical overturning. Existing data on vertical transport in the oceans indicated that this movement was too slow to efficiently sequester carbon

¹ Refer to discussion of Martin's claims in chapter 1 'OVERVIEW'.

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dioxide. Based on these conclusions they calculated only a nominal reduction of 10 ± 5% in predicted global atmospheric CO₂ concentrations in the year 2090 after 100 years² of continuous iron fertilization. This upper limit result assumes that fertilization was 100% successful, that is, that biological production and export of organic matter was able to proceed to total depletion of surface phosphate (Peng and Broecker 1991).

**Joos, Sarmiento and Siegenthaler, 1991**

The dynamical limitation approach adopted by Peng and Broecker (1991) has been disputed by Joos et al (1991) who argue that measurement uncertainties are too large to deem vertical transport rates a critical uncertainty. Adopting a different approach, and using an ocean-atmosphere box model of the biogeochemical responses to ocean fertilization Joos et al. (1991) forced nutrient utilization to 100% over the 16% surface area of the oceans that constitute the Southern ocean, for the six light months experienced in the Antarctic.

Joos et al projected that without fertilization, under a ‘Business as Usual Scenario’³ levels of atmospheric CO₂ would increase from 1990 concentrations of 355 ppm to 772 ppm in the year 2090. Successful fertilization for 100 years would reduce the predicted 2090 atmospheric CO₂ concentration to 665ppm. This represents only a 14% reduction in the total global atmospheric CO₂ concentrations in 2090.

The simulation was repeated for IPCC’s ‘Constant Emission Scenario⁴’. Under these conditions iron fertilization had a greater proportional impact on global atmospheric CO₂ concentrations. After 100 years, CO₂ concentrations of only 416 ppm were attained, in comparison with an unfertilized concentration of 506 ppm. This represents a small, but increased reduction of 18% in the predicted global atmospheric CO₂ concentrations in 2090. This result indicates that the

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² 100 year fertilization period commences from the base year of 1990.
³ The Intergovernmental Panel on Climate Change (IPCC) have predicted a number of alternative CO₂ emissions scenarios. Amongst these is the ‘Business as Usual Scenario’ which assumes continued growth with no controls on anthropogenic emissions.
⁴ See note 2. The IPCC ‘Constant Emissions Scenario’ assumes 1990 anthropogenic emissions are maintained due to the introduction of control measures.
control of anthropogenic emission would allow fertilization to yield a greater impact on the reduction of global atmospheric CO$_2$.

Calculations by Joos et al (1991) indicate that fertilization should be continuous. They found that when fertilization is stopped at 50 years under the Business-as Usual scenario, then the atmosphere-ocean system tended to revert to its unfertilized state. The resultant reduction in atmospheric CO$_2$ levels at 100 years is reduced to less than 5% of predicted final levels, compared with 14% under continuous fertilization.

Like Peng and Broecker (1991), Joos et al estimates rely on 100% successful fertilization, and were designed to provide upper limits for the potential sequestration of atmospheric CO$_2$. These results, which indicate fertilization is only partially effective, are likely to be even less favorable in practice (Joos et al. 1991).

**Sarmiento and Orr, 1991**

Sarmiento and Orr (1991) adopted a three dimensional ocean model coupled to a one dimensional atmospheric model to examine nutrient depletion in the Southern Ocean. They set the concentration of PO$_4$ as an upper limit for productivity, and investigated what would happen if this were forced to zero over a 100 year period as a result of fertilization. Once again, this model relied on the assumption of 100% successful fertilization, and ignored other limitations such as light and grazing. It presents an upper limit to CO$_2$ sequestration.

Model simulations indicated that fertilization under the Business as Usual scenario produces only a 9% reduction in 2090 atmospheric CO$_2$ levels. Results are improved under the constant emission scenario. In this latter case, up to a 12% reduction in 2090 CO$_2$ concentrations were predicted, supporting the work of Joos et al (1991) that the effectiveness of fertilization is improved when emissions are controlled (Fig 4-1).

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5 100% successful fertilization is assumed in all the climate models discussed. This assumes that surface nutrients are fully depleted during fertilization operations.

6 Cited as a 16.7% reduction in the forecasted increase in 100yr CO$_2$ levels (Sarmiento and Orr 1991).
Figure 4-1: Modeled CO₂ fluxes into the ocean under the 'Business as Usual' (standard scenario) with no fertilization; with 100 years of fertilization; and with 50 years of fertilization followed by 60 years without fertilization. [From Sarmiento and Orr, 1991].
Figure 4-1 also depicts how under continuous fertilization, the rate of CO$_2$ sequestration by the oceans, is not sustained, but is reduced to zero over a time scale of only a few millennia. This occurs because the deep waters that exchange with the surface waters of the Southern Ocean become sufficiently saturated with CO$_2$ to inhibit further exchange. Sarmiento and Orr's model also supported the earlier conclusions of Joos et al (1991) that the process was reversible. If fertilization were to be continued for only 50 years, it was estimated that all captured CO$_2$ would be released back to the atmosphere within an additional 60 years.

By manipulating their three dimensional model, Sarmiento and Orr were able to examine the sensitivity of new production to fertilization undertaken in various geographic regions (Table 4-1). The largest effect of iron fertilization was estimated for the Southern Ocean, where the predicted increase in new production was 12-14 Gt C/yr. This represents more than a doubling of the current estimates of global new production$^7$. The predicted increase in new production in other INLC ocean areas is much smaller.

In the equatorial Pacific a small reduction in new production was predicted as a result of fertilization. This occurred because nutrients are supplied primarily by upwelling in this region. Upwelling waters in the equatorial Pacific also spread to subtropical regions, providing a supply of nutrients to biota in the subtropical gyres. Thus, although fertilization may initially increase carbon export to depth in the upwelling zones, it will cut off the supply of carbon and nutrients to the subtropics, and subsequently be counterbalanced by an equivalent amount of reduction of activity in these regions (Cooper et al. 1996).

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$^7$ Refer Table 2-1, in chapter 2 under ‘FUNDAMENTAL CONCEPTS: Global Patterns of Primary Productivity’.
Table 4-1: Atmospheric CO₂ Perturbations and Total New Production (Gt C/yr) Perturbations for Nutrient Depletion of different Geographic Regions. Results are calculated using a three-dimensional ocean model, assuming a ‘Business as Usual’ scenario, and continuous fertilization for 100 years (Sarmiento and Orr 1991).

<table>
<thead>
<tr>
<th>Region</th>
<th>Atm. pCO₂ perturbation (ppm)</th>
<th>New production perturbation (GtC/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Atlantic</td>
<td>-12.7</td>
<td>1.4</td>
</tr>
<tr>
<td>North Pacific</td>
<td>-6.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Equatorial Region</td>
<td>-2.8</td>
<td>-0.2</td>
</tr>
<tr>
<td>Southern Ocean</td>
<td>-71.8</td>
<td>13.2</td>
</tr>
</tbody>
</table>

By applying fertilization to different oceanic regions, it was found that fertilization of just 18% of the ocean perched on top of the convective plumes - where the supply of nutrients to the surface can be maintained continuously - generates 37% of the total sequestration. Pacific equatorial regions were estimated to contribute only a minor 3 ppm reduction of atmospheric CO₂ over 100 years.

Sarmiento and Orr caution that their predictions are extreme and optimistic, and ignore many potentially limiting factors. As stated by the modelers, ‘It seems unlikely that such a scenario could be achieved in practice’ (Sarmiento and Orr 1991). In addition, the model identified a number of undesirable side effects of fertilization. The extreme utilization of nutrients in the Southern Ocean was found to slightly decrease the amount that were available in upwelling zones outside this region. Significantly, anoxia was also predicted in the south western Indian Ocean (Sarmiento and Orr 1991).

**Kurz and Maier-Reimer, 1993**

Modeling performed by Kurz and Maier-Reimer further substantiated the prediction that even under the most optimistic fertilization conditions complete mitigation of anthropogenic CO₂ emissions is not feasible. This three dimensional carbon cycle model demonstrated that $\frac{2}{3}$ of the CO₂ sequestration achieved by increased biological production is re-released back into the atmosphere, within 10 years, as a result of ocean circulation which carries a high return flux of remineralized products back to the surface. Results for the Business as Usual Scenario, predicted a 7% reduction in 2090 atmospheric CO₂ levels. Consistent with all other models, this reduction
was increased under the Constant Emission scenario to 9% of atmospheric 2090 levels (Kurz and Maier-Reimer 1993).

**Comparison of Models**

Table 4-2: Comparison of CO₂ sequestration model results. (Joos et al. 1991; Kurz and Maier-Reimer 1993; Martin 1990a; Peng and Broecker 1991; Sarmiento and Orr 1991). Level of reduction in 2090 atmospheric CO₂ concentrations cited.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Business-as-usual Emissions Scenario</th>
<th>Constant Emissions Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% reduction</td>
<td>ppm reduction</td>
</tr>
<tr>
<td>Joos, Sarmiento &amp; Siegenthaler, 1991</td>
<td>14</td>
<td>120</td>
</tr>
<tr>
<td>Broecker &amp; Peng, 1991</td>
<td>10 ± 5</td>
<td>116</td>
</tr>
<tr>
<td>Sarmiento &amp; Orr, 1991</td>
<td>9</td>
<td>72</td>
</tr>
<tr>
<td>Kurz &amp; Maier-Reimer, 1991</td>
<td>7</td>
<td>50</td>
</tr>
</tbody>
</table>

The modeling studies concur, that there would be at best, only partial oceanic uptake of anthropogenic CO₂ emissions as a result of iron fertilization. Results by Sarmiento and Orr (1991) are similar to Peng and Broecker (1991), but somewhat smaller than those obtained by Joos et al (1992). Maier and Reimer conclusions provide an even lower estimate.

In all instances, the Southern Ocean was explored as the only suitable option for climate mitigation goals. Models were designed to provide an upper limit value, and these illustrated with reasonable consistency that iron fertilization has a limited potential benefit of 10-20% reduction in atmospheric CO₂ concentrations over 100 years, even under the most optimistic circumstances.

It is interesting to compare modeling conclusions with the results of ocean experiments, IRONEX I and II (Coale et al. 1996; Martin et al. 1994). The IRONEX experiments were conducted in HNLC zones of the equatorial Pacific, over several days and thus results cannot be uncritically extrapolated to the very different biological and physical conditions of the Southern Ocean. Nevertheless, IRONEX observations do add to the weight of circumstantial evidence relating to ocean fertilization, and make interesting comparison.
During IRONEX I there was only a small recorded decrease in surface water CO₂ fugacity as a result of iron fertilization (Martin et al. 1994). IRONEX II showed more impressive results. The fugacity of CO₂ measured in the center of the fertilized patch dropped from 510uatm to 420 atm, which relates numerically to a 60% reduction in the ocean to atmosphere CO₂ flux of this region. However these effects were transient (Cooper et al. 1996). These observations are based on experiments of only several days duration, and should be treated warily, however they do reflect the ‘reversibility’ of the phenomena, clearly shown in models. This observation also supports modeling conclusions that continuous fertilization is necessary to keep carbon sequestered (Sarmiento and Orr 1991).

Recent studies by Tortell et al (1996) casts some shadow on the stated optimism of the climate models. In studying the iron requirements of protozoans in the sub-arctic Pacific it was revealed that iron concentrations of the grazers was greater that that in the phytoplankton itself. Indeed 20-45% of the biological uptake of iron was estimated to be undertaken by bacteria, indicating that there was direct competition between these organisms and phytoplankton. This implies that the interaction between iron and carbon is more complex than the modeled assumption of iron limitation of phytoplankton alone (Tortell et al. 1996).

Finally, projections of CO₂ sequestration by iron fertilization consider regeneration of CO₂ in surface and deeper waters, mixing, and ocean ventilation, but do not take into account factors such as limitation of production by light or grazers, secondy nutrient limitation by silica, and other trace elements, that would all serve to reduce the amount of carbon removed from the atmosphere (Fuhrman and Capone 1991). These factors as well as the biogeochemical implications of such an effort will reviewed in more detail in chapter 5.

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8 Under typical conditions the net flux of CO₂ in regions of the Equatorial Pacific is from ocean to atmosphere, unlike most other areas of the ocean where the reverse is true.
The most important conclusions that can be derived from these modeling experiments are as follows:

- Models are remarkably consistent and gain some support from experimental observations in the equatorial Pacific. They offer an upper limit value of possible sequestration by fertilization.
- Models of iron fertilization indicate a limited potential benefit of 10-20% reduction in 2090 CO₂ concentrations, even under the most optimistic conditions. It is believed this number may be significantly reduced due to secondary limitation and complex biological interactions.
- Fertilization can sequester proportionately more CO₂ when emissions are controlled.
- CO₂ sequestration by fertilization is most effective in the Southern Ocean, with only marginal effects in other regions such as the equatorial Pacific.
- Iron fertilization must be continuous in order to keep CO₂ sequestered in the ocean.
- The sequestration capacity of fertilization is not likely to be constant over time due to eventual depletion of surface water nutrients. Models indicate that the rate of CO₂ sequestration declines rapidly, within the first couple of years, from high initial uptake rates.
- The effects of fertilization are not limited to the region of application, due to global ocean circulation, and nutrient cycling patterns.

**OCEAN FERTILIZATION PROJECTS**

The viability of ocean fertilization has also been explored by the private sector. These estimates tend to be less well documented. Developers of Ocean Farming Inc. (OFI) and the PGGM nitrogen fertilization scheme offer the only known calculations of the fish production potential of ocean fertilization. Both Markels (1997a) and Jones and Otaegui (1997) have also recently completed CO₂ sequestration estimates of their respective OFI and PGGM proposals. Background information on these schemes has already been provided in chapter 3. These projects and estimates are now reviewed.

**Ocean Farming Inc.**

Plans by Ocean Farming Inc. for ocean fertilization have been previously outlined in chapter 3. In essence, Ocean Farming Inc. (OFI) intend to fertilize with a patented nutrient mix comprised
primarily of iron (Fe) and phosphorus (P) in the hope of stimulating diatoms that have endosymbiotic cyanobacteria. It is hoped that this cyanobacteria will fix sufficient atmospheric nitrogen to meet the nitrogen needs of the enhanced production. Some buoyancy material, ‘seed’ phytoplankton species and filter feeding fish may also be added. Although primarily to be applied for harvesting fish, OFI are investigating the commercialization of CO₂ sequestration as a by-product of this process (Markels 1997a; Markels 1997c, personal communication).

Markels (1997c) has completed calculations of the capacity and cost effectiveness of both fish production and CO₂ sequestration functions. These estimates are not accompanied by detailed workings, and it has been difficult to repeat and verify numbers. Nevertheless, it is interesting to compare Markels’ predictions and to review a number of his fundamental assumptions.

Markels predicts that by spreading five tons of the OFI fertilizer per square mile of fertilized patch each year, they will be able to harvest 1,000 tons of fish (Markels 1997c) and sequester 17,000 tons of CO₂ (Markels 1997a) per square mile per year. This equates to a yield of 200 tons of fish per kg of fertilizer, and a mitigation value of 5,500 tons of CO₂ per ton of fertilizer, at an estimated cost of $132/ton of fish⁹ (wet weight) and $0.40/ton CO₂ (Markels 1997a).

The primary assumptions through which Markels calculates these numbers are as follows:
1. Proposed fertilizer mix comprises 10% iron. The other major constituent is phosphorus, as well as float material and seed organisms (Markels 1997c)(Markels, personal communication).
2. 40% of added fertilizer is utilized by biota (Markels 1997c).
3. Biota utilize nutrients in accordance with Redfield Ratios (although precise value of Redfield ratio assumed by Markels is not provided) (Markels 1997c).
4. Approximately 50% of CO₂ utilized by biota is permanently sequestered (Markels 1997a).
5. Approximately 4000 pounds of phytoplankton generate 200 pounds of fish (wet weight)

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⁹ It appears that this value includes costs for harvesting and fertilization operations only.
Some comments on Markels calculations are as follows:

- OFI's scheme capitalizes on the large C:Fe Redfield ratio required by biota. This allows small quantities of iron to potentially have dramatic results, and gives it clear advantages over nitrogen fertilization schemes, provided it can be successfully implemented. For OFI's scheme to be successful iron addition must stimulate nitrogen fixing cyanobacteria. This effect has yet to be proven.

- A mass breakdown of the proposed fertilizer composition was attempted in order to test Markels assumption that it should comprise 10% iron. Calculations indicate that this mass proportion does not allow sufficient phosphorus to be added to meet the Redfield ratio requirements of the fertilizer-enhanced productivity. According to Redfield ratios, approximately 1000 moles (31,000 g) of phosphorus are required by biota for every 1 mole (56g) of iron. Thus, even when the weight contributions of other floatation and organism fertilizer constituents are optimistically ignored, this 10% iron criteria allows only 1/60th of the required phosphorus to be supplied in the fertilizer mix. Phosphorus limitation of production should therefore be a concern for OFI proposals. Although more phosphorus can easily be added to this fertilizer to meet biological demand, this will reduce the iron proportions in the fertilizer, and thus it's efficiency in stimulating production.

- Markels calculations also assume that 40% of fertilizer added to the open ocean is utilized by biota, and that the rest is lost. No reference for this 40% figure is cited. Significant fertilizer losses should be expected due to turbulence and mixing in the oceans. In addition, iron is a highly reactive metal readily oxidizes from the soluble Fe(II) to the highly insoluble Fe (III) state, precipitating out of solution (Martin 1990a). As a consequence iron tends to have a low residence time in the euphotic zone, and substantial quantities are not available to surface biota. This problem has been investigated by Markels who proposes the use of a nutrient mix, using a floatation system comprised of peanut hulls or ground corncobs. This system has been laboratory tested and patented by Markels (Markels 1996), who claims 100% iron utilization can be achieved using this system. These claims have not been verified. It does not seem likely however, that floatation systems will be entirely effective in maintaining iron concentrations in the euphotic zone, due to inevitable turbulence and diffusion losses after
discharge. More detailed discussion of this ‘loss’ term is undertaken in calculations presented later in this chapter. It should be made clear however, that an accurate assessment of the magnitude of fertilizer losses requires the development of a complex physical model. Thus, it is not presently known how valid this estimate is, but it is certain that the cost effectiveness of fertilization schemes will be extremely sensitive to fertilizer losses.

- Markels assumes a high sedimentation/CO$_2$ sequestration rate. The portion of new production which is sedimented varies throughout the oceans, but for comparison, the value used by Sarmiento and Orr (1991) in their global ocean model is 30%.

- The source of Markels fish production values is unclear and seem optimistic relative to the available primary production values cited above. Assuming optimistically that the efficiency improvements of naturally occurring highly productive zones are reproduced by fertilization (this is not proven), then approximately 25% of primary production will be likely to contribute to the fish food web (Pauly and Christensen 1995). This productivity is then available to be transferred up the food web to the second trophic level, from which the ‘average’ commercial fish species then feeds. At an average 10% trophic energy transfer efficiency (Pauly and Christensen 1995), 4000 lbs of biomass would yield only 10 lbs of fish. Assuming biomass value given is a dry weight of carbon, then a wet weight:carbon ratio should be applied to convert this value to a wet weight of fish. A conservative estimate of this ratio is 9:1 (Strathmann 1967). Thus the wet weight of fish produced from 4000 lbs of dry biomass, should be in the order of 90 lbs. This more than halves Markels estimates.

- In addition, the fish production value calculated by Markels does not appear to incorporate losses due to fish mortality and other losses during harvesting. It is impossible that 100% of production will be successfully harvested in open water conditions.

There are also some practical problems specific to OFI’s proposal which are noted below. Additional operational problems, common to ocean fertilization practice are discussed in the next section of this chapter.

- Quite simply, there is, as yet, no conclusive evidence that OFIs proposed fertilizer mix will work. Global application of iron fertilization based on Falkowski’s (1997) or
Johnson's (1997) work has yet to be confirmed, and OFI's proposals to stimulate nitrogen fixing cyanobacteria by iron fertilization are unproven. There is subsequently a great deal of uncertainty that still surrounds these proposals.

- OFI's proposals do not consider other nutrients and factors that might be limiting to growth in the open ocean waters where OFI intend to undertake operations. Even if nitrogen fixing bacteria are successfully stimulated and generate the necessary nitrogen, the nutrient phosphorus is likely to eventually become limiting\textsuperscript{10}. As explained in chapter 2, silica may also become a limiting factor for growth of diatoms. Diatoms were preferentially enhanced during iron fertilization experiments (Coale et al. 1996) and due to their large cell size, make a significant contribution to fish yield and carbon export (Ryther 1969). It is plausible to incorporate additional nutrients into the fertilizer mix to meet these biological demands. However, because these macronutrients are consumed in larger proportions relative to iron, it dramatically increases costs of operations by several orders of magnitude.

- Time dependent effects of fertilization are not considered. Markels' calculations estimate initial uptake rates. However, as shown in climate models these rates are likely to decline with time as nutrients are depleted. Thus, sequestration and fish production estimates will be over-estimated. Climate mitigation models also indicate that iron fertilization must be sustained to ensure long term sequestration of carbon\textsuperscript{11}.

- Environmental costs are likely to experienced as a result of ocean fertilization. There is also a significant risk that any CO\textsubscript{2} reduction achieved by fertilization, may be negated by production of other greenhouse gases potentially stimulated by these operations (Fuhrman and Capone 1991). Refer to chapter 5 for further discussion.

**Photosynthetic Greenhouse Gas Mitigation (PGGM)**

Jones plans to use ocean fertilization techniques for both fish production and CO\textsubscript{2} sequestration goals (Jones 1996a; Jones 1996b; Jones and Otaegui 1997; Jones and Young 1997). Detailed

\textsuperscript{10} As indicated by calculation, the phosphorus component of the fertilizer proposed by OFI does not currently provide sufficient phosphorus for enhanced growth, and will have to be supplemented by naturally occurring surface water supplies. It is feasible that these natural supplies may become depleted, limiting growth.

\textsuperscript{11} Refer earlier discussion this chapter under 'CLIMATE MITIGATION MODELS'
models of this strategy have not been developed, but a number of preliminary estimates have been attached to his proposal to fertilize open ocean areas with the macronutrient nitrogen\textsuperscript{12}.

Jones (1996b) broadly calculates the amount of nitrogen required to maintain a constant global per capita fish catch of 15 kg/person over the next century. Figures are based on United Nations forecasts for population growth, which predict a 2100 world population increase to approximately 11.5 Billion, from 1990 levels of 5.2 Billion (UN 1993). Ignoring external factors such as fishing effort, fisheries management and species variations, Jones assumes that fish landings is directly proportional to new primary production. Using the a molar redfield ratio of 106C:16N, ignoring other limiting nutrients, and assuming 70% of the added nitrogen is available and utilized by biota, Jones then calculates that 1 ton of pure nitrogen will produce 90 kg (wet weight) of fish. At a cost of $100 per ton of nitrogen he then calculates the cost of fish production to be $1.1/kg fish. This value does not appear to include operational and capital expenses of fertilization or harvesting (Jones 1996b).

In a subsequent paper, Jones explores the CO\textsubscript{2} sequestration capacity of his proposals (Jones and Otaegui 1997). For this calculation he uses the same redfield ratio of 106C:16N, and assumes the same biological utilization efficiency of 70%. He also appears to take into account the CO\textsubscript{2} emissions generated by the manufacture of proposed ammonia fertilizer. Jones estimates that using his PGGM scheme; the annual addition of 190,000 tons of ammonia fertilizer per year will sequester 2,000,000 tons of CO\textsubscript{2} per year. This equates to an estimated potential of 10.5 ton of CO\textsubscript{2} mitigation per ton of ammonia (NH\textsubscript{3}) per year. Jones prices the cost of mitigation, distributing capital investment and operations over a three year period, at $7.5 per ton of CO\textsubscript{2} sequestered.

Even presuming Jones’ qualifying assumptions are correct, it has been difficult to repeat his calculations, and they have not been verified.

\textsuperscript{12} Refer to chapter 4 under ‘OCEAN FERTILIZATION PROJECTS: Photosynthetic Greenhouse Gas Mitigation’ for more details of Jones’ Proposal.
Some comments on Jones' assumptions and calculations are offered below.

- Jones assumes that 70% of fertilizer added to the open ocean is utilized by biota. The source of this value is uncertain. It is reasonable to assume that not all fertilizer placed in waters during operations will be consumed by biota, and some losses should be expected as a result of water column mixing (Sarmiento and Orr 1991). More detailed discussion of this 'loss' term is undertaken in calculations presented later in this chapter. At this point it should simply be noted that these losses should be expected to be significant, but that an accurate assessment of the magnitude of these losses requires the development of a complex physical model.

- CO₂ sequestration estimates appear to assume that all CO₂ assimilated by biota remains sequestered. This ignores losses due to respiration and biomass production. In reality, sequestration (and thus sedimentation) represents only a portion of this initial CO₂ consumption.

- In fish production calculations, the initial assumption that fish landings is directly proportional to new production assumes a linear relationship which is difficult to defend. Firstly, fish landing values are not an accurate reflection of fish production due to the very significant external factors which he clearly states - fishing effort, fisheries management and species variation. Secondly, it ignores regional variations in biological efficiency, sedimentation and nutrient cycling processes (Chavez et al. 1991; Cullen 1991).

- Costs provided for fish production by Jones appear to include only fertilizer supply expenses. Substantial additional costs are likely to be incurred from capital investment, fertilizer application, operations, harvesting, fish processing and product distribution.

- Finally, the value calculated by Jones assumes primary limitation by nitrogen, and that all other nutrients essential for growth are present in sufficient quantities to sustain required levels of production. Jones (1996b) does examine phosphorus availability in the oceans to determine whether concentrations are adequate for the levels of fertilization discusses. He bases this assessment on influx quantities estimated by Tiesen (1995) that suggest that

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13 The portion of new production which is sedimentered varies throughout the oceans. The value used by Sarmiento and Orr (1991) in their global ocean model is 30%.
33Mtons of phosphorus per year is added to the ocean by farming, industry and domestic sewage. Jones ignores the fact that these influxes will be concentrated in coastal regions where anthropogenic impact is greatest. Oceanic environments are typically rather free of anthropogenic influence (Davis 1993). It is not correct to assume that this input is available for biological use within the central ocean gyres where fertilization is intended to occur.

For these reasons, the value calculated by Jones is thought to represent an unachievable upper limit to fish production and carbon sequestration potential.

There are also some practical problems specific to Jones’ proposal. These are highlighted below.

- No assessment is made of the possible biological and physical limits to the sequestration and fish production potential of the PGGM process. Jones assumes plant operations offer the only constraints to productivity enhancement.

- Time dependent effects of fertilization are not considered. Climate mitigation models\textsuperscript{14} indicate iron fertilization must be sustained to ensure long term sequestration of carbon. Although nitrogen is recycled in the euphotic zone more efficiently than iron, increasing its residence time, and dampening this depletion effect, some decline in net primary production is likely to occur over time during nitrogen fertilization also. This might re-release CO\textsubscript{2} to the atmosphere unless nitrogen is constantly re-supplied.

- Initial carbon uptake rates should also be expected to decline rapidly with time, as the naturally-acquired nutrients (e.g. P, Si and trace elements) are used and not replaced rapidly enough. This phenomena was detected by ocean models (Sarmiento and Orr 1991), and is particularly likely outside of the Southern Ocean where thermohaline circulation does not promote nutrient replenishment. It is thus probable that even if sequestration values calculated by Jones were achievable, they would not be sustained over time.

- Some environmental costs are likely to be experienced as a result of nitrogen fertilization. These will be similar to those proposed for iron fertilization (Jones 1996b) and are discussed in further detail in chapter 5.
FERTILIZATION OPERATIONS

In addition to the scheme-specific practical problems already outlined for the commercial ocean fertilization projects, there are several additional problems likely to be commonly encountered by these operations during implementation. Despite being a relatively low technology initiative the sheer magnitude, long-term commitment as well as chemical and physical conditions of the operations are likely to present substantial implementation obstacles.

Magnitude of time and scale

There is little dispute that ocean fertilization technology requires large scale and long term implementation to be practicable from both a commercial and scientific perspective, for climate mitigation, and to a lesser extent for fish production goals (Markels 1997c). Continuous fertilization is also required if results are to be sustained (Cooper et al. 1996; Joos et al. 1991; Martin et al. 1994). This is because the resident time of nutrients, particularly iron, in the euphotic zone is limited. This means that nutrients must be added continuously so that the atmosphere-ocean system does not revert to it’s unfertilized state. There are a number of difficulties associated with this requirement. An estimate of the necessary scale of the operation can be derived from examining proposals. This thesis undertakes an independent calculation for ocean fertilization operations, based on both fish production and climate mitigation goals. According to these revised estimates, iron fertilization of the entire Southern Ocean to achieve the 100 year CO₂ sequestration values predicted by Sarmiento and Orr (1991) requires a flotilla of 41,000 dispersing vessels, and 2,700 resupply tankers. Their activities would be spread over 57 million km² at an estimated annual cost of $475 Billion.

Although at a somewhat smaller scale, fish production in the Equatorial Pacific using an iron-fertilizer mix (as proposed by Markels (1997)) over a 100,000 km² area is estimated to require 75 dispersing vessels and 5 resupply tankers at an annual cost of $0.6 Billion.

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14 Although climate mitigation models were run for iron fertilization scenarios, they were based on nutrient depletion scenarios. Application of some of these results can therefore be made to nitrogen fertilization schemes.

15 This independent calculation is presented later in this chapter under ‘COSTS OF OCEAN FERTILIZATION’. It should be referred to for more detail.
This clearly illustrates the required magnitude of operations, that should have associated difficulties. The logistical problems of such an undertaking are daunting, but perhaps not unachievable. It is perhaps the requirement for continuous application which presents the largest obstacle to effective implementation. This is particularly relevant from the perspective of climate mitigation. Adoption of this technology as a ‘geoengineering’ solution requires a long term (100 year plus) commitment from national and global governments, so that captured emissions remain sequestered. Given that these entities operate on much shorter politically-driven and election-orientated time frames it may be difficult to secure such long term agreements.

**Fertilizer Supply**

Practical problems are also likely to be associated with fertilizer supply. Although nutrients are typically available commercially in abundant supply, it may be difficult, and costly to secure quantities in ‘pure’ form - particularly at the large volumes required.

Jones (1996b) calculates that the additional global nitrogen demand required for implementation of his proposal at a scale sufficient to maintain current fish consumption rates in the year 2100, demands an eightfold increase in current world nitrogen-fixing capacity (e.g. fertilizer plants).

The additional problem of maintaining iron in a bioavailable form is a practical issue already discussed in relation to the Ocean Farming Inc. proposal\(^\text{16}\).

**Commercial viability**

From a commercial perspective, the viability of climate mitigation and fish production schemes is also of question.

**Climate Mitigation**

It is feasible that corporations will be interested in undertaking ocean fertilization as a means of generating ‘carbon credits’ which they could then sell to nations or companies. This approach relies on the establishment of an emissions trading regime and international acceptance of ocean
fertilization as a sequestration option. Under current international agreement an emissions trading regime is planned, but exchange is limited to developed nations. Further, the oceans are not currently recognized as an acceptable sink for carbon credit (UN 1992; UN 1997)\(^{17}\). On this basis there is presently little incentive to implement fertilization for CO\(_2\) sequestration. Although this fact seems to have done little to deter the private sector from developing the CO\(_2\) sequestration options as part of their ‘fish-based’ proposals (Jones 1996b; Markels 1997c), it does inhibit implementation of this scheme for the moment.

**Harvesting Fish**

The commercial viability of fertilization for fish production will rely on the ease and nature of harvest. There is no guarantee that fertilization will stimulate organisms of commercial interest. Indeed, experiences of nutrient enrichment, or eutrophication, in the Black Sea(Kideys 1993), Baltic Sea(Cederwall and Elmgren 1990; Hansson and Rudstam 1990), and the Chesapeake Bay (Seliger et al. 1985) show that commercially undesirable species have been preferentially stimulated by nutrient loading. Kenchington (an independent fisheries scientist in Musquodoboit Harbour Novia Scotia) had the following comment on fertilization scheme proposed by the Maricult program ‘It could even result in fewer commercial fish...if there are more algae, they could mostly be eaten by non-commercial species that then compete with the commercial fish....or it could just result in masses of jellyfish....such changes may be irreversible’ (MacKenzie 1996).

**Location**

An essential factor which also appears to have been overlooked by commercial proposals is the issue of location. This is particularly relevant for CO\(_2\) sequestration goals. Recall from chapter 2 that the Southern Ocean offers the greatest potential for CO\(_2\) sequestration because of the thermohaline circulation which causes surface waters to sink and enhances the action of the biological pump in this unique zone. Climate mitigation models show that CO\(_2\) sequestration effects are minimal and not sustained in other oceanic regions because CO\(_2\) laden surface water

\(^{16}\) Refer earlier discussion in this chapter under ‘OCEAN FERTILIZATION PROJECTS: Ocean Farming Inc.’

\(^{17}\) Further discussion of the implications of International Climate Change agreements is provided in chapter 6 under ‘OTHER LEGAL CONTROLS: United Nations Framework Convention on Climate Change’.
rapidly equilibrates with the atmosphere and is not readily replenished from surface waters below. Sustained fertilization of the equatorial Pacific has been shown to eventually reduce the amount of new production in the region (Sarmiento 1991). This physical constraint to sequestration is present in almost all oceanic regions, except the poles. It is likely to limit the magnitude and duration of CO₂ drawdown outside of polar zones.

Thus, the values calculated for sequestration may be applicable only if operations occur in the Southern Ocean. However, operations are difficult and several times more expensive in the Southern Ocean due to ice hazards, and dangerous climatic conditions. Another difficulty arises because this region is dark for half of the year, so that no photosynthesis can occur. This effectively halves the possible amount of biological activity that can be achieved (Peng and Broecker 1991).

And so a catch 22 situation arises: CO₂ sequestration capacity is likely to be dramatically reduced in any place but the polar oceans. In the polar oceans however operational costs will be much higher, and can only be sustained for half the year. Either way, the sequestration values cited by Jones (1997a) and Markels (1997c) in commercial proposals are unrealistic.

Ocean fertilization to produce fish has a much broader area of application than for climate mitigation goals, yet also remains constrained by a number of factors. Fish production is optimized in zones where water is deep and barren, currents and winds are benign, and there is constant light(Markels 1997b). These criteria are best met in the oligotrophic waters of the tropics. Significantly, areas where fish production will be optimized do not relate to areas in which climate mitigation effects are maximized, indicating limited success if attempting to achieve both goals.

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18 Upcoming Southern Ocean Experiments will test this hypothesis (Coale 1997). For further discussion refer to chapter 3, under ‘CLIMATE RESEARCH AND EXPERIMENTS: Southern Ocean Experiments’.  
19 Fish production in the Southern Ocean is not likely to be commercially viable or practicable due to dangerous climate conditions. Likewise, it has been demonstrated that CO₂ sequestration is minimized in the Pacific where fish production conditions are optimum.
In oligotrophic waters regenerated production and microbial processes comprise a large part of the net primary production. Tortell (1996) has found that microbes may also be iron limited, and therefore likely to compete with phytoplankton for iron if fertilized (Tortell et al. 1996). Microbial food webs tend to be long and primarily based upon regenerated phytoplankton production. As a result microbial production will consume iron but will contribute little to fish production, and therefore reduce the efficiency of fertilization (Kiorboe 1993).

**Climate Mitigation vs Fish Production**

Finally the conflict between both food production and climate mitigation goals must be questioned. It has already been shown that fish production and climate mitigation have vastly different areas of application\(^{20}\). These two distinct goals also rely on opposing mechanisms. The sequestration of CO\(_2\) demands high levels of phytoplankton activity, and thus minimum grazing. In direct contrast, fish production relies on the generation of a large grazing population, which not only consume the photosynthesizing phytoplankton but generate additional CO\(_2\) through respiration. This threat of grazing overtaking CO\(_2\) sequestration, or vice versa, in combined climate mitigation-fish production proposals should be considered. Combining both goals will ultimately require efficiency compromises.

**COSTS OF OCEAN FERTILIZATION**

There have been many claims regarding the cost effectiveness of ocean fertilization. A couple of these claims have already been reviewed. Few have been supported by rigorous calculation. Nevertheless, through repetition, they have gained widespread acceptance.

One of the only assessments of ocean fertilization costs that includes clearly documented calculations, was conducted in 1991 by the Committee on Science, Engineering and Public Policy at the National Academy of Sciences (NAS 1992). This committee examined the climate mitigation potential of iron fertilization in the Antarctic Ocean. Their preliminary estimates indicate that if successfully implemented, iron fertilization could cost between $1-15/tCO\(_2\) per year.

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\(^{20}\) Refer previous section in this chapter.
Other cost estimates for climate mitigation and fish production using ocean fertilization have been completed by Markels (1997c) and Jones and Otaegui (1997). The absence of detailed workings has made it difficult to repeat these calculations and to thus substantiate these values.

Given the large amount of debate and publicity which has surrounded ocean fertilization to date, the absence of a single, detailed, evaluation of costs is remarkable. Independent calculations of the cost of sequestration and fish production are therefore completed as part of this thesis. These are based on current understanding of ocean functions, and have been designed to provide an upper limit value for the sequestration and fish production potential of ocean fertilization. They will thus provide an optimistic assessment of the climate mitigation, and of fish production.

The completed calculations are outlined on the following pages. Estimates assume iron-based fertilization. If successful, this is expected to be more cost effective than fertilization with alternative nutrients such as nitrogen, which is proposed by Jones. This is because iron-based fertilization requires comparatively low fertilizer:C ratios\(^{21}\).

Carbon sequestration and fish production are not complementary goals, and will not be optimized in the same geographic location\(^{22}\). Thus, in order to obtain upper limit estimates of both these functions two separate calculations were completed. An estimate of iron fertilization in the Southern Ocean has been undertaken to obtain maximum CO\(_2\) sequestration values. To obtain maximum fish production estimates, fertilization of the Equatorial Pacific using an iron-mix fertilizer is considered.

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\(^{21}\) Theoretically, the Redfield Ratios will dictate the efficiency of carbon sequestration and fish production. Strict application of the Redfield ratio indicates that 100,000 moles of C is captured in primary production for every mole of Fe. In contrast, only 106 moles of C will be captured in primary production for every 16 moles of N. There is thus substantially improved efficiency of Fe over N.

\(^{22}\) Refer earlier discussion, in the previous section of this chapter.
Iron fertilization of the Southern Ocean

The unique characteristics of the Southern Ocean make it the optimum location for CO₂ sequestration through fertilization. In this polar region, thermohaline circulation transports saline, cold, surface waters downwards. This action complements the biological pump allowing easy transport of sequestered carbon to depth.

The Southern Ocean is also characterized by high nutrient, low chlorophyll (HNLC) surface waters. In these regions there is significant evidence to indicate that biological production is limited by iron (DeBaar et al. 1995; Martin et al. 1990a; Martin et al. 1990b). These conditions are ideal for the implementation of iron fertilization; because biota are iron-limited, and surface waters also have an available supply of macro-nutrients to at least partially meet the requirements of enhanced production. For these two reasons, the sequestration capacity of ocean fertilization is likely to be greatest in the Southern Ocean, and this is supported by ocean model simulations (Sarmiento and Orr 1991).

An estimate of the likely sequestration capacity of iron fertilization in the Southern Oceans was obtained from model predictions by Sarmiento and Orr (1991). This model assumes 100 years of continuous iron fertilization, over 16% of the total ocean surface. Results assume biota utilize 600,000 tons of iron per year, and fully deplete surface water nutrients, generating new production according to a molar C:Fe ratio of 100,000. Sarmiento and Orr assume that 30% of photosynthetically produced organic carbon in the Southern Ocean sinks to the deep ocean or is transported there by circulation thus being sequestered (Sarmiento and Orr 1991).

From the model it is clear that there is substantial variance in the rate of sequestration over time, which were predicted to decline from high initial uptake rates of 11-12 GtC/yr, to between 1 -2 GtC/yr within a couple of years. Indeed model results indicate nutrient depletion diminishes to 0 over a time scale of a few millenia because both the deep and surface ocean waters become CO₂ saturated, countering the effects of nutrient depletion. As a result, to determine the total carbon
(C) sequestered by fertilization it is necessary to examine the cumulative sequestration achieved over long periods. Under a 'Business as Usual' scenario, Sarmiento and Orr (1991) calculate that a total additional 152 GtC is removed from the atmosphere over the next 100 years as a result of continuous iron fertilization of the Southern Ocean. Assumed model parameters are as follows:

**Model Parameters: (Sarmiento and Orr 1991)**

- Duration of Fertilization = 100 years
- Area of Fertilization = 16% Oceans = 57,120,000km²
- Molar Ratio of C:Fe = 100,000
- Quantity of Fe utilized by biota = 0.0006 Gt/yr
- Total Atm. C sequestered = 152 GtC over 100 yrs = 1.52 GtC/yr average

Sarmiento and Orr calculate this value of sequestered carbon, based on a specified quantity of iron being utilized by biota. However, as already suggested, not all Fe placed in waters during fertilizer operations will be consumed by biota. Some will be 'lost' or unavailable to production. Currents and turbulence are unpredictable and will inherently result in some Fe loss. Thermocline depths which dictate the depth of mixing, and thus concentrations, are also variable. Iron is a extremely reactive metal and additional losses from speciation and oxidation of Fe to less bioavailable forms should be expected (Bruland et al. 1991; Sarmiento and Orr 1991). For all these reasons, iron losses during ocean fertilization will be unavoidably large. Therefore the

---

23 Refer chapter 2, under 'FUNDAMENTAL CONCEPTS: Thermohaline Circulation' for description of this mechanism.

24 For estimation purposes the amount of C sequestered is averaged over the 100 year fertilization period. In reality, rates vary significantly over time as clearly indicated in Sarmiento and Orr's conclusions (Sarmiento and Orr 1991).
amount of fertilizer added to the waters will be greater than the amount of iron actually used by biota.

During Ironex II, mixing losses in the order of 90% were measured using a SF$_6$ tracer (Coale et al., 1996) despite reportedly calm conditions (Cavender-Bares, personal communication). These losses might be reduced under continuous fertilization schemes. An accurate assessment of the magnitude of these losses requires the development of a complex physical model. We should however expect iron losses to be significant. Jones (1996) assumes a 30% 'uptake efficiency' of biota under his scheme - although the origin and precise definition of this value is not stated. Markels (1997) adopts a comparable 60% loss value. Again, the source of this estimate is not indicated. Although neither of these values are confirmed OFI's estimate of 60% will be adopted for comparison purposes.

**Quantity of Fe Required**

Assuming 0.0006 Gtons of Fe are utilized by biota, and that 60% of added Fe is lost before being consumed in production, then the total quantity of added Fe must be:

\[ = \frac{0.0006}{(1-0.60)} \text{ Gt/yr} \]

\[ = 0.0015 \text{ Gt of Fe/yr} \]

However, Fe is to be provided in the form of FeSO$_4$. This is the form of iron used during the Ironex II experiment (Coale et al. 1996), and is selected for costing purposes because it is relatively inexpensive, and available in bulk quantities (NAS 1992). Using molar weights, we know that 2.7 tons of FeSO$_4$ will provide the equivalent of 1 ton of Fe. This conversion factor can then be applied to determine the quantity of fertilizer required.

**Quantity of Fertilizer Required**

If, \[ 1 \text{ t Fe} = 2.7 \text{ t FeSO}_4 \]

then, \[ 0.0015 \text{ Gt of Fe/yr} = 0.0041 \text{ Gt of FeSO}_4/\text{yr} \]
Now we have an estimate for both the amount of C sequestered, and for the amount of fertilizer required, each year, for a 100 year period of fertilization.

0.0041 Gt/yr of fertilizer sequesters an average over 100 years of 1.52 GtC/yr

This sequestration ratio must be converted to costs. On a preliminary basis, the costs of fertilization will primarily comprise the cost of application (or operations), as well as the cost of fertilizer supply. There should also be some consideration of overheads, administration, and the substantial risk involved in undertaking operations in the Southern Ocean.

An estimate of operational costs has been compiled based on rates obtained from Drewry Shipping Consultants (Drewry 1997). It is assumed that a 15,000 DWT general cargo ship is used for fertilizer dispersal, and that these are resupplied with fuel and fertilizer by 80,000-110,000 DWT general cargo/bulk carrier tankers. Shipping costs used in calculations are listed below:

**Shipping Costs (Drewry 1997)**

- **DISPERERING VESSEL:**
  
  ⇒ TOTAL OPERATING COST $1,126,600/yr comprised of:
    
    ◊ Manning (3 crew) $111,600/yr
    ◊ Insurance $550,000/yr
    ◊ Repair & Maintenance $150,000/yr
    ◊ Other Operating Costs $140,000/yr (includes stores, supplies)
    ◊ Administration $175,000/yr

  ⇒ TOTAL CAPITAL COST $2,263,000/yr
RESUPPLY TANKERS:

⇒ TOTAL OPERATING COST $ 2,237,450/yr
⇒ TOTAL CAPITAL COST $ 4,440,000/yr

A number of operational parameters have also been assumed. In order to continuously fertilize, dispersing vessels will be required to continuously steam back and forth over the fertilized area discharging iron. Based on a dispersing swath of 1 km (c.f Ironex II which traversed at 400m distances (Coale et al. 1996)); an average vessel speed of 10 knots (or 380 km/day); and twice weekly traverses of all lengths of the patch, in order to maintain fertilizer concentrations; it is estimated that a total of 41,000 vessels will be required to service the 57,120,000 km² patch proposed by Sarmiento and Orr. Resupply tankers must in turn, service these dispersing vessels. Based on the assumption that each vessel must be refueled once per month, and resupplied with fertilizer once per month; and that tankers can achieve one refuel/resupply on average each day; it will be necessary to operate 2,700 tankers. From this we can calculate the total operating cost.

Total Operating Cost

Dispersing Vessels
= ($2,263,000 + $1,126,600)/yr * 41,000 vessels
= $140 B/yr

Tankers
= ($4,440,000 + $2,237,450)/yr * 2,700 tankers
= $18 B/yr

An additional factor should now be applied to the above estimate to incorporate the increased difficulties and risks associated with operations in the Southern Ocean. In their previous estimate\(^{25}\), the National Academy applied a factor of 3 increase to operations to take into account weather contingencies, overheads, systems administration, monitoring operations and vessel downtime (NAS 1992). This factor is considered reasonable. Overheads and administration of

\(^{25}\) Refer discussion earlier this section.
such a large operation are expected to be high and additional allowances should be made for the
difficult climatic conditions, additional insurance requirements, and reduced ship life likely to be
experienced in the Southern Ocean. The same factor will therefore be applied here.

\[
\text{Total Operational Costs} = 3 \times (\$140 + \$18) \text{B/yr} \\
= \$474 \text{B/yr}
\]

To the operations estimate must be added the cost of the iron fertilizer - FeSO\(_4\). This can be
purchased in bulk for an average of $12/t (Chemical Market Reporter, 1991: as cited by
(NAS 1992)).

\[
\text{Total Fertilizer Costs} = \$12/t \times 0.0041 \text{ Gt/yr} \\
= \$0.05 \text{ B/yr}
\]

Adding the operations cost to the fertilizer cost we get a cost for ocean fertilization.

\[
\text{Total Cost of Fertilization} = \$475 \text{ B/yr}
\]

This will mitigate, over a 100 year period, an average of 1.52 Gt C/yr. Applying molar ratios this
number can be expressed in terms of mass.

Thus, 1.52 GtC/yr is equivalent to 5.6 Gt CO\(_2\)/yr

And so, Sarmiento and Orr's model indicates that the sequestration rate achieved by Southern
Ocean fertilization is on average, 5.6 Gt CO\(_2\)/yr. This result can now be used to obtain a final
unit cost of mitigation.

\[
\text{Unit Cost of Fertilization} = \$475 \text{ Billion}/5.6 \text{ GtCO}_2 \\
= \text{approx. } \$85/\text{ton CO}_2
\]
This value is a lower limit cost estimate. Nevertheless it is at least an order of magnitude higher than previous estimates.

Table 4-3 Comparison of CO₂ sequestration cost estimates

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cost of CO₂ sequestration (S/ton CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS (1992)</td>
<td>1-15</td>
</tr>
<tr>
<td>Jones and Otaegui (1997)</td>
<td>7.50</td>
</tr>
<tr>
<td>Markels</td>
<td>0.40</td>
</tr>
<tr>
<td>Revised Estimate</td>
<td>85</td>
</tr>
</tbody>
</table>

The wide discrepancy in the revised value when compared to previous estimates appears to occur because it adopts sequestration rates predicted by model simulations. These sequestration rates are reduced from those obtained through the direct application of the Redfield ratio, because they incorporate physical ocean processes. Further discrepancy arises due to differences in assumed sedimentation rates, and in ‘fertilizer losses’. It is clear that cost effectiveness of operations will be sensitive to these parameters, and further investigation of these values is required. The revised calculation casts some serious doubt on the viability of ocean fertilization as a sequestration option at present.

Iron-mix fertilization of the Equatorial Pacific

Although the Southern Ocean represents ideal conditions for CO₂ sequestration, it is far from suitable for fish production because of the operational, climatic, seasonal and practical difficulties of fish harvest in this region.²⁶ Optimum fish production conditions are described as those where waters are barren and deep, currents are benign and winds are low, and there is sufficient light (Markels, personal communication). These conditions are well met in regions of the equatorial Pacific. An upper limit estimate for fish production by ocean fertilization has therefore been calculated assuming fertilization of this region.

Typically, HNLC conditions are not observed in regions of the equatorial Pacific, and certainly not in regions that are currently being considered for commercial fertilization (Jones and Young

---

²⁶ Refer earlier discussion this chapter under ‘COSTS OF OCEAN FERTILIZATION: Iron fertilization of the Southern Ocean.’
1997; Markels 1997c). Further, iron-limitation has not convincingly been established in the area. A pure iron fertilization strategy in this region does not currently appear feasible. Instead an iron-mix fertilizer (including phosphorus, and some seed cyanobacteria to fix nitrogen) such as that proposed by Ocean Farming Inc. is assumed for costing purposes (Markels 1997b). Calculations have attempted to reproduce the analysis undertaken by Markels (1997) based on OFI’s scheme proposed for the Marshall Islands. In the absence of precise scientific data, a preliminary calculation is completed from first principles.

To calculate the fish production potential of ocean fertilization, a scale of operation similar to that proposed by OFI will be considered. Assume 100,000 km² of ocean is to be fertilized with 5 ton/mile²/yr of fertilizer comprising 10% Fe, some phosphorus, buoyancy additive and ‘seed’ organisms (Markels 1996; Markels 1997c). Although this Fe fertilizer proportion has been previously questioned, it will be adopted here for comparison purposes.

**Operational Parameters: (Markels)**

- Area of Fertilization = 100,000 km²
- Fertilizer Application Rate = 5 t/mile²/yr
  = 2 t/km²/yr
- Fertilizer Composition = 10% Fe

Based on these parameters, 0.2 Mt/yr of fertilizer will be applied to surface waters in order to generate fish production. Only ten percent of this, or 0.02 t/yr will be Fe.

As mentioned for the previous calculation, not all Fe placed in waters during fertilizer operations will be utilized by biota, but will be ‘lost’ or unavailable to production as a result of water column mixing, as well as speciation and oxidation of Fe to less bioavailable forms (Bruland et

---

27 Refer earlier discussion this chapter under ‘OCEAN FERTILIZATION PROJECTS: Ocean Farming Inc.’
al. 1991; Sarmiento and Orr 1991). Therefore, only a portion of this iron will be available for fish production. An accurate assessment of the magnitude of these losses requires the development of a complex physical model. A comparison of values measured from field experiment, and those cited by commercial proposals is provided in the CO₂ sequestration calculation above. Loss estimates range from 90% (Ironex II: (Coale et al. 1996)) to 30% (Jones 1996b). The 60% loss value applied by Markels, will be adopted, to minimize inconsistencies with Markels estimates (Markels 1997c).

**Quantity of Fe used for production**

Assuming 0.02 Mt of Fe is provided to surface waters, and 60% of this is ‘lost’ or unavailable for biological production, then total quantity of iron utilized by phytoplankton must be:

\[
\begin{align*}
= 0.02 \text{ MtFe } \times (1-0.60)/\text{yr} \\
= 0.008 \text{ Mt Fe/yr} \\
= 143.2 \times 10^6 \text{ moles of Fe/yr}
\end{align*}
\]

The Redfield ratios can now be applied to determine the level of enhanced primary production that this Fe addition can generate. A molar C:Fe ratio of 100,000 will be adopted. This is the average value used by Sarmiento and Orr (1991) in their model simulation, and was derived from culture studies undertaken by Anderson and Morel (1982); Morel and Hudson (1985) and Sunda et al. (1991).

Thus, the addition of 143.2 x 10⁶ moles of Fe/yr will stimulate new primary production of 143.2 x 10¹¹ moles C/yr

Or, in terms of mass: The addition of 0.008 Mt Fe/yr will stimulate new primary production of 172 Mt C/yr
Not all the primary production generated by iron addition will contribute to the food web, and thus fish production. Pauly and Christensen (1995) calculate values for the 'Primary Production Required (PPR)' by different marine ecosystems. This value is defined as 'the primary production required to sustain each group of species'. Using global fish catch and discard statistics, and assuming a 10% trophic energy transfer efficiency\(^{28}\), Pauly and Christensen calculate the amount of ocean primary productivity which is required to maintain the fish food web [PPR = (dry catch weight)\(\times\)10\(^{\text{TL}-1}\)] (Pauly and Christensen 1995)\(^{29}\). They present this PPR value for different ocean zones. For open ocean areas, such as those to be fertilized, this number is typically 1.8%. In upwelling zones, that are characterized by high levels of production, the PPR value increases to 25.1% (Pauly and Christensen 1995).

Markels (1997) claims that ocean fertilization will effectively reproduce the conditions of naturally occurring highly productive zones. For this reason he argues the PPR value for these zones should be adopted. This assumption is not tested and could be somewhat optimistic. It will nevertheless be adopted for consistency, and as a means of establishing an upper limit to fish production. Thus, it will be assumed that 25% of the primary production will be used to generate fish production.

Therefore, 25% of the fertilizer enhanced primary production of 172 MtC/yr will contribute to the food web = 43 MtC/yr

This primary production is then transferred up the trophic levels, with a 10% transfer efficiency (Pauly and Christensen 1995). The average trophic level for commercial fish species is trophic level 3 (Pauly and Christensen 1995), which means that energy will be subject to losses at 2 trophic level transfers before being utilized by fish.

\(^{28}\) For fuller explanation of trophic energy transfer efficiencies refer to discussion in chapter 2 under 'OCEAN PRODUCTION: Energy Transfer in Marine Food Webs'.
Thus, total fish production will be \( (0.10)^2 \times 43 \text{ MtC/yr} \)
\[= 0.43 \text{ MtC/yr} \]

Now, the carbon value must be converted to a fish wet weight. A conservative estimate of the ratio of wet weight to carbon is 9:1 (Strathmann 1967).

Thus, total wet weight of fish will be 3.9 Mt/yr and this will be generated from the addition of 0.2Mt of fertilizer. This is equivalent to the production of 19.5 t of fish per t of fertilizer.
(c.f Markels (1997c) value of 200 t of fish per t of fertilizer)

It should be noted that this represents an upper limit fish production estimate. Also, some fish losses are unavoidable during harvest operations, and also as a consequence of natural mortality. This value therefore does not directly translate to the quantity of fish caught.

To estimate the costs of this ocean fertilization operation, a similar approach to that undertaken for CO₂ sequestration calculations will be applied. On a preliminary basis, the costs of fertilization will primarily comprise the cost of application (or operations), as well as the cost of fertilizer supply. There should also be some consideration of overheads, harvesting operations, administration, and risk.

For operational costs, shipping cost estimates provided by Drewry Shipping Consultants, will be used (Drewry 1997). Appropriate values have been outlined earlier. Again, it will be assumed that 15,000 DWT general cargo ships will disperse fertilizer. In order to ensure continuous operations, the dispersing vessels will need to be resupplied with fuel and fertilizer by 80,000-110,000 DWT general cargo/bulk carrier tankers. It is assumed that dispersing vessels will steam back and forth over the fertilized area at traverses of 1km (c.f. Ironex II which

---

29 'Dry catch weight' is used to refer to the dry mass of organic C in any fish catch. Fish catch is typically measured as a wet weight. This can be converted to a dry catch weight using the estimated wet weight to carbon (dry weight) ratio of 9.1 (Strathmann 1967).
traversed at 400m distances (Coale et al. 1996)); travelling at an average vessel speed of 10 knots (or 380km/day); undertaking twice weekly traverses of all regions, in order to maintain fertilizer concentrations. Resupply tankers must in turn, service these dispersing vessels, refueling once and resupplying once, each vessel per month. It is expected that each tanker can either refuel or resupply one vessel per day.

Based on these parameters, it is estimated that a total of 75 dispersing vessels and 5 tankers will be required to maintain fertilization operations over the proposed 100,000 km² area. Estimated costs are as follows:

Total Operating Cost (Drewry 1997) as listed above

- Dispersing Vessels = $ 254 M/yr
- Tankers = $ 33 M/yr

An additional factor should now be applied to the above estimate to incorporate overheads, contingencies, systems administration and vessel downtime. Although these costs are unlikely to be as significant as in the Southern Ocean, they should still be expected to be substantial. A precise factor is difficult to predict, although a twofold increase might reasonably be applied.

Total Operational Costs = $ 574 M/yr

To the operations estimate must be added the cost of the fertilizer. Precise details of the fertilizer composition proposed by OFI are not available, and thus independent cost assessment is not possible. Markels suggests that 'fertilizer in the ocean is $1.40 per pound' (Markels 1997a)(Markels, personal communication).

A value of $1.40/lb translates to a cost of $ 3080/ton of fertilizer. Working back from the operational costs calculated above (estimated to be $ 2870/ton) this would indicate that OFI are expecting fertilizer to cost $210/ton. It is difficult to confirm the cost of fertilizer because
laboratory prices of proposed chemicals are not realistic (bulk purchase is likely to be substantially more cost effective), but this does appear reasonable. The operations costs calculated above also appears consistent with Markel’s estimate and lend some support to his cost figures. Thus, in the absence of other information, it will be assumed that the OFI estimate is correct.

Using Markel’s value of $3080 per ton of fertilization; a rate of application of 2 ton per square kilometer; over the 100,000 km² area of fertilization proposed, a total cost of fertilization can thus be calculated.

\[
\text{Total Fertilization Costs} = \$ 3080/\text{t} \times 2 \text{t fertilizer/km}^2\text{yr} \times 100,000 \text{ km} = \$ 616 \text{ M/yr}
\]

This will produce 3.9 Mt of fish. This result can now be used to obtain a final value for the cost of fish production per ton of fish.

\[
\text{Unit Cost of Fertilization} = \$ 616 \text{ M/3.9 Mtfish} \approx \$158/\text{t fish} = ($0.16/\text{kg fish})
\]

The value calculated does not include the cost of harvesting. Markel (1997c) estimates that harvesting operations will cost an additional $0.13 per kilogram (cited as $0.05/lb), although admittedly qualifies this value as a ‘best guess’.

A preliminary check of this harvesting figure can be undertaken by comparing costs with ocean fertilization cost. Given that harvesting operations are likely to be of a similar scale to fertilization operations, a similar investment in shipping might be expected. Operational costs alone were calculated above as $2870/t of fertilization, which translates to an additional cost of $147/t fish (or $0.15/kg fish). This is similar to Markel’s figures confirming his value.
Thus assuming harvesting cost remain as stated by Markels, at $0.13/kg, the total cost of fish production can be obtained.

\[
\text{Total Cost of Fish production} = \$ 0.30/\text{kg fish}
\]

This estimate does not include the cost of processing and distribution. It must therefore be compared to the price obtained for fish ‘at the dock’. Markels (1997c) claims that the average dock price for OFI fish product is $0.66 - 0.88 per kilogram (cited as $0.30 to $0.40 per pound., Markels 1997c).

Thus, on a preliminary basis, there appears to be some commercial merit to fish production operations, although this is conditional on operations being entirely successful, and takes little account of risk. Fertilization must achieve the optimistic production rates assumed above, to be reasonably profitable. The numbers calculated here indicate costs are at least twofold higher than the equivalent values for fish production (harvesting + fertilization) which are estimated by Markels. Figures remain lower than that calculated by Jones (Table 4-4).

Table 4-4 Comparison of fish production cost estimates

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cost of Fish Production ($/kg)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jones (1996b)</td>
<td>1.10</td>
<td>*Does not include fertilizer application</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and harvesting</td>
</tr>
<tr>
<td>Markels</td>
<td>0.13</td>
<td>*Cost of Fertilization and Harvesting only</td>
</tr>
<tr>
<td>Revised Estimate</td>
<td>0.30</td>
<td>*Cost of Fertilization and Harvesting only</td>
</tr>
</tbody>
</table>

**CONCLUSION**

Upon closer evaluation it seems that ocean fertilization, is not as effective, practically achievable or as cost efficient as so often claimed. In light of ocean model predictions the ability of ocean fertilization to contribute significantly to climate mitigation must be seriously questioned. The fish production capacity of ocean fertilization has attracted little rigorous investigation, but assumptions underlying current commercial estimates raise many questions. Revised
calculations completed in this chapter indicate that costs of both climate mitigation and fish production are substantially higher than anticipated by commercial interests. In addition, implementation proposals appear to overlook some formidable operational obstacles. All these factors combine to raise serious doubt about the feasibility of ocean fertilization. And yet economic and practical issues are but one measure of the ocean fertilization viability, and do not incorporate the costs and risks of side effects and certainty of effect. Because ocean fertilization involves manipulation of natural systems with unknown consequences, and limited precedent it has high associated risk. To get a better understanding of some of the implications of ocean fertilization, we now turn to a discussion of potential environmental impacts, biogeochemical consequences and the outstanding scientific unknowns.
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Impacts, Unknowns and Problems

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INTRODUCTION
Limited quantitative research has been undertaken on the likely impacts and risks
associated with ocean fertilization. The precise response of the global ecosystem to such
large scale manipulation is unknown, and remains an area of serious concern. This
chapter will review some of the potential environmental impacts and critical scientific
unknowns that have been associated with ocean fertilization, highlighting areas which
require further investigation.
ENVIRONMENTAL IMPACTS

Marine biogeochemical and biological systems are difficult to predict and subtle in nature. In addition, there is a scarcity of relevant physiological and ecological data. These factors combine to make it difficult to define possible limits to the environmental effects of ocean fertilization. Nevertheless, scientists have identified a wide range of environmental impact with varying degrees of certainty.

Toxic effects

Toxic effects of ocean fertilization may arise due to toxins introduced directly with the nutrient source, or indirectly from the stimulation of toxic biota.

Full scale implementation of ocean fertilization will demand massive quantities of pure nutrients. There is significant risk that contaminants will be introduced with nutrient supplies, leading to toxicological impacts. Beyond the poisoning effects on direct trophic levels, toxins may accumulate in, and be transferred through marine food webs, affecting consumers at higher trophic levels, including fish, seabirds, marine mammals, and ultimately humans (Turner and Tester 1997). This is of particular concern if fish are to be directly harvested from fertilized patches.

The stimulation of naturally occurring toxins is also a concern. Fertilization achieves it’s success by generating massive blooms of phytoplankton. In modified fertilization proposals such as those suggested by OFI cyanobacteria are to be likewise stimulated in order to supplement the nutrient supply by fixing atmospheric nitrogen. It is not unreasonable to speculate that in such large uncontrolled situations, that toxic species of both phytoplankton and cyanobacteria might be accidentally stimulated. *Trichodesmium* is a species of cyanobacteria which has been found to be toxic (Devassy et al. 1978; Hawser and Codd 1992; Hawser et al. 1992) and may respond to fertilization in the low nitrogen, low iron regions being targeted by OFI’s proposals. Experience suggests that this can have disastrous ecological consequences. Algal blooms are responsible for variously killing or impairing zooplankton, fish, birds, or cetaceans (Geraci and al 1989; Smayda and Shimizu 1993; Smayda 1992; Work and al 1993) and have had serious toxic
effects on people, including paralytic, neurotoxic and amnesic shellfish poisoning (Hallegraeff 1993).

Eutrophication
Eutrophication is now an endemic environmental problem, affecting a growing number of marine environments around the world (Nixon 1990). The onset of ‘human-induced’ or cultural eutrophication1 occurs as a result of increased nutrient fluxes from anthropogenic sources that subsequently stimulate primary productivity. In many ways, this is equivalent to the process that is to be forced under ocean fertilization.

Although typically confined to shallow water ecosystems the effects of eutrophication have also been observed in large scale systems such as the Baltic Sea (Cederwall and Elmgren 1990), the Black Sea (Mee 1992) and Chesapeake Bay (Boynton et al. 1995). Regions of the ocean that are particularly susceptible to eutrophication are those with relatively stagnant conditions, where vertical and horizontal mixing are inhibited by low currents and low rates of water exchange. Notably, benign wind and current conditions also minimize fertilizer mixing and dispersal losses and so are also favorable for fertilization operations (Markels 1997a).

Documented ‘symptoms’ of marine eutrophication include increased production, changes in species composition, increased occurrence of algal blooms (often harmful and even toxic), hypoxia, reduction of water quality and clarity, changes in the structure of benthic communities, and reduction of amenity (Kennish 1997; Valiela 1995). Despite enhanced levels of primary productivity, some eutrophied systems have also experienced declines in fish stocks and reduced species diversity over time. Eutrophication has resulted in declining oxygen levels in the deep water of the nutrient-rich Black Sea, and is thought to have contributed to declining fish catches (Leppakoski and Mihnea 1996). In the Chesapeake, shifts in fish species caused by eutrophication have tended to be from those

1 Cultural eutrophication should be distinguished from the natural process of eutrophication that occurs over time, transforming water bodies and ecosystems slowly over many decades or centuries. Cultural eutrophication occurs as a result of anthropogenic impacts over much shorter time frames, and has had dramatic effects on ecosystems.
used as a food source by higher trophic levels to those of little value in the food chain (Officer et al. 1984). Direct extrapolation of these system responses to the open oceans may not be entirely accurate, and yet it does serve to illustrate that increased primary production may not necessarily induce productive outcomes at higher trophic levels, and could be accompanied by significant and detrimental side effects.

Fertilization will clearly have to be undertaken in carefully selected areas and thoroughly monitored to ensure enhanced productivity is not accompanied by undesirable consequences.

**Shading/coral deaths**
The generation of massive phytoplankton blooms, whether it results in eutrophication or not, will intercept light and may potentially cause the death of coral reefs, tightly coupled ecosystems, and other benthic organisms. Coral deaths in the Red Sea are reported by Genin (1995) as a result of both shading and covering by large algal mats (Genin et al. 1995). Markels (1997b) concurs that these systems are likely to suffer under OFI fish production proposals although hopes to limit impacts by fertilizing away from reef zones. However, ocean currents cannot be controlled and unpredictable shifts in prevailing flows could damage reef systems permanently.

**Species composition, diversity and ecosystem change**
Experimental evidence indicates that fertilization will lead to shifts in species composition. IRONEX I and II, as well as other *in situ* experimental trials (Cavender-Bares et al. 1997; Coale et al. 1996; Martin et al. 1994; Pollingher et al. 1995) show that diatoms are preferentially stimulated by iron fertilization. During IRONEX II the biomass of diatoms was disproportionately increased in relation to other species, elevated 85 times over ambient concentrations. In contrast, smaller phytoplankton were controlled by grazing of microzooplankton (Coale et al. 1996; Frost 1996). These changes in species composition will be propagated up the food web with profound implications for the ecosystem. For example, diatoms have been found to be an inferior food source for certain zooplankton and is also associated with lower egg viability in copepods (Ianora et
al. 1996; Poulet et al. 1995; Uye 1996). This weakens a link in the food chain and should be a serious concern for fish production fertilization operations (Cavender-Bares et al. 1997).

Nutrient enrichment has also been linked to shifts in ecosystem composition in eutrophied aquatic systems (Officer et al. 1984; Rosenzweig 1972). Fish production proposals, such as OFI’s, in fact rely on the cultivation of a few select fish species. As the interactions of existing communities are highly interdependent and individual responses to fertilization are likely to vary, the extent and impacts of long term species changes are very difficult to predict (Chavez et al. 1991; Cullen 1991). Yet experience indicates that such shifts can alter both the structure and function of organisms in the food web with dramatic consequences (Orians et al. 1986).

We hold limited knowledge on many of the species likely to be successful under ocean fertilization. For example, scientists currently know little about the nitrogen fixing cyanobacteria which are to be seeded under OFI proposals (Markels 1997b). The role of these organisms in marine food webs is unknown because they have not been observed in significant quantities in marine ecosystems. Predators for these microorganisms are not defined, impacts are unspecified, and there is uncertainty about how fish communities would be altered in a cyanobacteria dominated ecosystem (Chisholm, personal communication)

The wealth of possible ecosystem responses and numerous other unknowns, indicate that impacts will extend beyond primary productivity increases, although quantifying the ecosystem reaction to fertilization is difficult (Fuhrman and Capone 1991). The dramatic results of IRONEX II relative to those of IRONEX I demonstrate that ecosystems as a whole can have different responses to iron fertilization due to differences in community biological responses, as well as variations in the physical stability of the ocean and other external conditions. It is clear that an increase in primary productivity - of sufficient magnitude to sequester intended levels of CO₂, or to a lesser extent for large scale
commercial fish harvest - over concentrated areas of the world's oceans, will have a
dramatic and unpredictable effect on marine ecosystems (Sarmiento and Orr 1991). This
possibility should at very least, warrant some caution.

**Oxygen Deficiency**

Oxygen depletion is a significant and likely consequence of large scale, sustained ocean
fertilization. Models by Peng and Broecker (1991), Sarmiento and Orr (1991) and Joos
et al (1991) concur that increased organic matter supply to the deep sea, in the form of
sinking particles from the euphotic zone, has the potential to create anoxic conditions in
regions of the ocean. Fertilization will enhance the fluxes of nutrients and carbon from
surface waters, increasing respiration and degradation, and contributing to oxygen
consumption, eventually leading to oxygen deficiency.

Sarmiento and Orr (1991) quantified the likely extent of anoxia caused by iron
fertilization of the Southern Ocean using their numerical modeling experiment². Nutrient
depletion of the Southern Ocean was predicted to induce anoxia in the mid-depths of the
southwestern Indian Ocean. Anoxia was also forecast in the Pacific Ocean off South
America, and in the Indian Ocean for equatorial fertilization scenarios; and over much of
the Northern Pacific for nutrient addition in the Northern subtropics (Sarmiento and Orr

Results of this type indicate that large scale fertilization strategies which rely on depletion
of naturally occurring nutrients are likely to have unacceptable ecological consequences.
Occurrences of anoxia, even if of limited extent and duration, has the potential to kill
organisms at all trophic levels and dramatically alter, or even eliminate biological
communities in the ocean (Hansson and Rudstam 1990; Seliger et al. 1985). Many
marine organisms exhibit extreme sensitivity to low oxygen concentrations. Even if
fertilization is limited and induces only lower ambient oxygen conditions or episodic
anoxic events, similar effects may be realized (D'Avanzo and Kremer 1994). Decreased
oxygen gradient and a lower diffusive flux to replenish oxygen depletion by respiration
could also give rise to the creation of anoxic microzones in organic aggregates and metazoan guts (Fuhrman and Capone 1991).

**BIOGEOCHEMICAL CONSEQUENCES**

In addition to the dramatic ecological impacts of anoxia there are significant biogeochemical consequences if ocean fertilization is implemented on global scales.

**Sulfide**

In the open ocean, sulfate reduction to sulfide occurs under anoxic conditions. This is a quantitatively important process in the organic cycle of the sea (Jorgensen 1982). It is speculated that sufficient and sustained nutrient additions that induce anoxia may accelerate this process increasing its significance in the water column. Sulfide produced via sulfate reduction consumes further oxygen and has the potential to amplify anoxic conditions and its consequent effects (Fuhrman and Capone 1991).

**Methane**

Methanogenesis is typically observed under extremely anoxic bulk water conditions (Cicerone and Oremland 1988), but can also occur in isolated microzones (e.g. animal guts) of otherwise oxygen replete waters (Oremland 1979). Fertilization is designed to increase primary productivity and will thereby increase biomass of zooplankton and fish, creating more sites for methanogenesis in animal digestive tracts and elsewhere (Fuhrman and Capone 1991). Methanogenesis produces methane (CH₄), a potent greenhouse gas, with a global warming potential 21 times CO₂ (Shine et al. 1990). It is already a significant global problem and atmospheric levels are increasing rapidly (Watson et al. 1990). Introduction of a new marine source of CH₄ would significantly exacerbate the problem.

**Nitrous Oxide**

An overall increase in nitrogen cycling should be expected as a result of fertilization and it is likely that this will be accompanied by a shift in the relative importance of specific

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² Refer earlier discussion of these models in chapter 4 under ‘CLIMATE MITIGATION MODELS’.
nitrogen pathways (Fuhrman and Capone 1991). An important implication of these changes is the enhanced production of the intermediate gas nitrous oxide (N₂O). N₂O is a powerful greenhouse gas with a global warming potential approximately 206 times greater, per molecule, than CO₂ (Shine et al. 1990), and is also implicated in the destruction of stratospheric ozone (Crutzen 1981; Shine et al. 1990). Estimates by Fuhrman (1991) indicate that the enhanced release of N₂O alone, could totally negate any potential climate-cooling benefit from fertilization and probably even worsen global warming and ozone depletion. Although only a preliminary calculation, it does demonstrate the need for a more quantitative understanding of the processes that control marine N₂O emissions before embarking on full scale implementation of fertilization.

**Fe mobilization**

Another possible side effect of fertilization with iron is the ‘self mobilization’ of this trace element. Under aerobic conditions, Fe exists primarily in the Fe(III) state remaining particle bound, and unavailable for biological or chemical use. In anoxic conditions (or microzones) however, biological and chemical mechanisms reduce Fe(III) to the Fe(II) state which is more soluble and bioavailable (Landing and Bruland 1987). This creates a potential mechanism for uncontrolled ‘self-fertilization’ of the ocean. The anoxic zones generated by large scale fertilization might lead to Fe solubilization and mobilization, enhancing the availability and residence time of iron in surface waters and inducing self-fertilization (Fuhrman and Capone 1991). Although this may be desirable from an engineering perspective the uncontrolled nature of this process is a concern, and would make reversal of processes difficult. Although only a remote possibility, this mechanism needs to be further investigated.

**Dimethyl sulfide**

Dimethyl sulfide (DMS) is released into the atmosphere by certain species of marine phytoplankton. Emitted DMS is then oxidized to form atmospheric sulphate particles (SO₄). This aerosol exerts both direct and indirect climate effects -it scatters and absorbs solar radiation, and influences cloudiness and hence indirectly, global albedo (Charlson et al. 1987). Although clouds are known to display a significant influence on the global
climate, the direction and extent of this effect are not well understood. Lovelock (1990) has proposed that DMS production by phytoplankton may provide a negative feedback in regulating production and global climate. Quantification of the impact of DMS on climate is uncertain. What is known however is that iron fertilization will alter the relative abundance of DMS/non-DMS producing organisms, and there will be a net and unpredictable change (Fuhrman and Capone 1991). IRONEX experiments have indicated, for the equatorial Pacific at least, that changes in DMS production are likely to be climatically more significant than iron-induced changes in the uptake of CO₂ by the oceans (Lovelock 1990; Turner et al. 1996).

Notably, DMS producing phytoplankton species are particularly abundant in Antarctic waters (Frost 1996), therefore the DMS effects of fertilization in this region are likely to be at least as significant as those observed in IRONEX II (Turner et al. 1996). In addition, the Southern Ocean is especially susceptible to DMS-induced changes in cloud albedo because the density of cloud condensation nuclei in the region is low and there is an absence of other sources (Twomey 1991).

**SCIENTIFIC UNKNOWNS AND POTENTIAL PROBLEMS**

There now exists considerable empirical and experimental support for the iron hypothesis (Behrenfeld et al. 1996; Coale et al. 1996; Cooper et al. 1996; Frost 1996; Martin et al. 1994; Martin et al. 1993). And yet it is premature to be applying it in large scale geoengineering projects. There are key scientific uncertainties relating to this process which require further investigation before we should even consider such options.

**Unrealistic extrapolation of IRONEX results**

IRONEX I and II experiments were successful in eliminating the remaining doubt regarding iron limitation in the HNLC regions of the equatorial Pacific. It is optimistic however to unilaterally extrapolate these results to other regions of the ocean. Proposals for fertilization of the Southern Ocean and the non-HNLC equatorial Pacific will encounter vastly different physical, chemical and biological conditions that are likely to substantially alter the effects of fertilization. The Southern Ocean for example, is much
colder, experiences much lower mean light, deeper mixing, and much slower maximum growth rates, so that there is no guarantee that regions of this ocean would respond in a similar manner to iron additions. Hence in reality, although bottle experiments support the iron hypothesis in the Southern Ocean (DeBaar et al. 1995; Martin et al. 1990a; Martin et al. 1990b) the effects of field scale fertilization is still untested in the part of the ocean where its significance to atmospheric CO₂ is greatest. There is even less experimental support for commercial proposals which employ other ocean fertilization techniques, and it is incorrect to cite IRONEX results as justification for these very different proposals.

**An issue of rates**

An important factor that is often overlooked in the ocean fertilization debate is the issue of rates. Ultimately the magnitude of sequestration or fish production produced by ocean fertilization will depend on the rate at which phytoplankton are capable of growing and reproducing. This will be effected by the rate of fertilizer supply, rate of grazing, rate of sedimentation, rate of nutrient cycling and rate of biological growth. For example, if grazing exceeds these growth capacities, or nutrients are unable to be recycled sufficiently rapidly, then the full impact of fertilization will not be realized. It is therefore vital that temporal constraints are considered when assessing fertilization proposals.

**Other limiting factors**

Considerable debate remains concerning the geographical and biological extent and nature of nutrient limitation in the oceans (Banse 1990; DeBaar 1994). There is limited evidence that iron is a limiting factor outside the geographically limited HNLC zones originally proposed (Falkowski 1997). Some concerns about growth limitation assumptions have already been discussed in relation to commercial PGGM and OFI proposals. It will therefore suffice to re-state that field experimentation has yet to show that iron limitation theory applies beyond the IRONEX-tested region of the equatorial Pacific. It is premature to assume iron fertilization can be applied to other oceanic

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3 Further discussion of Falkowski's findings is undertaken in chapter 3 under 'CLIMATE RESEARCH AND EXPERIMENTS: New Twists to Nutrient Limitation'

4 Refer to discussion in chapter 4 under 'OCEAN FERTILIZATION PROJECTS'.
regions. Other fertilization techniques which rely on macro-nutrient nitrogen and phosphorus fertilization are likely to have broader application, but at significantly higher cost.

The premise of ‘infinite’ primary nutrient limitation has also been questioned in chapter 4. This is likely to constrain fertilization geographically, and over time. When fertilization supplies the naturally limiting nutrient, primary production is likely to increase only until it meets the next natural constraint. According to current understanding in oceanography, a single nutrient may only be one of a suite of limiting factors in most, if not all ecosystems and seasons. A classic example of the temporal nature of limitation is provided in the North Atlantic spring blooms. During the bloom a succession of algal species can be observed, as nutrient limitation shifts from one element, silicate (Si) followed by nitrogen, then phosphorus depletion, which in turn limits other species (DeBaar 1994).

A nutrient which has received little attention in fertilization proposals to date is silicate. And yet it’s importance as a macro-nutrient to ocean productivity is well established. Dugdale (1998) suggests that surface waters of some regions of the ocean are silicate limited for diatoms (Dugdale and Wilkerson 1998). The significance of silicate is even more important under fertilized conditions. Diatoms were preferentially stimulated during IRONEX experiments (Coale et al. 1996), indicating that biological demand for this nutrient is likely to increase in ecosystems impacted by fertilization.

Grazing also has continued support as a potentially limiting factor under fertilization scenarios (Brandini 1993; Frost 1991; Riley 1946; Riley 1947). Zooplankton keep phytoplankton populations in check through grazing. When grazing increases, so does the recycling of carbon in the surface waters. This promotes biomass production but reduces the amount of carbon buried in the deep sea. During IRONEX experiments small and large zooplankton increased in abundance and grazing rate, and were held responsible for limiting small phytoplankton growth in the fertilized patch (Banse 1995; Cavender-
Bares et al. 1997; Coale et al. 1996). Their response however was insufficient to prevent the diatom bloom. Under sustained conditions it is possible that zooplankton and grazers at higher trophic levels would have time to respond to the phytoplankton growth.

**Long term fate of carbon**

The long term fate of carbon sequestered during iron fertilization could not be satisfactorily determined during the short duration of the IRONEX experiments (Trefil 1996). Although a large decrease of fugacity was observed in response to fertilization, effects were transient (Cooper et al. 1996). Although continuous fertilization may maintain sequestration for longer periods, the question remains as to how long will CO₂ be sequestered.

**External effects**

A concept often forgotten in ocean fertilization debate is the impacts experienced external to fertilized patches. The ocean is a tightly coupled system in which nutrients are carefully recycled throughout the oceanic system. This process have evolved over thousands of years.

The basic intent of all fertilization proposals is to utilize these nutrients in locations where they are not naturally optimized. But in depleting nutrients in one zone, the supply of nutrients to other areas must be reduced. The moral of the story is that 'there is no free lunch'. Fertilization may have the capacity to localize and intensify new production, altering food-web relationships, but it must ultimately reduce new production downstream with an unknown net effect on CO₂ flux and ocean production for the system. Modeling studies by Sarmiento and Orr (1991) have predicted that iron fertilization of the Southern Ocean will lead to a reduction in new production in other oceanic regions. This is because nutrients from the Southern Ocean are depleted, reducing upwelling concentrations of nutrients to other parts of the ocean.

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5 The mechanics of the 'ocean conveyor belt' are described in chapter 2, under 'FUNDAMENTAL CONCEPTS: Thermohaline Circulation'.

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OFI’s proposal for fertilization relies on the external addition of iron, and nitrogen (from the atmosphere) and therefore theoretically does not deplete the natural supplies of these nutrients. However, as shown in calculations completed in chapter 4, the phosphorus content of the proposed fertilizer mix will be insufficient to meet full anticipated biological demand, and so this nutrient, as well as others essential for growth, such as Si, will be depleted from natural supplies, and disrupt natural global cycling patterns.

**Positive impacts**

The potential benefits of ocean fertilization have already been clearly elucidated:

(i) potential climate mitigation through carbon sequestration; and

(ii) the possibility of productivity enhancement leading to increased fish harvest.

Proponents claim additional benefits to ocean fertilization. One of these favorable characteristics is claimed to be the ‘reversibility’ of the phenomena. ‘*Unlike erosion of land, none of the changes are permanent*’ (Markels 1997a). Markels argues that when fertilization ceases, the impacts disappear. The results of the 7 day fertilization undertaken in IRONEX II do indeed exhibit a return to pre-existing conditions when fertilization is stopped (Frost 1996). However, these results simply cannot be extrapolated to a 100 year, or even shorter enrichment process applied over the large scales proposed. For long term, large scale fertilization schemes the ecosystem should be expected to adjust to changed conditions\(^6\), and such permanent changes will prevent the easy reversibility witnessed during IRONEX II.

In addition Markels (1997a) claims fertilization will benefit dolphins, whales and migratory fish who will be able to feed in the artificially high nutrient zones. Skeptically, it is difficult to imagine a commercial fishing operation which would encourage the consumption of valuable and stimulated phytoplankton by marine mammals, especially when they compete with fishing and carbon sequestration interests.

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\(^6\) Ecosystems responses to environmental changes are the subject of textbooks. The long and well-documented history of eutrophication provides but one example of how elevated nutrient loads have altered existing ecosystems.
CONCLUSION

There are a wide range of suggested indirect effects of ocean fertilization. Given the formative nature of the science, and the unpredictability of the physical and biological system, it is highly likely that there are many more impacts not yet considered. The potential benefits of ocean fertilization need to be weighted against these considerations. This chapter has delineated some of the environmental and biogeochemical risks and uncertainties. We now turn and consider some of the social, political and legislative dimensions of ocean fertilization.
REFERENCES


INTRODUCTION
An evaluation of ocean fertilization would be incomplete without an analysis of international and national regimes, public consensus and politics. The marine environment is controlled and protected by numerous global and regional conventions - this chapter identifies and analyses key international laws and principles considered relevant to fertilization strategies. It also reviews historical precedents to assess potential public response. Finally, global politics can be expected to factor in the consideration of ocean fertilization, and some of the broad issues to be considered for climate geoengineering and food production schemes are outlined.

MARITIME LAW
There exist more than 70 conventions associated with the protection and preservation of the marine environment - over half of these are regional agreements (Matthews 1992). Although there has been regional regulation to control deliberate nutrient enrichment of coastal waters, there appears to be no direct legal precedent for ocean fertilization in the open seas.\(^1\)

Law of the Sea (UNCLOS)
The United Nations Convention on the Law of the Sea (UNCLOS) was opened for signature in 1982. However, it was not until 1994 that it received the required number\(^2\) of ratifications to enter into force. Today, UNCLOS is the globally recognized regime dealing with all matters relating to the laws of the sea. It is monitored by the United Nations (UN) General Assembly and supported by a dedicated UN Division for Ocean Affairs and the Law of the Sea (DOALAS).

Although now broadly accepted, and ratified by 124 countries (as of May 1998), UNCLOS has not been signed by many developed nations (UN 1998b). Nevertheless, its wide international acceptance has meant that many of the provisions of UNCLOS, including those relevant to ocean

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\(^1\) The growing problem of coastal marine eutrophication has propagated regional and national legislation controlling anthropogenic nutrient discharges. The PARCOMM recommendations 88/2 and 89/4 are but one illustration of this regulatory trend. Through this agreement the contracting parties to OSPAR (Oslo and Paris Commission) agreed on measures to achieve substantial reduction of nutrients into the North Sea, Skagerrak and Kattegat and other Convention waters (Lutter 1996). Although many similar precedents can be cited for coastal marine waters, there is no known equivalent regulatory example for the open seas.

\(^2\) UNCLOS could not enter into force until it had obtained sixty (60) ratifications.
fertilization, have become part of customary international law\(^3\) (McCullagh 1996)

The Convention is of a framework nature, leaving the elaboration of precise rules to national governments and international organizations (Churchill and Lowe 1988). To provide this framework the oceans have been legally divided into various zones - the 'territorial sea', the 'exclusive economic zone', the 'continental shelf', and the 'high seas' (Fig. 6-1). Within each zone parties are subject to distinct rights and responsibilities. A description of these provisions and their relevance to ocean fertilization follow:

**Territorial Sea**
The territorial sea extends 12 nautical miles (nm) from the baseline of a coastal state (Part II, Article 3) (UN 1983). Within this zone the coastal state maintains sovereign jurisdiction, allowing only foreign vessels 'innocent passage' for purposes of peaceful navigation. Adjoining the territorial sea is the contiguous zone which extends from the territorial sea up to 24 nm from the baseline of a coastal state (Part II, Article 33) (UN 1983). In the contiguous zone the coastal state exercises control of customs, fiscal, immigration and sanitary laws and regulations (UN 1983; Wang 1992).

It is unclear whether the provisions of UNCLOS allow ocean fertilization in territorial waters. Although sovereignty is granted to coastal states in these zones, this jurisdiction is limited by international regulations - such as the London Convention, the Biodiversity Convention and the Transboundary Convention\(^4\) - which hold party states responsible for protecting and preserving the marine environment (McCullagh 1996).

What is clear however, is that any fertilization project undertaken within a State's territorial sea would require the consent of that State. Any pipeline laid across a territorial sea for the purpose of fertilization would also require the consent of the coastal State (Part II, Article 2) (UN 1983).

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\(^3\) 'Customary law' consists of legal principles that have acquired international acceptance through common behavior and/or declaration.

\(^4\) Refer later discussion in this chapter under 'OTHER LEGAL CONTROLS' for fuller interpretation of these various international regulations.
Figure 6-1: Maritime jurisdictional zones (modified from Ormerod, 1996). The oceans are legally divided into the 'territorial sea', the 'exclusive economic zone', the 'continental shelf' and the 'high seas'. Within each zone, parties are subject to distinct rights and responsibilities.
In contrast, any ship carrying fertilizer across the territorial sea, for discharge outside the territorial sea, has the right of free passage through this zone (Part II, Article 21) (UN 1983).

**Exclusive Economic Zone**
The exclusive economic zone (EEZ) extends up to 200nm from the baseline of a coastal State (Part V, Article 57) (UN 1983). Within this zone coastal States have sovereign rights over natural resources and certain economic activities, and jurisdiction over certain types of scientific research and environmental protection. All other states have freedom of navigation and overflight, as well as freedom to lay submarine cables and pipelines (Part V, Article 56) (UN 1983).

Coastal States have sovereign power to resources and economic activities within the EEZ, however these rights are subject to all international regulation to which the coastal State is party (McCullagh 1996); must not cause harm to other States (Article 56(2)) (UN 1983) and are also accompanied by several additional duties regarding (a) the protection and preservation of the marine environment, including the control of pollution and dumping (Part XII) (UN 1983); and (b) the conservation of natural resources and marine life (Article 58(3)) (UN 1983).

**(a) Protection and Preservation of the Marine Environment**
The obligations of the coastal State under UNCLOS, for the protection and preservation of the marine environment are delineated in Part XII of the convention. States agree to take measures to prevent, reduce and control pollution arising from activities in their EEZ (Article 194) (UN 1983). UNCLOS defines the 'pollution of the marine environment' as:

> 'the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities’

**(Article 1(4))(UN 1983)**
Thus, ocean fertilization will be subject to regulation under UNCLOS if it can be proven to cause marine harm. Notably, the burden of proof will lie with opponents to ocean fertilization, who will have to scientifically establish that practices have deleterious effects on the marine environment. Further investigations are still required to fully understand the immediate environmental effects of adding iron and other nutrients to ocean surface waters, and to unequivocally establish the indirect effects of increased productivity on other marine life (Fuhrman and Capone 1991). Until such further research is undertaken, these claims will be difficult to make.

Under certain conditions, it could be argued that fertilization operations represent a ‘hindrance to marine activities’ and therefore should be classified as a pollutant. This may be particularly applicable if ocean fertilization is used for fish production, and harvesting activities are found to hinder the operations of existing fishing vessels. However, fertilization operators could easily avoid this ‘loophole’ through thoughtful planning to mitigate the impacts of their activities. It therefore should not be considered a significant impediment.

One of the specific discretions granted to the coastal State in the EEZ is the control and regulation of ‘dumping’ (Part XII, Article 210) (UN 1983). It is unclear however, whether the addition of fertilizers to open ocean waters will classify as ‘dumping’. Dumping is defined in the convention as:

‘any deliberate disposal of wastes or other matter from vessels, aircraft, platforms or other man-made structures at sea’

(Article 1(5(a)(i)) (UN 1983)

but does not include:

‘the placement of matter for a purpose other than the mere disposal thereof, provided that such placement is not contrary to the aims of the convention’

(Article 1(5(b)(ii)) (UN 1983)

The first ambiguity relating to ocean fertilization, concerns the interpretation of ‘wastes or other matter’. This terminology is not defined by UNCLOS. It is uncertain whether fertilizer mixes
which comprise inorganic chemicals that occur naturally in the sea, will satisfy this description. If the fertilizer mix comprises additional man-made additives it is more likely to be comply with this description, and thus satisfy this portion of the ‘dumping’ definition.

A second ambiguity surrounds Article (5(b(ii))). The primary intent of fertilizer addition is not disposal, and so it may not be considered subject to dumping regulation unless a convincing argument can be made that it is ‘contrary to the aims of the convention’.

If, on the one hand, fertilization is deemed to be ‘dumping’, control falls clearly under the jurisdiction of the coastal State. Those coastal States which are parties to the London Convention (LC) must then enforce within their EEZ, the onerous obligations they hold under this agreement. This is of significance, because unlike UNCLOS regulation, the LC applies the precautionary principle with respect to pollution. This means that all substances are assumed to be harmful (and a ‘pollutant’), unless they are demonstrated NOT to cause detrimental effects to marine life. Thus, according to the LC, the burden of proof lies with ocean fertilization operators who must prove that fertilizer does not damage the marine environment before permission for dumping can be obtained. This is likely to be a significant impediment to operations (LC 1972).

On the other hand, if fertilization is not recognized as ‘dumping’, then control of this practice will fall under the broader requirements of UNCLOS Part XII for the ‘Protection and Preservation of the Marine Environment’ (UN 1983). In this instance the somewhat more ambiguous definition of pollutant, as described in Article 1(4), holds. In direct contrast to the London Convention, UNCLOS places the burden of proof with opponents to fertilization. As pointed out earlier, further research will be required before fertilization can be controlled as a pollutant under this scenario.

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5 For example, Markels (personal communication) proposes to incorporate floatation additives, chelators and seed organisms into a iron/phosphorus fertilizer mix to be used for open ocean fertilization.
6 Discussion of the London Convention is undertaken later in this chapter under ‘OTHER LEGAL CONTROLS’
7 The precautionary principle requires the use of preventative measures whenever there are reasonable grounds for believing that an activity will detrimentally impact the marine environment, whether or not causation can be shown (Cameron and Abouchar 1991).
8 As described previously in this section
UNCLOS regulation of ocean fertilization will also be distinctly different depending on whether operations require fertilizer discharge from ships or pipelines:

(i) For *ship-based fertilization* proposals there is a wide breadth of possible interpretations of both ‘pollutant’ and ‘dumping’. This means that, in reality, the coastal state is likely to be able to use their independent discretion to approve or disapprove of fertilization proposals. The only constraints on a coastal State’s discretion is it’s general obligation to have ‘due regard’ to the rights and duties of other States; and any obligations the State may hold under international treatise. If party to the London Convention or other marine pollution conventions, fertilization activities will require closer review. In all instances, the State must allow free passage of ‘fertilizing’ vessels enroute to fertilization sites outside their EEZ (LC 1972; UN 1983).

(ii) For *pipeline nutrient discharge* proposals, such as those by Jones and Otaegui (1997), legislation is even more complicated. All states have the right to lay pipes within exclusive economic zones, however this is subject to the coastal States rights to:

> ‘take reasonable measures for the exploration of the continental shelf, the exploitation of it’s natural resources and the prevention, reduction and control of pollution from pipelines’ *(Article 79(2)) (UN 1983)*

This would appear to indicate that the coastal State has the right to impede the laying of pipelines if deemed necessary to control pollution or protect marine life (Churchill 1996).

With respect to the control of pipe discharge; the coastal state has the authority to regulate pollution from pipelines in the EEZ which originate within its own territory. They do not have such authority for pipelines that originate from outside the state. (However, pipelines that originate from other states do not appear to have authority to discharge within the EEZ of another state) *(Part V, Article 56) (UN 1983)*. In order for discharge from a pipeline to be classified as a pollutant under UNCLOS it must satisfy the Article 1(4) pollutant description described above³. As mentioned already, additional scientific research is likely to be required to unequivocally
prove ocean fertilization causes marine harm. For pipelines, it will potentially be more difficult to use ‘hindrance to marine activities’ as a reason for designating fertilizer as a pollutant. This is because pipelines tend to be less intrusive, and could be designed not to affect other activities. This may mean that fertilizer discharged from carefully planned and located pipes may not be subject to control within the EEZ (UN 1983).

As noted in Article 1(5) previously, dumping includes disposal from ‘man-made structures’ (UN 1983). Thus, it is feasible that pipeline discharge, along with ship based proposals, may be subject to the international rules of the LC. (However, as explained previously, this hinges on whether the action of fertilization, which is not necessarily ‘disposal’ can be appropriately defined as ‘dumping’). If pipe discharge is deemed dumping, the coastal State has the authority to control all pipelines, and the definition of pollution can become the more all-encompassing precautionary term applied under the London Convention (LC) - provided of course, that the coastal State is a party to the LC or adopts LC principles in national or regional regulations.

(b) Marine Life
In addition to pollution control, UNCLOS binds party States to a commitment to conserve living resources in their EEZ. Coastal States must ensure that marine life resources are not over-exploited in the EEZ, but have a simultaneous obligation to promote the ‘objective of optimum utilization of the living resources’ (Part V, Article 62(1)) (UN 1983) within the EEZ. Where the coastal State does not have the capacity to harvest the entire allowable catch, it must give other States access to the surplus of the allowable catch (Part V, Article 62(2)) (UN 1983). This means that, provided a party has authority from the coastal State, and does not over-exploit stocks, then it should be allowed to harvest fish from the within a nation’s EEZ

Continental Shelf
The continental shelf of a coastal State comprises the sea-bed and subsoil of the submarine areas extending beyond the territorial sea to the outer edge of the continental margin up to 200nm from

\footnote{Recall that fertilizer can be classified as a pollutant if (i) it is proven to cause harm to marine life, and/or (ii) it hinders other marine activities. Refer earlier discussion this section.}

\footnote{Refer earlier discussion this section.}
the shore baseline (Part VI, Article 76) (UN 1983). If the true shelf extends further than this
limit, the boundary may be extended up to 350nm, or alternately 100nm outward from the 2500
meter isobath\textsuperscript{11}. Coastal States have the right to exploit the natural resources of the seabed and
subsoil on the continental shelf (UN 1983; Wang 1992).

Rights and obligations of the coastal State in relation to both dumping and pipeline laying remain
the same in the continental shelf as in the EEZ. However, unlike the EEZ, these responsibilities
are confined to activities on the sea-bed. Thus:

(i) \textit{Pipe Laying}: Conditions for pipe-laying will be the same as those discussed for the exclusive
economic zone\textsuperscript{12}, because pipes will be laid on the sea bed and are therefore subject to
coastal state control.

(ii) \textit{Discharge}: Because both ship and pipe discharges are likely to occur in the water column
(and not from the sea-bed), these activities will not fall under the jurisdiction of the
continental shelf. Thus, the provisions will be the same as those discussed for the high
seas\textsuperscript{13}. The only exception would be if discharge can be shown to have negative impacts on
benthic organisms or seabed resources (Part XII) (UN 1983).

\textbf{High Seas}

Beyond the continental shelf is an area declared to be the ‘\textit{common heritage of mankind}’, or the
high seas. Seabed resources in this area can be exploited only by the International Sea-Bed
Authority. Otherwise UNCLOS dictates that the zone remain open to all States, allowing:

(a) freedom of navigation;
(b) freedom of overflight;
(c) freedom to lay submarine cables and pipelines;
\hspace{1cm} (subject to conditions)
(d) freedom to construct artificial islands and other installations
\hspace{1cm} permitted under international law;
\hspace{1cm} (subject to conditions)

\textsuperscript{11} The 2,500 meter isobath is a line connecting the depth of 2,500 m. The outer limit of the continental shelf is the
lesser of the 350nm boundary and a distance of 100nm from the 2,500m isobath (UN 1983).
\textsuperscript{12} Refer earlier discussion this chapter under ‘EXCLUSIVE ECONOMIC ZONE’
\textsuperscript{13} Refer next section, this chapter under ‘HIGH SEAS’
(e) freedom of fishing; *(subject to conditions)*
(f) freedom of scientific research. *(subject to conditions)*

*(Part VII, Article 87(1)) (UN 1983)*

Each one of these rights are conditional on the States showing:

‘due regard for the interests of other States in their exercise of the freedom of the high seas’

*(Part VII, Article 87(2)) (UN 1983)*

Thus, it is clear that within the high seas, States have the freedom to conduct any operation provided it is not actually prohibited by international law. On this premise, ocean fertilization may currently be legally undertaken on the high seas by any State provided they exhibit due regard to the interest of other States, as well as any other obligations binding upon them (such as those under the London Convention). A problem arises because UNCLOS does not clearly define the obligation of *due regard*. Because it is somewhat ambiguous, it might conceivably be used to impose restrictions on ocean fertilization practices, in some instances. This is a matter that will largely be left to the discretion of interested parties and would be subject to negotiation *(Part VII)* (UN 1983).

**Other UNCLOS Provisions**

There are numerous other UNCLOS Provisions which might be relevant to ocean fertilization practices. Two of particular significance are:

a) Environmental Monitoring and Assessment *(Section 4, Part XII); and*

b) Marine Scientific Research *(Part XIII) (UN 1983)*

*(a) Environmental Monitoring and Assessment*

The UNCLOS provision for Environmental Assessment could have significant bearing on ocean fertilization proposals. Under this requirement States must analyze and monitor all activities under their jurisdiction\(^\text{14}\) as follows:

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\(^{14}\) *Coastal State jurisdiction* includes territorial waters, EEZs and the sea-bed of the continental shelf
‘When States have reasonable grounds for believing that planned activities under their jurisdiction or control may cause substantial pollution of or significant and harmful changes to the marine environment, they shall, as far as practicable, assess the potential effects of such activities on the marine environment and shall communicate reports of the results ....’

(Article 206) (UN 1983).

The detail of information demanded for a UNCLOS Environmental Impact Assessment (EIA) is limited in extent to that which is ‘practicable’. However, the United Nations Environment Program (UNEP) have now established international codes for EIA preparation that are significantly more onerous, requiring large amounts of impact data (UNEP 1995). Although these are not legally binding they may be legitimately applied. Once again, much depends on the coastal states definition of pollution, and commitment to the protection of the marine environment. A wide range of opinions and applications of this principle can be expected.

(b) Marine Scientific Research
Finally, a brief mention should be made of the UNCLOS position concerning research. It is clear that further field experiments of ocean fertilization will be required before implementation, and are indeed planned and/or underway in different parts of the world\(^{15}\). Part XIII of UNCLOS specifically outlines the rights and obligations for Marine Scientific Research. In general the convention requires that:

‘research shall be conducted exclusively for peaceful purposes,.... shall be conducted with appropriate scientific methods,... shall not unjustifiably interfere with other legitimate uses of the sea... (and) shall be conducted in compliance with all relevant regulations adopted in conformity with this convention including those for the Protection and Preservation of the marine environment.’

(Part XIII, Article 240) (UN 1983)

(i) In Territorial Waters, EEZ and the Continental Shelf: In the territorial waters, EEZ, and continental shelf, the coastal State has the authority to regulate, control and conduct research.

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\(^{15}\) Refer earlier discussion in chapter 3, which outlined current planned activities involving ocean fertilization.
The EEZ and continental shelf zones however, are subject to the limitation of 'implied consent' (Article 246(3)) (UN 1983). This means that states are instructed to grant consent for research by other states under normal circumstances. However, coastal States maintain complete discretion with respect to applied research projects, if that project is:

a) of direct significance for the exploration and exploitation of natural resources whether living or non-living;

b) involves drilling into the continental shelf, the use of explosives or the introduction of harmful substances into the marine environment;

c) involves the construction, operation or use of artificial islands, installations and structures....'

(Article 246(5)) (UN 1991)

Similarly, consent can be denied if marine scientific research:

'unjustifiably interfere(s) with activities undertaken by coastal States in the exercise of their sovereign rights and jurisdiction provided for in this convention'

(Article 246(8)) (UN 1983)

In addition, all marine scientific research is subject to the general provisions of UNCLOS that relate to the protection and preservation of the marine environment (Part XII) (UN 1983). This means that field experiments of ocean fertilization within a coastal states jurisdiction could potentially be cited as a violation of the States responsibilities to 'prevent, reduce and control pollution of the marine environment' (Part XII, Article 194 (1)) (UN 1983) - provided fertilizer is deemed a pollutant16. However, it is also possible that this same argument may be used to support fertilization proposals. Advocates may justify experiments by using the argument that the experiments will be used to prevent harmful effects on the marine environment caused by climate change and over-exploitation of fisheries (McCullagh 1996).

Article 246(5(a)) may be significant for experiments exploring the fish production potential of fertilization. Conceivably, the coastal state could protest activities on the basis that they are of 'direct significance for ...the exploitation of natural resources'
(ii) On the High Seas: The United Nations 'Marine Scientific Research - A Guide to the Implementation of the Relevant Provisions of the United Nations Convention on the Law of the Sea' (UN 1991) provides no advice with respect to research on the high seas. This zone is the 'common heritage of mankind' and scientific research is explicitly referred to as one of the freedoms of the high seas (Article 87(1)(f)) (UN 1983). Therefore, consent is not required for research in this zone. Party States to UNCLOS however would be bound, as they are elsewhere, to comply with the general provisions of UNCLOS that concern the protection and preservation of the marine environment (Part XII) (UN 1983; UN 1991).

Other Legal Controls
The Law of the Sea Convention (UNCLOS), is not the sole international instrument regulating the use of the oceans. The provisions of other international conventions with more specific goals must also be considered in examining fertilization proposals for fish production and carbon sequestration. As already alluded to, the London Convention is likely to have considerable bearing on ocean fertilization discussions. Other international conventions include MARPOL, the Transboundary Convention and the Biodiversity Convention. These regulations apply to member States for their activities on the high seas, and to all zones within the jurisdiction of member States (territorial waters, EEZs and continental shelf) (Part XII) (UN 1983). Each is discussed briefly below, in the context of ocean fertilization.

The London Convention
Pollution of the oceans from dumping activities is controlled through the '1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter'. This convention, with a membership of 74 States (as of 30 April 1998) (UN 1998a), is commonly known as the London Convention (and formerly referred to as the London Dumping Convention). The Convention came into force in 1975, and has subsequently undergone numerous amendments. In 1996 a Protocol to this Convention was signed. When/if it enters into force this Protocol will dramatically increase the stringency of dumping regulations (LC 1972; LCP 1996).

Refer earlier discussion in this section regarding the appropriate classification of fertilizer. It remains uncertain whether fertilizer can be described as a pollutant under the UNCLOS definition.
The London Convention is global in scope and makes a general commitment to prevent the pollution of the marine environment caused by dumping. It achieves this by requiring each contracting party to regulate its own activities, nationals and areas of jurisdiction, in accordance with the Convention procedures (Nauke and Holland 1992). Administration of the convention occurs through its Secretariat - the International Maritime Organization (IMO) - a specialist agency of the United Nations. Under the current regulatory system, all dumping at sea requires a permit, which must be issued by a competent national authority (LC 1972).

The 1996 Protocol, which amends the original London Convention, installs the *precautionary principle* into the regulation of ocean waste disposal (LCP 1996). The precautionary principle, is a relatively recent legal doctrine that has been implemented in a variety of forms. The term is not fully defined in the London Convention, but implicitly promotes the use of preventative measures whenever there are reasonable grounds for believing that an activity will detrimentally impact the marine environment, whether or not causation can be shown (Thorne-Miller 1992).

Under the 1996 Protocol dumping of substances in the oceans is severely restricted. The protocol:

> 'prohibit(s) the dumping of any wastes or other matter with the exception of those listed in Annex1' *(Article 4) (1996)*

Annex 1 substances are:

1. Dredged Material
2. Sewage Sludge
3. Fish waste, or material resulting from industrial fish processing operations.
4. Vessels and platforms or other man-made structures at sea.
5. Inert, inorganic geological material
6. Organic material of natural origin
7. Bulky items primarily comprising iron, steel, concrete, and similar unharmful materials for which the concern is physical impact and limited to those circumstances, where such wastes are generated at locations, such as small islands with isolated communities, having no practicable access to disposal options other than dumping *(LCP 1972).*
It might be argued that fertilizer mix fits the description of item 5: ‘inert, inorganic geological material’ and therefore could be excluded from LC control under Annex 1. Ocean fertilization would thus be allowed under this convention. However, if fertilizer mix is comprised of additional floatation and other additives, it is unlikely to fit the Annex 1 substance descriptions, and will be controlled by the LC. It is also likely, given the strict precautionary philosophy that trademarks this Convention (Thorne-Miller 1992), that a case might be mounted to amend the Convention and explicitly exclude iron and other nutrient additives from Annex 1.

Thus, if ocean fertilization can be shown to be regulated by the LC, it could potentially be banned (depending on the fertilizer mix composition). In order to be subject to regulation however it must first meet UNCLOS’s definition of dumping\textsuperscript{17}. This requires that fertilizer is discharged with the intent of ‘deliberate disposal’ but does not include ‘placement of matter for a purpose other than mere disposal’ (Article III (1)(a) & (1)(b)) (UN 1983). As stated previously under current proposals, fertilization of the ocean with nutrient is not presently likely to be considered dumping, as the purpose of placing the fertilizer in waters is not disposal, but rather to increase primary productivity. However, while the present provisions of the London Convention appear to allow ocean fertilization, this regulation has become increasingly restrictive, through a series of recent amendments. As noted, the convention also strictly adheres to the precautionary principle. For these reasons, there is the possibility that parties to the convention may amend provisions by appeal (McCullagh 1996).

**MARPOL 73/78**

The ‘International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978’ (commonly referred to as MARPOL 73/78) is an instrument which combines two treaties adopted in 1973 and 1978 respectively. The convention has now been ratified by 97 States, and the Protocol received the required 16 ratifications to enter into force in late 1997 (UN 1998a). Like the London Convention, the provisions of this agreement are administered by the International Maritime Organization (1998; 1998).

\textsuperscript{17} UNCLOS provides the international framework for the implementation of the LC at the international, regional and national levels (Part XII, Article 210) (UN 1983). Thus the UNCLOS definition of dumping must be satisfied before the LC can be applied.
The objective of MARPOL is to eliminate both the intentional and accidental contamination of the marine environment from oil and other harmful substances discharged by ships. Ocean fertilization will be subject to MARPOL control only if (i) fertilizer is classified as a 'harmful substance' AND (ii) fertilizer input is classified as 'discharge' (MARPOL 1998; MP 1998).

As stated earlier, fertilizer mixes such as those to be used in current proposals will satisfy the definition of a harmful substance given under UNCLOS Article 2(2) only if it can be proven to cause harm. MARPOL does not adopt the precautionary approach, and so harm must be proven by opponents to fertilization. This is likely to involve additional scientific research, but in the presence of scientific data demonstrating detrimental environmental impact, it could be argued that full scale ocean fertilization should be controlled or banned under MARPOL provisions.

For scientific research purposes MARPOL is not likely to present an obstacle because it makes explicit provision for the release of harmful substances where this is for the purpose of legitimate scientific research into pollution abatement or control (MARPOL 1998; McCullagh 1996). Thus, the release of fertilizer, even if proven harmful, may be justified on an experimental scale, if the goal is to mitigate climate changes (i.e. atmospheric CO₂ pollution).

The Transboundary Convention
The 'Convention on Environmental Impact Assessment in a Transboundary Context' officially entered into force late in 1997 (UN 1998b). This is the first convention to prescribe detailed rules, procedures and practices for 'transboundary' environmental impact assessment. Under this Convention, additional environmental impact assessment will be required prior to implementation of fertilization proposals.

Although ocean fertilization does not appear to be explicitly covered under this Convention, the general intent of the Convention is clear: it requires parties to prevent, reduce and control significant adverse transboundary environmental impacts (Article 2(1)) (TC 1991); which includes an environmental assessment that permits public participation (Articles 2(2) and 2(6) (TC 1991)); as well as a duty to inform other affected states of proposed activities (Article 3) (TC
1991). In essence, this convention formalizes States’ obligations to incorporate the concerns of neighboring nations in decision-making. It could potentially be used as a tool for concerned nations to question ocean fertilization practices in other States (McCullagh 1996).

**The Biodiversity Convention**
The ‘1992 United Nations Convention on Biological Diversity’ entered into force in December 1993 and is now ratified by 168 countries (as of March 1998) (UN 1998a). The convention was one of several agreements developed from the 1992 Rio Earth Summit. Its primary intention is to conserve biological diversity and to promote equitable distribution of the benefits of biological diversity (BC 1992).

Contracting parties to the convention must:

> ‘as far as possible and as appropriate, ..take into account the environmental consequences of its programmes and shall initiate action to prevent or minimize conditions that present an imminent or grave danger or damage to biological diversity’

Article 14 (1(b),(d)) (BC 1992)

The Biological Diversity Convention can thus be applied to ocean fertilization if fertilization can be demonstrated to reduce, or negatively impact ecosystem diversity. From a review of potential environmental impacts (provided in chapter 5) it does seem likely that diversity will be decreased by fertilization\(^{18}\), and thus this convention may be pertinent. However, since both global warming and ocean fertilization have potentially detrimental consequences for biological diversity\(^{19}\), this provision could arguably be used to either support, or prevent, ocean fertilization practices focused on climate mitigation. For fish production scenarios, this counter argument cannot be used and thus the Biodiversity Convention might be legitimately used to inhibit operations (1992).

\(^{18}\) The preferential stimulation of some species of phytoplankton, observed during IRONEX II experiments, is likely to be propagated up the food web, with a consequent reduction in overall ecosystem biodiversity. Refer chapter 5 for further discussion.

\(^{19}\) Amongst the potential impacts of climate change identified by the IPCC Second Assessment Report, is the reduction of biodiversity (Houghton et al. 1995).
United Nations Framework Convention on Climate Change (FCCC)
The United Nations Framework Convention on Climate Change (commonly referred to as the ‘Climate Convention’), entered into force in 1994, developed as a result of growing international concern over increasing concentrations of greenhouse gases. It’s primary goal is to reduce/stabilize atmospheric greenhouse gas concentrations, with particular emphasis on CO₂ (UN 1992). Now ratified by over 174 countries (as of April 1998) (UN 1992), the convention has gathered considerable international weight. The almost unanimous acceptance of its conditions arguably lends it’s terms seniority over almost all other treaties, which are less widely ratified (McCullagh 1996).

As a framework convention, the FCCC provides only general guidelines and objectives in relation to CO₂ reduction. A Protocol to the FCCC was accepted at the 3rd Conference of the Parties, in Kyoto in late 1997 (now known as the ‘Kyoto Protocol’) which served to define more clearly some of the goals and requirements of the original FCCC agreement (UN 1997).

Little emphasis is placed within the convention on how specified goals are to be met. All parties are asked to:

‘promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems’
(Article (4(1)(d))) (UN 1992)

Thus, as well as recognizing the importance of the oceans as sinks of CO₂, the Convention commits parties to the sustainable management of these sinks of CO₂.

On the other hand, the subsequent 1997 Kyoto Protocol to the FCCC restricts the number of definable sinks to afforestation, deforestation and reforestation, with the possibility of extending the definition only to incorporate agricultural soils and other sinks in the land-use change and forestry sector (Article 3(3)) (UN 1997). It is uncertain the reasoning behind this decision. The conflict between these two international instruments has served to introduce some confusion with
respect to the legal and commercial feasibility of ocean fertilization proposals for climate mitigation. To add to the ambiguity, the Kyoto Protocol calls on Developed Nations to implement policies such as:

‘Research on, and promotion, development and increased use of, new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies’

(Article 2(1(iv)) (UN 1997)

Thus the Kyoto Protocol, despite disallowing the use of oceans as carbon sinks, specifically promotes research and development of CO₂ sequestration technologies (presumably including ocean fertilization strategies). Based on this contradiction, it might be speculated that oceans may be re-included as a carbon sink in the future. An amendment to the current agreement would be required in order for this to occur.

Throughout the FCCC considerable importance is placed on sustainable development as well as economic concerns. The FCCC clearly states that the response to the threat of climate change should not adversely impact economic development and also recognizes State sovereignty to exploit resources pursuant to its own economic and developmental policies (Preamble) (UN 1992). This philosophy is re-iterated in the Kyoto Protocol (Article 2(3)) (UN 1997). This overriding emphasis of the FCCC on reducing the threat of anthropogenic greenhouse emissions - but not at the expense of development - appears to provide nations with considerable leeway, to both contribute to climate change, and to seek alternative disposal options, even if it results in other environmental harm (McCullagh 1996). Little is done to amend this situation in the recent Kyoto Protocol.

The FCCC adopts a somewhat unconventional Precautionary Principle in its commitments, as stated in the following clause:

‘The parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate it’s
adverse effects. Where there are threats of serious or irreversible
damage, lack of full scientific certainty should not be used as a
reason for postponing such measures, taking into account that
policies and measures to deal with climate change should be cost-
effective so as to ensure global benefits at the lowest possible
cost....’
(Article 3(3)) (UN 1992)

Thus, parties to the agreement are called to take action to combat climate change, even when the
effectiveness of this action is uncertain. Only scientific certainty or excessive cost can be used to
postpone preventative measures under this agreement. In summary the FCCC authorizes the use
of the oceans as a sink for carbon dioxide. The subsequent Kyoto Protocol does not recognize
oceans as sinks. Yet, ocean fertilization is consistent with both the original FCCC and Kyoto
Agreement in the following ways:

(i) If successful, ocean fertilization can conceivably reduce atmospheric concentrations of CO₂
(ii) Storing CO₂ in the oceans would be an active use of a sink, as prescribed by FCCC - but not
     by the Kyoto Protocol.
(iii) Use of the oceans as a CO₂ sink is likely to have less visible economic and social costs than
     alternative mitigation strategies, and thus is consistent with the FCCC and Kyoto goals to
     coordinate climate control with social and economic development.
(iv) Ocean fertilization complies with the precautionary principle, as defined by FCCC. Even a
     lack of scientific certainty that the desired CO₂ sequestration can be achieved will not be an
     obstacle to implementation of the activity. A lack of scientific certainty is not a sufficient
     excuse to postpone a potential climate mitigation activity under the FCCC (UN 1992; UN
     1997).

A final important issue that should be raised in relation to the FCCC, is that, even if it lends legal
support to parties for ocean fertilization, it does so only if this option provides global benefits at
the lowest comparative cost. From the economic analysis presented in chapter 7 ²⁰ it is dubious
whether ocean fertilization is currently the most cost effective means of achieving climate
control. Conservation, afforestation, cleaner technology, emissions trading and even 'do
nothing’ option (i.e. accept climate change damage), are presently likely to be less expensive strategies. If so, the scientific uncertainty associated with ocean fertilization proposals may be deemed sufficient to forestall operations (UN 1992).

Certainly, it should be made clear that as a commercial CO₂ sequestration venture, ocean fertilization is not presently a viable option. The Kyoto Protocol, which represents a move towards tradable emission permits, has not explicitly recognized the oceans as a sink. This means that CO₂ sequestered by ocean fertilization cannot be claimed for credit and so is not a tradable or economic commodity at present (UN 1997).

**Regional Conventions**
A broad suite of regional agreements have been developed in parallel with the various international conventions. The large number and variety of such conventions, means that independent discussion of each is not possible. Typically they cover a range of topics including pollution, dumping and environmental impacts. Although varied, regional conventions tend to be better enforced, narrower in scope and more precise than international agreements. An analysis of their relevance to ocean fertilization strategies must be completed on a project-specific basis. Nevertheless, some illustrative examples of Conventions, pertinent to the ocean fertilization discussion are provided below.

**OSPAR (Oslo and Paris Commission) Convention**
Within Europe, a regional agreement has already been used to dispute fertilization proposals. The *Maricult*21 research program (Hoell 1994) provides an interesting case study of potential legal issues associated with fertilization. This research program has been cited in violation of the ‘*Convention for the Protection of the Marine Environment of the North East Atlantic*’ (commonly referred to as the OSPAR Convention)22 (Lutter 1996).

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20 Refer to chapter 7 under ‘RE-EXAMINING OCEAN FERTILIZATION GOALS’
21 For fuller discussion of the *Maricult* program and activities, refer to chapter 3 under ‘MARINE PRODUCTION INITIATIVES’
22 The ‘OSPAR Convention’ was adopted by 15 riparian countries and the EU in 1992. It recently came into force at the end of 1997.
The primary objective of the OSPAR Convention is to prevent and eliminate pollution, and to protect the sea area from the adverse effects of human activities. It places specific controls on the introduction of substances or energy, either directly or indirectly, into the marine environment which might prove hazardous to human health, harm living resources and marine ecosystems, damage amenities or interfere with other legitimate uses of the sea. The convention adopts the precautionary principle in its implementation, and thus holds even when there is no conclusive evidence of causal relationship between inputs and effects (GGY 1998b).

Environmentalists claim that artificial fertilization of coastal or offshore waters; manipulation of currents; imitation of upwelling conditions, as well as field projects to test the feasibility of such options; all breach the provisions of the OSPAR convention (Lutter 1997a). As a result, active environmental groups have used the this Convention to challenge EU funding of the Maricult program and may yet prove sufficiently powerful to halt the entire research program (Lutter 1996; Lutter 1997a; Lutter 1997b).

UNEP Regional Seas Programme
The ‘UNEP Regional Seas Programme’ has been responsible for establishing a series of conventions, that now cover 13 different regions, such as the Mediterranean, Carribean, South Pacific and Black Sea (Matthews 1992; UNEP 1998). These are general conventions, affirming the provisions of Part XII of UNCLOS for the Protection and Preservation of the marine environment, and are supplemented by protocols on specific subjects. Although these conventions do not appear to introduce any new provisions relevant to ocean fertilization, through regional cooperation they serve to define and reinforce the UNCLOS guidelines (Wang 1992).

Antarctic Treaty
The ‘Antarctic Treaty’ is another regional treaty likely to be significant in the context of current fertilization proposals, because of it’s geographic relevance to Southern Ocean fertilization proposals. It applies to the area south of 60°S. Although initially designed in 1957-58 by the United States and the Soviet Union to prohibit military use of the Antarctic zone, the treaty had been signed and ratified by 13 nations as of April 1998 (UN 1998a) and now encompasses all
aspects of Antarctic matters. Key nations to the agreement include Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, Poland, Union of South Africa, Union of Soviet Socialist Republics, United Kingdom and the United States of America (UN 1998a).

The primary objectives of the treaty are:

a) to ensure that Antarctica is used for peaceful purposes only;
b) to ensure the continuance of freedom of scientific investigation and international cooperation in scientific investigation in Antarctica; and
c) to set aside disputes over territorial sovereignty (AT 1959).

A number of international instruments fall under the umbrella of what is known as the 'Antarctic Treaty System (ATS)'. Amongst those of importance for ocean fertilization is the 'Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), of 1980'. CCAMLR specifically addresses the conservation and rational use of marine living resources in the Antarctic (AT 1959).

Ocean fertilization schemes which focus on the Southern Ocean will have to comply with the provisions of this entire treaty system, and most specifically CCAMLR. Both experimental scale and full scale fertilization in the Southern Ocean is also likely to be closely supervised by the Antarctic Treaty Consultative Parties (ATCPs) established under the ATS. This body of international representatives hold regular meetings and monitor scientific research, conservation of resources, and environmental protection in the Antarctic zone (Wang 1992), providing an active mechanism through which issues can be addressed and monitored.

**Fishery Conventions**

Fishery practices are also guided by both International and Regional agreements. At present there are more than 20 international fisheries commissions that coordinate and regulate fishing on a regional basis (Wang 1992). Any ocean fertilization proposal which seeks to harvest fish will have to abide by the principles established under these regimes. Typically such agreements deal with conservation of living resources and encourage sustainable use of fish resources.
Convention on Fishing and Conservation of the Living Resources of the High Seas
The 1958 UN ‘Convention on Fishing and Conservation of the Living Resources of the High Seas’ has as it’s primary aim, the conservation of living resources of the sea, so as to obtain the maximum sustainable yield, and thereby secure a maximum supply of food and other marine products (Wang 1992). The stimulation of fish production by ocean fertilization is therefore not a violation, and indeed appears to comply with the spirit of this agreement, provided fertilization and harvesting processes are deemed ‘sustainable’.

The Straddling Stock Agreement
Another agreement concerned with the management of living marine resources arose from the ‘1995 Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks’ (The Straddling Stock Agreement). This agreement adopts a regional approach to conservation of Straddling and Migratory fish stocks. Coastal States and States with an interest in such stocks join in a regional arrangement or organization and cooperate to conduct scientific research, establish Total Allowable Catch (TAC), and agree on enforcement measures for conservation of these fish resources (IISD 1996). Although this agreement is not likely to directly impact fertilization practices, compliance will be required by operators when harvesting fertilized produce. This means that ownership of straddling and migratory fish species, even those enhanced by fertilization, will remain the province of the region. This agreement seems to strengthen the power of regional bodies in determining allowable fish catches, making independent action by nations more difficult.

The Compliance Agreement
In an effort to restrict overfishing worldwide, the Food and Agricultural Organization (FAO) have developed a parallel process to the Straddling Stock agreement, which extends protection beyond the two specific kinds of stocks dealt with by this earlier convention, to include all fish stock. This ‘FAO Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas’ is also known as the ‘Compliance Agreement’. It aims to universally impose upon all States fishing on the high seas, obligations

23 ‘Straddling fish stocks’ are those found in one or more EEZs and the high seas; ‘Highly migratory fish stocks’ are defined by the distance they travel (FAO 1993).
designed for conservation and better management of fish resources, and increase collection and dissemination of data. This agreement is binding only for operations on the high seas, and does not apply to zones of national jurisdiction (i.e. the Territorial Sea, EEZ and Continental Shelf) (FAO 1993). Ocean fertilization operations that harvest fish on the high seas will have to comply with the obligations of this agreement.

**FAO Code of Conduct for Responsible Fisheries**
The 'FAO Code of Conduct for Responsible Fisheries' incorporates the text of the Compliance Agreement, but is global in scope, more broadly regulating fishing activities both within areas of national jurisdiction, and on the high seas. It establishes greater responsibilities for the States:

> 'The Code provides principles and standards applicable to the conservation, management and development of all fisheries. It also covers the capture, processing and trade of fish and fishery products, fishing operations, aquaculture, fisheries research and the integration of fisheries into coastal area management.'  

(Article 1(3)) (FAO 1995)

The application of the precautionary approach is strongly emphasized by this document, meaning that the conservation and management measures are not postponed or undermined by a lack of complete scientific certainty. In theory, ocean fertilization strategies should comply with the specific requirements of this code. The Code of Conduct however remains a voluntary agreement²⁴, and its application will rely on the discretion of regional and State bodies (FAO 1995; IISD 1996).

**Governments and International Organizations**
Finally, it would be incorrect to assume that legal control is reflected only in regulation. All issues of international concern, whether appropriately covered by existing legislation or not, are subject to decisions and recommendations of governments and international organizations. There are many such organizations. Those that might be interested in discussing ocean

²⁴ Although largely voluntary, certain parts of the code are based on relevant rules of international law, including provisions outlined in UNCLLOS. The code also includes provisions that have already been given binding effect by means of other obligatory legal instruments amongst the Parties (e.g. The Compliance Agreement).
fertilization further include the EEC, OECD, UN Economic Commission for Europe, North Sea Ministerial Conferences, UN Regional Commissions, ASEAN, the South Pacific Forum and the Commonwealth Secretariat, to note just a few (Matthews 1992).

**Legal Implementation**

Ultimately, legislation will only be as effective as its implementation. This will involve several jurisdictional and enforcement issues, which are discussed below.

**Which Convention Rules?**

An intrinsic feature of international law is that they are not universal - all States will not be subject to identical provisions. Membership status of conventions vary amongst nations, particularly where treatise are regional in extent. In general, States are bound only by those treatise to which they are signatories. Where inconsistencies arise between treaties/conventions, then the provisions of the most recent treaty and the most specific treaty avail, except where authority is explicitly otherwise stated (McCullagh 1996).

The all-encompassing nature of UNCLOS introduces a further complexity. Through reference, UNCLOS incorporates major international and regional rules, standards and codes of practice for the control of marine pollution. Subsequently, although a State may not specifically be party to a particular international agreement, they may be bound by it’s obligations through the UNCLOS prescriptions. In contrast, those States that are not yet party to UNCLOS but are signatories to major international agreements such as the London Convention, FCCC and Transboundary Harm must abide only to the terms of the individual conventions except where there exist issues of customary law. What becomes abundantly clear from this review is the ambiguity of current conventions and the need for case by case legal assessment (McCullagh 1996).

**Who Enforces?**

A final word is necessary on the enforcement of international conventions. All of the conventions/treatise described above rely on voluntary accession and self-enforcement by States. Even where central administrative bodies have been established to monitor agreements, these bodies typically lack enforcement power. Although international pressure may induce a general
commitment to the prescription of a treatise, the vague wording of much international regulation has left considerable room in provisions for interpretation. As to be expected there is currently a wide reported discrepancy between what states claim and what they do (Bodansky 1995).

This issue becomes of particular concern in the high seas where rights and responsibilities for enforcement are not clear. Although an International Tribunal does exist to deal with UNCLOS infringements (UN 1983), no single party is responsibly for enforcing compliance in these zones. It is conceivable that that international regulation which is currently in place may be legitimately avoided by fertilizing on the high seas, and thus taking advantage of the freedoms of activities in these zones. An alternative approach is that undertaken by OFl who hope to purchase rights directly off the government. There is no known precedent for this, no immediately obvious regulating body to monitor activities, and thus probably limited legitimate avenues for international interference - particularly where these commercial operations carefully select regions where environmental lobby groups are not strong and public outcry is likely to be minimal.

Law and Ocean Fertilization: Summary and Case Studies

Overview
What becomes most apparent from an overview of likely legal issues surrounding ocean fertilization, is the tremendous ambiguity in current legal environmental doctrine. Interpretation is therefore necessarily speculative, and a subject for further debate. Nevertheless, following is summarized what is considered to be some relevant legal provisions that could potentially constrain both research and full scale implementation of ocean fertilization proposals:

- Under Part XII of UNCLOS, for the Protection and Preservation of the marine environment, there appears to be a reasonable argument to ban ocean fertilization in zones of coastal State jurisdiction, if it can be proven scientifically to cause 'harm to marine life', 'hinders other marine activities', or has detrimental effects 'on other States'. Coastal States must allow

25 Refer earlier discussion of the UNCLOS provisions for the high seas, this chapter, under ‘HIGH SEAS’
26 Details of OFI’s proposals can be reviewed in chapter 3, under ‘OCEAN FERTILIZATION PROJECTS: Ocean Farming Inc.’
fertilizer vessels free passage enroute to fertilization sites, but are likely to have control over the laying of pipelines across sovereign waters, even if discharge occurs external to the zone.

- Within the high seas, and above the continental shelf (i.e. not including the sea bed of the continental shelf), ocean fertilization can occur unconstrained unless activities can be shown to have violated the requirement for ‘due regard’ to other States. States undertaking fertilizing activities in this zone also remain bound by any other international obligation they have binding upon them.

- An Environmental Impact Assessment will be required for ocean fertilization practices under UNCLOS. Depending on the policy of the coastal State this could be quite limited in extent. However, EIA’s could be made significantly more detailed if parties are obliged to adopt UNEP standards, or if bound under provisions of the Transboundary Convention.

- Marine Scientific Research within zones of national jurisdiction requires permission from the coastal State. On the high seas, no such permission is required. Ocean fertilization experiments with the specific goal of fish production may be legitimately refused under the provision that it is of direct significance for the exploitation of living natural resources (Article 246(5)). Experiments which involve pipe laying could also be refused. More generally, ocean fertilization experiments both within regions of jurisdiction, and on the high seas, could be banned if they were shown to cause harm to the marine environment.

- Ocean fertilization (by ship or pipe) does not strictly meet the UNCLOS definition of ‘dumping’, but may be able to be shown to be ‘contrary to the aims of the (UNCLOS) convention’. Alternately, an appeal may be made to the International Maritime Organization to explicitly include ocean fertilization under its provisions. If it is recognized as ‘dumping’, then signatories of the London Convention, who adopt a precautionary approach to marine pollution, may legitimately ban ocean fertilization by nationals, and within areas of coastal jurisdiction, depending on the composition of the fertilizer mix. If the fertilizer comprises additives other than naturally occurring nutrients, this provision could be readily enforced.

- MARPOL regulation may also control ship based full-scale ocean fertilization schemes, if marine harm can be demonstrated, however will have limited bearing on research scale experiments.
- The Biodiversity Convention will control ocean fertilization activities if operations can be shown to reduce ecosystem diversity. This effect has already been convincingly established from experiments. However, the application of the Biodiversity convention may be limited to ocean fertilization schemes for fish production. This is because a counter argument could be mounted for climate mitigation schemes - a case might be made that ocean fertilization reduces the biodiversity losses that are associated with climate change.

- The Kyoto Protocol (although somewhat in conflict with the earlier Framework Convention for Climate Change) does not ban ocean fertilization, in fact, it appears to encourage research into this climate mitigation strategy. It does however discount the use of the oceans as a sink of CO₂, and thus prevents ocean fertilization sequestration ventures from being commercially viable.

- There is some precedent for the control of nutrient (fertilizer) discharge in coastal marine waters through strongly enforced regional conventions such as OSPAR. It is conceivable that these may be extended to incorporate open ocean areas. However this would require negotiation, and at the very least, significant amendment to existing regulation.

- Governments and International Organizations also have a role in determining the acceptability of ocean fertilization practice, and may legitimately enforce constraints on implementation.

- Any harvesting operation associated with ocean fertilization must obtain permission from Coastal States for fishing, and are also obliged not to over-exploit stocks. Fishing activities may require Regional as well as National permission where there are regional fishing conventions or agreements in place. Codes of Conduct are in place both in jurisdictional zones of the Coastal States, as well as on the high seas.

- Ultimately, any regulation that may control ocean fertilization will only be effective if it appropriately enforced

**Case Studies**

Due to the lack of precedent, the precise legislative ruling on ocean fertilization remains ill defined. The previous discussion highlights some of the more prominent conventions requiring consideration when examining fertilization strategies, but should by no means be considered
comprehensive. Relevant legislation should be assessed on a case by case basis. A footnote on some of the more current ocean fertilization proposals is therefore provided. Ocean Farming Inc’s (OFT) scheme for the Pacific Ocean surrounding the Marshall Islands, as well as Southern Ocean fertilization proposals, is examined.

The Marshall Islands
The Marshall Islands ratified the Law of the Sea convention in 1991 and is therefore subject to all the provisions of this convention. In addition, they are party to MARPOL 73/78, which prevents accidental and deliberate pollution from ships; but are not specifically bound by the London Convention whose strict provisions regulate the dumping of wastes. The Marshall Islands is not a signatory to the Transboundary Convention. It is thus not required to complete the additional Environmental Impact Assessment of Transboundary effects of ocean fertilization projects. It will however, remain subject to the standard EIA provisions of UNCLOS. The Marshall Islands was one of the first parties to sign the Biodiversity Convention. This could be sufficient to warrant control over fertilizer induced fish production, if a loss of ecosystem diversity can be established (UN 1998a; UN 1998b).

The Marshall Islands may also be bound to other international obligations under the Regional Seas Programme. Additional conventions applicable to this region of the Pacific include the 'Lima Convention for the Protection of the Marine Environment and Coastal Areas of the South Pacific’ and the 'South Pacific Declaration on Natural Resources and the Environment (the Raratonga Declaration)’ 27. These documents contain guidelines for the sustainable management of land, air and sea resources for the region (Degenhardt 1985). The South Pacific region of the Marshall Islands is also the subject of a number of regional fisheries agreements. The ‘South Pacific Forum Fisheries Agency’ has been established ‘to promote regional cooperation and coordination of fisheries policies, to assist with the collection and analysis of fisheries statistics and economic data in the region, to optimize benefits from living marine

27 The Lima Convention was adopted under UNEP auspices in November 1981. The Raratonga Declaration was drafted for the region in cooperation with the South Pacific Regional Environment Programme, the South Pacific Bureau for Economic Cooperation, the South Pacific Commission, and the UN Economic and Social Commission for Asia and the Pacific.
resources for the people of the region, and to coordinate policing of member state's EEZs' (Degenhardt 1985). Although the Marshall Islands does not appear to currently be a member of this organization the current ocean fertilization proposals being negotiated between the Republic of Marshall Islands and Ocean Farming Inc. (OFI) do fall within the general geographical scope of this regional organization and are likely to be of interest to the Fisheries agency. Although an agreement has reportedly been formally signed between OFI and the Marshall Islands, it is uncertain whether negotiations have yet been cleared with this agency. This agency has no legal powers over the Marshall Islands, but could exert some regional pressure on the nation, if deemed appropriate.

Another relevant fisheries organization in the region is the 'South Pacific Islands Fisheries Development Agency'. This agency does claim the Marshall Islands as a member. The aim of the South Pacific Islands Fisheries Development Agency is to provide technical assistance and to promote information sharing amongst the nations of the region for the purpose of assessing and developing marine resources (Degenhardt 1985). Again, although without legal powers, this organization is likely to be interested in examining Ocean fertilization practices in the region and should be kept informed of activities.

The Southern Ocean
All regions of the Southern Ocean lying beyond territorial water claims, are formally classified as the 'high seas' under UNCLOS, and therefore activities in this area must comply with the provisions associated with this zone (Part VII) (UN 1983). In addition, States that undertake fertilization on the high seas must comply with the provisions of all international conventions to which they are party. Fertilization operations undertaken in the Southern Ocean at either research or implementation scale, will also have to abide by the provisions of the Antarctic Treaty System and are likely to be closely monitored by the Antarctic Treaty Consultative Parties (ATCP).

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28 According to most recent obtainable 1985 records, the Marshall Islands is not a party to this Declaration (Degenhardt 1985).
29 For discussion of this agreement refer to chapter 3 under 'OCEAN FERTILIZATION PROJECTS: Ocean Farming Inc.'
PUBLIC OPINION

Formal legal issues represent only part of the story in evaluating the potential of ocean fertilization. The significance of public opinion in determining the ultimate fate of both experimental research and implementation of this science simply cannot be overstated. Recent ocean related activities clearly illustrate this point - two notable precedents are the Brent Spar Disposal and the Acoustic Thermometry of Ocean Climate (ATOC) Experiments. These demonstrate how powerful public opinion can radically alter and even halt legally approved ocean activities.

ATOC Experiments

The ‘Acoustic Thermometry of Ocean Climate (ATOC)’ experiments were designed by the Scripps Institution in USA to study ocean temperature. Temperature was to be determined by measuring the speed of low frequency sound through the ocean over great distances. Public concern over potential harmful effects to marine life from the repetitive sound-broadcasts delayed the experiments for almost two years, and ultimately led to a radical adjustment of the experiments. Although now underway, the levels and frequency of sound have been reduced, and although ocean temperature measurement are still being recorded, the focus of the experiments has been entirely re-directed towards a study of the effects of sound on marine mammals (ATOC 1998). Interestingly, these events show how public outcry and political forces were successful even in the absence of substantial scientific data (Brandon 1995; Scitil 1995).

Brent Spar Platform

Another illustration of the significance of public reaction is provided by the ‘Brent Spar’ incident. Organized opposition from environmental activists to the sinking of Shell’s Brent Spar oil platform in the deep sea, was successful in preventing what was, a legally sanctioned activity. Despite incurring a fourfold cost increase, Shell eventually voluntarily opted for land-based disposal of the platform. Land disposal has it’s own set of risks, and it is unclear whether there were net environmental benefits from this decision, yet the strength of public opinion and economics of public protests prevailed - arguably at the expense of science and logic (Sutherland 1996).
Public Opinion Poll
It is clear that there is considerable awareness, and powerful public concern regarding the oceans. A recent poll conducted in the US by Mellman Group Inc. indicated that 85% of the American public believed that the government was not doing enough to protect the sea. It was reported that 25% would not vote for a politician who did not support their ideas on sea protection (News 1996).

Thus, the marine environment has assumed importance as a public and political issue. It would be foolish to expect ocean fertilization activities to be immune from these influences. Outcry is likely to be stronger if fertilization proposals occur in more developed regions where environmental lobby groups typically have greater strength. However activists from these regions are expressing increasing interest in less developed regions, and the global nature of climate manipulation (particularly if instituted at large scales) is likely to generate worldwide expressions of concern. Vocal public opposition should be expected if activities are publicized.

In the long term however, it is possible that it is the same public whose reactions may fundamentally lead to the implementation of geoengineering technologies such as ocean fertilization. Resistance to the behavioral change demanded for CO₂ emission reduction may be instrumental in encouraging the use of ocean sinks (Kildow 1997). In the advent of urgent land shortages, and food pressures, public reaction is also likely to sway in support of fish production through fertilization techniques. All of these presumptions, of course, rely on ocean fertilization proving successful.

GLOBAL POLITICS
The prominence of climate mitigation and food production issues in contemporary international affairs, together with the fundamentally global nature of ocean fertilization, make it a likely target for global politics.
Climate Mitigation
Ocean fertilization as a climate control technique is likely to be subject to the politics generic to such geoengineering schemes - it violates international ‘polluter pays’ principles, is surrounded by issues of liability, and demands strong central and sustainable management. On the other hand, ocean fertilization is often politically perceived as a mechanism for simplifying policy issues. If successful, ocean fertilization could potentially remove climate mitigation emphasis from curbing emissions (which requires human behavioral change), to what is seen to be a simple allocation of funds$^{30}$.

Amongst the issues of contention in the climate change debate, during the FCCC and the subsequent protocol negotiations, has been the ‘fairness’ of imposed CO$_2$ restrictions on developing nations who, unlike the developed world, have yet to benefit from fossil fuel energy production. It is clear that ocean fertilization, like other geoengineering schemes might aggravate this debate, especially if ‘CO$_2$ credits’ were issued in return for that CO$_2$ sequestered. Developed countries individually benefit most from fossil fuel energy production and are also the most able to implement large scale geoengineering schemes such as ocean fertilization. By using ocean fertilization they can potentially benefit by minimizing the social and economic losses of emission cutbacks, but in so doing spread the risk of environmental harm from these activities to all users of the oceans, violating the polluter-pay principle$^{31}$.

There is also a high potential for liability claims and disputes to arise from the use of ocean fertilization as a climate control means. There is an intrinsic but not very well understood link between the earth’s ocean and climate system$^{32}$. It is feasible that any natural weather disaster occurring during a period of deliberate climate modification could lead those affected by that disaster to claim the climate modifiers liable. This leaves considerable room for contention and international conflict (Schneider 1996).

$^{30}$ Note, this perception is perhaps incorrect. Indeed the political, human and management issues involved in ocean fertilization operation, means it can never be a simple matter of funds. Refer to later discussion in this section. $^{31}$ The ‘polluter-pay’ principle, over decades of use, has acquired international recognition. In essence this principle seeks to shift all costs associated with pollution, including reduction, control and prevention to the polluter. This is considered equitable, because ultimately it is the polluter who benefits from the pollution generating activity.
Of primary concern however, is the appropriate means for management of climate modification. The question needs to be asked - who would manage ocean fertilization projects for the world community over the century or so that it is deemed necessary? A centralized coordinated effort would probably be preferable, however Institutions currently do not exist with the firm authority to assess or enforce responsible use of the global commons - this is clearly illustrated in the difficulties commonly cited enforcing current international regulation (Bodansky 1995). Although the Montreal Protocol does offer a single successful example of international control, it is arguable whether there is currently sufficient ‘global mindedness’ to sustainably control climate and provide compensation mechanisms for any potential losers. It may simply not be feasible to develop such a long term, administratively sustainable, institution without the interruption of wars and ideological disputes. The potential for conflicts poses serious social and political obstacles irrespective of how cost effective or technically feasible the ocean fertilization scheme may eventually be (Bodansky 1995; Keith and Dowlatabadi 1992; Schneider 1996).

The only alternative would be to organize climate control efforts as independent ventures, with individual governments seeking their own solutions. Under these conditions the results are likely to be even more uncontrollable - and the cumulative effects of varied and unaccounted climate control approaches could be alarming. Put simply - who would control the climate controllers?

On the other hand, ocean fertilization does arguably simplify the policy problem of global climate change. Carbon emission reduction is necessarily decentralized, very participatory, and regulatory, requiring changes in human behavior with social and political ramifications. Geoengineering schemes such as ocean fertilization are politically popular because, on a preliminary evaluation, they seem to simply require spending money.

It ‘is a sound economic solution because it simplifies greenhouse policy, transforming complex regulatory regime dependent on population behavior to a problem in international cost sharing where all that is to be decided is what to do, how much to do and who is to pay for it’ (Schelling 1996)

32 Refer chapter 2 for current understanding of this ocean-climate system.
The great difficulty with this argument is that it assumes ocean fertilization works successfully; that it can be politically sustained; and that there are no harmful associated side effects.

**Fish Production**

The potential political repercussions of the use of ocean fertilization as a food production technology are perhaps less significant than for climate mitigation. This is a result of both the scale and nature of operations. Fertilization with the intent of fish production is likely to be a commercially driven operation, and so is at least one step removed from inter-governmental politics. Polluter-pay arguments are no longer valid and there is no need for central control and management of operations (although central overseeing regulation would certainly be advisable). Because of the smaller scale of operations necessary for fish production, liability issues are likely to be smaller, and can be determined under commercial litigation, dictated by market forces. Yet it would be naive to imagine politics will be entirely removed from this process.

Perhaps the most disturbing political issue associated with fertilizing the oceans for fish production is that it contributes to current global inequity, benefiting richer nations over poor. This is inexcusable on ethical grounds, but also aggravates ‘north-south’ politics, particularly if it also disproportionately disadvantages poorer States. Global food shortages are generally attributed to poor distribution and not from overall lack of supply. Indeed food surpluses continue to be experienced in developed regions of the world (Ingro et al. 1996).

Successful ocean fertilization promises increased food production, however the large scale of operations and the large capital investments required preclude it as serious alternative for capital-limited developing countries where food need is greatest. Instead, it is a large scale, capital intensive operation suitable only for the developed world.

Sure - an increase in fish production may potentially decrease world prices with trickle-down benefits to the developed world, but it should be made absolutely clear, that those who will profit

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33 Refer chapter 7 under ‘RE-EXAMINING OCEAN FERTILIZATION GOALS: World Food Supply’ for description of this issue.
most from fertilization will not be the poor. If current intentions are an indication of future directions in this technology, it is apparent that fertilization will actually be undertaken by 'first world' companies within the waters of developing regions where the lack of environmental lobby groups and political forces make conditions most amenable. Even if local employment, and thus some income benefits, accrue to the developed region as a result of fertilization, these are likely to be minimal because of the low labor and high technology requirements of the process. This must also be weighted against the negative effects on existing artisan fisheries that may not be able to compete against these large commercial operations. Thus, developing nations are most likely to feel the negative environmental consequences of fertilization practice, but experience only small, indirect benefits.

**CONCLUSION**

Law, the Public, and Politics, are likely to play an important, and ultimately even a dominant role in any decision making process relating to the implementation of ocean fertilization for either climate change or food production goals.

Legally, it appears that currently, there are no international instruments that, in their existing form, conclusively control ocean fertilization. Existing regulation is also somewhat contradictory. Legal action will rely on future interpretations and amendments to current laws, and the chosen region of fertilizer implementation. Much needs to be done in this arena to ensure activities are properly controlled and monitored for the 'global good'. Public reaction to ocean fertilization is unpredictable and might conceivably go either way, however historic precedents, and current opinion polls suggest that the public is likely to at least initially, be averse to ocean fertilization practices.

By far the largest challenge appears to be the international politics of sustaining a large scale, continuous and sustainable management regime for ocean fertilization, particularly for climate mitigation schemes. If this cannot be achieved (which is indeed dubious) we are faced with the much more alarming scenario of disjointed, uncoordinated fertilization efforts, with no party
responsible for monitoring cumulative effects of actions. In the following, final chapter, we review and consolidate some of these outstanding issues.
REFERENCES


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Should We Fertilize the Oceans?

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INTRODUCTION
Discussion, thus far, has focused on identifying and critiquing the operational, economic, legal and political constraints to implementation of ocean fertilization. The results of this evaluation give us a sound fundamentals with which to assess the feasibility of ocean fertilization - and to ask the preliminary question ‘Can we fertilize the oceans?’ But, now to return to the true subject of this thesis. The question this thesis poses is ‘SHOULD we fertilize the oceans?’ - a question of substantially greater meaning. To respond to this query we must re-examine how effectively ocean fertilization addresses the global problems of climate mitigation and food production. Most importantly however, it calls for an investigation of the broader ethical concerns presented by ocean fertilization.

RE-EXAMINING OCEAN FERTILIZATION GOALS
Fertilization of the oceans has been heralded as a panacea to CO₂-related climate problems, as well as a solution to food production shortages (Markels 1997; Martin 1990). These are
impressive claims. But how urgent are these two global issues? What are the alternative remedies? And, how does ocean fertilization compare as a possible solution?

**Global Climate Change**

Scientists suggested, as early as the first decade of this century, that the Earth will warm as the level of CO₂ in the atmosphere increases (Arrhenius 1908). However, it was not until more recent decades that concern was expressed at the global environmental consequence of steadily rising emissions of so-called ‘greenhouse gases’. Carbon dioxide is generated predominantly from the combustion of fossil fuels and is the largest constituent of the family of greenhouse gases (except for water vapor). Today, anthropogenic related CO₂ emissions are responsible for the annual addition of approximately eight billion tons of carbon into the atmosphere. This has resulted in an atmospheric increase of carbon concentrations of about 30% since the industrial revolution (Houghton et al. 1995).

Although there is little dispute regarding this observation, there is considerable more uncertainty in relation to future trends and the precise effects that rising CO₂ concentrations will have on global climate. The Intergovernmental Panel on Climate Change (IPCC)¹, in their most recent report concluded that the observed increase in concentration of greenhouse gases had coincided with an increase in global mean surface temperature of 0.3 - 0.6°C since the end of last century. They forecast that if the current rate of accumulation is allowed to continue, it will cause an increase of between 2 and 3.5°C in global mean temperature by the end of next century. An average rise in temperature of only a few degrees is expected to cause significant changes in precipitation shifts in climate patterns, sea level rise, a shift in geographic distribution of crops, expansion of tropical diseases, and dispersal of plant and animal species (Houghton et al. 1995).

¹ The Intergovernmental Panel on Climate Change (IPCC) was formed jointly by the World Meteorological Organization, and the United Nations Environment Programme 'to provide an authoritative international statement of scientific opinion on climate change' (Houghton et al. 1995). Through periodic assessments this body of several hundred international scientists review the causes, impacts and possible response strategies to climate change. The most recent of these assessments was the Second Assessment Report - 'Climate Change 1995' (Houghton et al. 1995).
These conclusions are not universally accepted and there are substantial scientific uncertainties (Lindzen 1990). Further, observed changes in climate do not currently exceed the limits of natural variability and therefore can not be considered conclusive (Paterson 1996).

Yet, despite these uncertainties, the international community are committed to action. In 1992 the United Nations Framework Convention on Climate Change (FCCC) was drafted. This was followed in 1997 by the negotiation of the Kyoto Protocol. These international instruments call for a reduction of the emission of atmospheric greenhouse gases, with particular reference to CO₂ (UN 1992; UN 1997a)\(^2\). These agreements clearly show the prominence of climate change issues.

Thus, climate change appears to be a relevant and pressing global concern. Carbon dioxide has been defined as one of the primary culprits of this so called ‘greenhouse warming’, and as such it is not surprising that techniques to reduce the amount of CO₂ entering the atmosphere are currently being explored.

There are a number of different options for mitigating the problem of anthropogenic climate change. International regulation focuses on controlling greenhouse gas emissions (UN 1992; UN 1997a). Research is also currently examining means of reducing the impact of altered climate by adaptation. Ocean fertilization is but one of a number of climate mitigation options commonly referred to as ‘geoengineering’, defined as ‘the intentional large-scale manipulation of the global environment’\(^3\) (Keith and Dowlatabadi 1992).

**Geoengineering**

Typically, geoengineering ‘solutions’ attempt to mitigate climate change by either increasing the amount of outgoing infrared radiation (through a reduction in the concentration of CO₂ and other greenhouse gases); or alternately, try to reduce the quantity of absorbed solar radiation (by

\(^2\) Refer to chapter 6 for a fuller discussion of these international agreements.

\(^3\) According to this definition, *geoengineering* could legitimately be applied to manipulation of any aspect of the global environment. Historically however, the term geoengineering has tended to be applied to options that attempt to reduce the undesired climatic changes caused by humans.
increasing albedo) (Schneider 1996). Many different proposals for geoengineering climate have been tabled\(^4\). Amongst these options are included:

1. **Afforestation**: This is perhaps the most thoroughly studied of the geoengineering options and is the only approach with formalized international support (UN 1997a). Afforestation involves the development of large-scale, intensive forestry with the aim of sequestering CO\(_2\) from the atmosphere using natural photosynthetic processes (Keith and Dowlatabadi 1992). It is estimated, that the replanting of forests, with fast-growing trees, over an area equivalent to the amount already cleared by human settlement, would be sufficient to offset total worldwide anthropogenic emissions (Office of Technology Assessment 1991; WRI 1990). To capture carbon continuously at this rate however, requires that trees are carefully harvested and discarded so that carbon is not given the opportunity to re-enter the atmosphere (Keith 1997).

2. **Direct Ocean Disposal**: This geoengineering solution involves the direct injection of CO\(_2\) into the deep ocean either by ship disposal of dry ice; piped discharge to the open sea, or platform discharge (Fujioaka et al. 1997). By bypassing the slow equilibration of the atmospheric and oceanic carbon reservoirs, direct injection can remove CO\(_2\) from the atmosphere more rapidly than what occurs naturally. CO\(_2\) input into the ocean is expected to form a dilute mixture with sufficient density to sink, eventually forming stable calcithrites or mixing into surrounding water (Broecker and Peng 1982; Heinze and Maier-Reimer 1991), where it is not expected to re-enter the atmosphere for 500-1000 years\(^5\) (Siegenthaler and Sarmiento 1993). Both the environmental consequences of this geoengineering option, as well as the long term fate of sequestered carbon under this scheme are still being investigated (Ormerod 1996).

3. **Space-based Shields**: One of the more technologically extravagant of the geoengineering schemes aims to control climate by shielding the earth with orbiting space mirrors. The National Academy of Sciences calculated that 50,000 mirrors, each 100km\(^2\) in area would have to be placed into to the earth’s orbit to mitigate CO\(_2\) effects (NAS 1992). From an

\(^4\) For a comparative review of a variety of current geoengineering proposals refer to (Keith 1997; NAS 1992; Watts 1997).
energetic consideration, space is the most desirable location for the shields because the high flux of incoming sunlight allows efficient reduction of radiation. However implementing such a scheme involves significant capital investments, and mirrors must be lofted and sustained in space indefinitely (Seifritz 1989; Watts 1997).

4. *Aerosol Enhancement:* Sulfate aerosols have direct and indirect influences on global radiative fluxes. They contribute to optical scattering and re-radiation of incoming radiation, and also increase the albedo and the lifetime of clouds (Charlson et al. 1987). For this reason they are being considered as a potential geoengineering option (Budyko 1982). A number of innovative mechanisms have been proposed for injecting sulfate aerosols into the atmosphere, including the use of rifles, rockets, balloons, aircraft exhaust, ship and power plant dispersion. It is estimated that the quantity of sulfate that must be injected in the atmosphere in order to reverse the effects of doubled CO₂ concentrations on the global radiative balance, would need to be far less, and of more dilute concentration than that sulfate currently contributing to acid rain (Watts 1997). Costs estimates for this option are typically low, but the complex chemical dynamics are uncertain, and there is some speculation that aerosols may lead to stratospheric ozone destruction (NAS 1992; Tolbert et al. 1988). The sky might also become white from optical scattering, and direct solar radiation might be reduced substantially affecting solar energy sources and photosynthetic processes (Watts 1997).

In order to get a better comprehension of the viability of ocean fertilization, relative to these alternate geoengineering schemes, it is interesting to compare estimated costs of mitigation (Table 7-1) with cost data compiled from a synthesis of current geoengineering literature, and ocean fertilization cost estimates reworked in chapter 4. The cost of climate change is also included for comparative purposes.

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5 This is the turnover rate of the ocean. Any parcel of water will take approximately this length of time to return to the surface, where CO₂ can re-equilibrate with the atmosphere.
Table 7-1: Cost Comparison of Ocean Fertilization with other Climate Geoengineering Schemes

<table>
<thead>
<tr>
<th>Climate Mitigation Proposal</th>
<th>Cost of Mitigation COM * ($US/ton CO₂)</th>
<th>Cited Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptation</td>
<td>5-125</td>
<td>(Bruce et al. 1996)⁶</td>
</tr>
<tr>
<td>Afforestation</td>
<td>3-10</td>
<td>(NAS 1992)</td>
</tr>
<tr>
<td>Direct Ocean Disposal</td>
<td>30-80</td>
<td>(Fujioaka et al. 1997)</td>
</tr>
<tr>
<td>Space-based Shields</td>
<td>10-100</td>
<td>(Keith 1997)</td>
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<tr>
<td>Aerosol Enhancement</td>
<td>&lt;1</td>
<td>(NAS 1992)</td>
</tr>
<tr>
<td>Ocean Fertilization *</td>
<td>85</td>
<td>Chapter 4 estimate</td>
</tr>
</tbody>
</table>

On a preliminary basis, it becomes apparent that ocean fertilization is not the economically attractive option originally cited. There are at least four other geoengineering options which are more attractive on economic grounds than ocean fertilization, including afforestation, which is the current low-risk strategy preferred under international agreement (UN 1992). Ocean fertilization costs do not even compare favorably with the estimates for climate change adaptation. On this basis it seems to have very little economic justification.

It should be emphasized that each of the geoengineering options outlined above has its own set of risks, advantages and disadvantages. Even if geoengineering proposals were to eventually have sufficient technical capacity to cool the planet, and were achievable at the costs predicted, they possess tremendous inherent uncertainty. A simple cost comparison of geoengineering options is inadequate because it does not incorporate the risk of side effects, overall effectiveness of schemes and the social distribution of cost. Their climate change potential and repercussions have yet to be comprehensively evaluated. A qualitative risk assessment undertaken by Keith (1997), suggests that ocean fertilization is one of the higher risk strategies. For many of the reasons described in chapter 5, it should be expected to compare unfavorably on this risk criteria as well. A more detailed risk analysis of these various options requires further investigation.

It should be made clear that much further research is required before any of geoengineering option could be seriously implemented. The discussion of alternative geoengineering strategies

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⁶ The 'Cost of Mitigation (COM)' is the ratio of geoengineering cost to amount of mitigation effect. It is generally used as the simplest economic measure to compute mitigation costs. It is typically measured in $/ton CO₂.
⁷ IPCC does not endorse any particular range of values for the damage of CO₂, but the Second Assessment Report does cite published estimates as ranging between these nominated value. This cost does not include social damage.
is provided primarily to illustrate that ocean fertilization is one of a selection of options, each with its own set of benefits and risks. On a preliminary basis, it does not compare favorably. Any decision on ocean fertilization should be made with an awareness of the comparative costs of alternative geoengineering options, emissions reductions and adaptation.

**World Food Supply**

Another of today’s foremost global concerns is ensuring that the world’s population has enough food for a healthy and productive life. An important question being asked by the global community is whether increases in food production can keep pace with rising world population (Ingro et al. 1996; Kendall and Pimental 1994).

**Population**

The earth is presently populated by 5.7 billion people, growing at an average rate of 1.5% (or 90 million people) per year. This growth is concentrated in the developing world, whose 4.6 billion people are growing in number by 1.9% annually. Indeed, the least developed nations, with a total population of 560 million continue to grow at 2.8% per year. This contrasts with the 0.1% growth rates observed in the industrial, wealthy countries⁸ who comprise 1.2 billion of the world’s people (UN 1997b).

If current trends are maintained, the United Nations predicts that the world population will reach about 8.5 billion in 2025, will almost double to 10 billion by 2050, and possibly reach 12 to 14 billion before the end of the next century. Virtually all of this growth is expected to occur in the developing world (UN 1993).

**Food Demand**

If the world’s food supply had been distributed evenly in 1994, it would have provided an adequate diet of about 2,350 daily calories per person for 6.4 Billion people - more than the actual population (Borlaug 1995). Despite this abundance, regional food shortages continue to be experienced in the developing world. Approximately 800 million people presently go hungry in developing countries and 2 billion are at risk from micronutrient deficiencies (WB 1996). It

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⁸ Countries included in this description are Japan, and the nations of Europe and North America.
seems that although overall food supply is not an immediate threat, global poverty and nutrition are significant problems. Current food shortages could be alleviated with more equitable distribution of food, without increasing overall food supply (Ingro et al. 1996; WB 1996).

For future decades, overall food supply perhaps warrants more concern. To provide adequate food for the increasing population it will be necessary to expand food production faster than the rate of population growth. This is because dietary changes and increases in average nutritional intake are expected to accompany rising world affluence trends. A doubling of world food demand is forecast by 2025-2030 (Borlaug 1995; Plucknett 1995).

**Food Supply**

In the past, increases in food supply has been met by expanded agriculture, accompanied by enhanced productivity from irrigation and fertilization. This was particularly the case during the decades of the green revolution (Mann 1997).

Some scientist now argue that limits are being imposed on land based production by the availability of fresh water (Postel 1993); the availability and productivity of land, and the physiological constraints of existing crop varieties (Brown 1995; Brown et al. 1995). Current agricultural practices are thought to be unsustainable and cannot be relied on for future food yields (Kendall et al. 1997).

There are nevertheless a number of alternative practices that have potential for increasing land based agricultural productivity. These include improving pest control; expanding and improving efficiency of irrigation; improving livestock management; and developing new crop strains with increased yield, pest resistance and drought tolerance using bioengineering and other techniques (Kendall et al. 1997).

It is also likely that the increasing demand for food will heighten pressure on non-agricultural food sources. Marine harvest has a clear role in meeting future food requirements, and is attracting increasing attention as at least, a partial solution (Shephard 1997 a &b).
Fish Production

Global fish production increased during the past decade, reaching a peak of 112.9 million in 19959 (FAO 1997b). But this can be largely attributed to a rapid growth in aquaculture production (FAO 1997a).

It is estimated that the total marine capture harvest has remained at the level of 92 million tons since 1994 (FAO 1997a). Production levels have reportedly been sustained by greater exploitation of less commercially valuable species, which have masked declines in the catch of more profitable species (FAO 1992). According to the Food and Agricultural Organization of the United Nations, who compile such statistics, traditional marine fisheries are suffering from widespread overfishing (FAO 1991). It is estimated that the potential sustainable yield of marine fish is between 62 and 87 million metric tons per year. Total annual fish harvest began to exceed this level as early as the mid 1980’s (McGoodwin 1990). This provides convincing support for the argument that more fishing will probably not boost existing fish yields.

On the other hand, provisional production figures for mariculture and aquaculture show an estimated increase from 18.4 million tons in 1994, to 20.9 million tons in 1995. This has compensated for the stagnant marine harvest. Subsequently the average annual per capita availability of food fish has increased in 1995 to 14.3 kg, largely as a result of aquaculture (FAO 1997a).

There is clearly a capacity to expand aquaculture and mariculture to support global food supplies in the future. There are also alternate means of increasing marine fish production, either by utilizing technology, or by improved management of existing fish resources. Some options currently being discussed in the literature include:

1. Eliminate Waste: Large bycatches10 are characteristic of current fisheries practice and could be reduced by improved management, eliminating an estimated 27 million tons of annual waste (Alverson et al. 1994).

---

9 1995 is the latest year for which complete data is available.
2. *Reduce Over-exploitation:* By utilizing fisheries at more sustainable levels it is thought that catches may be able to be sustained in the long term (Holt 1997). It has been demonstrated that fish population, especially top predators\textsuperscript{11}, were significantly higher prior to human exploitation. This suggests that sustainable management could conceivably increase fish biomass. It is estimated that a three to fourfold increase in fish biomass is possible before reaching ecosystem carrying capacity (Shepherd 1997).

3. *Intelligent Harvesting:* The productivity of fisheries may also be enhanced by harvesting marine organisms at lower trophic levels. In this way the amount of energy lost to trophic energy transfer is minimized\textsuperscript{12} (Christensen 1997).

4. *Productivity Enhancement:* Various technologies are also being discussed for increasing fish harvest. The development of aquaculture is clearly one option which is currently successfully being pursued. Mariculture (open water marine aquaculture), has also had some commercial success (Bodvin 1997). Other schemes attempt to increase the productivity of the oceans by using various mechanisms which improve the utilization of existing nutrients (e.g. artificial upwelling). Before productivity enhancement of the oceans can be seriously considered, research is required into the structure and dynamics of marine ecosystems. These are currently understood at only a general level, insufficient for reliable prediction of the consequences of human intervention (Shepherd 1997).

In order to place ocean fertilization in the context of these fish production alternatives, it is interesting to compare estimated costs. Although cost estimates for resource management schemes are difficult to forecast, some provisional wild fish harvest, aquaculture and mariculture estimates, as well as cost of wild harvest have been collected and are presented (Table 7-2).

\textsuperscript{10} 'Bycatches' is defined as the unintended capture of marine animals, most of which are discarded or die. This is especially a problem if bycatch comprises depleted species. For example, haddock - a severely overfished species - is often accidentally netted by trawlers that target pollock (NOAA 1991). Bycatches often go unreported because fishermen do not want to risk penalties for netting protected species.

\textsuperscript{11} Top predators are typically the most commercially valuable species, and are preferred human consumption.

\textsuperscript{12} Refer to chapter 2 under 'OCEAN PRODUCTION: Energy Transfer in Marine Food Webs' for fuller explanation of the principle of trophic energy transfer efficiencies.
Table 7-2: Cost Comparison of Ocean Fertilization Estimates with other Fish Production alternatives. Most prices cited are ‘first hand prices’ and therefore do not incorporate distribution and processing. * denotes an average market sale price.

<table>
<thead>
<tr>
<th>Fish Production Alternative</th>
<th>Cost of Fish Production ($US/kg)</th>
<th>Price of Fish ($US/kg)</th>
<th>Profit Margin (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARICULT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Cod</td>
<td>0.11-0.13</td>
<td>1.30</td>
<td>90</td>
<td>(Hoell 1994)</td>
</tr>
<tr>
<td>-Herring</td>
<td>0.05-0.07</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AQUACULTURE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Trout</td>
<td>0.82-1.07</td>
<td>1.25</td>
<td>24</td>
<td>(Hinshaw et al. 1990)</td>
</tr>
<tr>
<td>WILD HARVEST (commercial species average)</td>
<td>1.70</td>
<td>0.97</td>
<td>(net loss)</td>
<td>(FAO 1992; FAO 1997b; WRI 1994)</td>
</tr>
<tr>
<td>OCEAN FERTILIZATION</td>
<td></td>
<td></td>
<td></td>
<td>Revised cost estimate from chapter 4. Fish price obtained from (Markels 1997)</td>
</tr>
<tr>
<td>(commercial species average)</td>
<td>0.30</td>
<td>0.66-0.88</td>
<td>61</td>
<td></td>
</tr>
</tbody>
</table>

It is clear from these estimates that alternatives to current fish catch practices are required. Over capacity in the fishing industry makes marine harvest unprofitable with estimated losses of approximately $54 million annually (WRI 1994). In comparison, Maricult estimates are commercially attractive. Aquaculture also appears to yield potential returns, at least for the trout farming operation examined. Provided ocean fertilization is successfully implemented, and achieves the optimistic production estimates calculated, then it does offer a commercially attractive option for enhancing marine harvest, when compared to these schemes on a strict cost basis. The tremendous uncertainty of side effects associated with this unproven technology make this venture less appealing. It’s merit as a fish production venture requires further examination.

This discussion has served to illustrate that both climate change and food production are prominent global issues worthy of attention. Ocean fertilization, if successful, does attempt to address, but only partially, some of these problems. It is also essential to remember that it is but one of many options available. When compared on a cost basis to theses alternatives, it is not commercially attractive for climate mitigation, but may have some potential as a food production
option. Although risks are difficult to quantify for each alternative, the inclusion of risk into this assessment is likely to reduce the attractiveness of proposed ocean fertilization schemes.

ETHICAL CONCERNS

Perhaps the most important component of the question ‘Should we fertilize the oceans?’, and one that has been overlooked thus far, deals with ethical concerns of ocean fertilization proposals. To do this subject justice requires a comprehensive debate, sufficient to fill the scope of many further, and much needed, theses. At least two thesis already partially address this topic (Anderson 1991; Chen 1993). A detailed discussion won’t be attempted, however it would be remiss to complete an evaluation of ocean fertilization without airing a number of holistic concerns about these proposals.

At a fundamental level, ocean fertilization presumes to manipulate intrinsic ocean systems. This presumption is based on human’s unfailing confidence that we can dominate nature directly, if only we know the laws that magically govern it (Ludwig 1993). It should be remembered that proposals to use ocean fertilization as a climate mitigation strategy, in particular, have not insignificant impact on the atmosphere-ocean climate system. Ocean model simulations indicate that proposals to reduce 2090 atmospheric CO₂ concentrations by a limited 10-20% will require a fairly dramatic doubling of current estimates of global new production, and a substantial contortion of delicately balanced natural systems (Eppley 1989; Najjar 1990). Although smaller scale implementation of ocean fertilization for fish production goals may not have global repercussions of this magnitude, regional effects on ecosystems will be equally substantial.

Before embarking on a practice with such uncertain consequences we need to demonstrate caution. History clearly reflects the abysmal record of human’s interference in natural systems. In the past, the practical outcome of even the most well-meaning attempts at large-scale resource management have been very different from it’s theoretical objectives, and biological laws have a

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13 As outlined already in chapter 2, the ocean’s are known to play an intrinsic role in an otherwise not well understood global climate system.
tendency to correct human-induced imbalances in less than favorable ways. The current crisis in the global fisheries provides a clear example of man’s failure to adequately manage natural resources, and the consequences of human interference. Despite it being in our common interest to control global fisheries at levels which ensure sustainable yield, attempts at managing this resource and controlling the amount, distribution and nature of fishery effort, have been unsuccessful. As a result natural ecosystems have collapsed and commercial fish stock have been eliminated one by one throughout the world (FAO 1991; Larkin 1977). The history of forestry has been equally bleak. A review of forest management in 12 countries reveals widespread and long standing wastage of forest resources (Repetto and Gillis 1988). Despite the initial promise of the green revolution, sustainable high production agriculture has also fallen well short of success (Ponting 1991). In short, mankind has had limited success in sustainably altering nature, and it would be unrealistic to assume ocean fertilization would be an exception.

Finally, the similarities between ocean fertilization proposals and the processes underlying the growing international problem of marine eutrophication\textsuperscript{14} are startling (Nixon 1990). Fundamentally, both processes give rise to enhanced marine productivity as a result of nutrient enrichment. Eutrophication is being increasingly witnessed in the coastal zones and inland seas, of our marine environment as a result of excessive anthropogenic inputs of nutrients from sewage, agricultural runoff and land clearing. Some of the observed consequences of eutrophication in these zones are changes in species composition, increased occurrence of algal blooms (often harmful and even toxic), hypoxia, reduction in water quality and clarity, and death of benthic organisms\textsuperscript{15}. In order to counter this growing problem Regional Action Plans are now being developed and legislation being implemented to control anthropogenic inputs to affected waters (Boesch 1997; Lutter 1996; Mee 1992; UNEP 1998).

Admittedly marine regions most susceptible to eutrophication are likely to be those with shallow depths and benign currents. These physical characteristics are not necessarily observed in the

\textsuperscript{14} Refer to chapter 5 under ‘ENVIRONMENTAL IMPACTS: Eutrophication’ for a fuller discussion of marine eutrophication.

\textsuperscript{15} Refer to Valiela (1995) for a review of some of the common impacts associated with eutrophication.
open ocean areas proposed for fertilization schemes. But again, there remains considerable uncertainty with respect to the impacts of ocean fertilization, and we must ask ourselves whether, without proper information, we are willing to accept this risk. It does seem ironic that in undertaking ocean fertilization, we will be replicating actions that are at this moment, in the process of being banned in other marine zones.

CONCLUSION
There is no question that uncertainty is inherent to science, and that we will never understand all the consequences of ocean fertilization. However, given that humans have a poor track record of interfering with natural system; that there are huge remaining unknowns associated with ocean fertilization; that there remain questions concerning it’s effectiveness in meeting food production and climate mitigation goals; that there is an outstanding amount of additional research required into this field; and that ocean fertilization manipulation and impacts are potentially global in nature - it seems of particular importance to select policies that are precautionary (Costanza and Cornwell 1992; Costanza and Perrings 1990). Indeed it would seem extremely rational to give the environment the benefit of the doubt.
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Chapter 8
Summary and Conclusions

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OVERVIEW
Ocean fertilization represents a remarkable new field which has captured the attention of the
scientific, public and private sectors alike (Chisholm 1995; Hoell 1994; Jones and Young 1997;
Kelley 1995; Markels 1997b; Martin 1990b; Vovcsko 1997; Warsh 1996; Wells 1994). By
fertilizing the oceans with naturally occurring nutrients, and stimulating the production of
phytoplankton, it is hoped to both sequester carbon dioxide and to produce fish. Ocean
fertilization is thus being heralded as a cure for global climate change and world food supply
shortages (Markels 1997b; Martin 1990b). It continues to attract widespread interest.

Current Status
Publicity has tended to focus on ocean fertilization as a climate mitigation option (Blakeslee
1990; Kerr 1994; Monastersky 1994; Monastersky 1995; Roberts 1991). Scientists have also
centered their investigations on understanding the response of climate to ocean fertilization, and considerable research effort has been invested towards this end (Chisholm and Morel 1991; Chisholm 1995; Martin 1990a). Future research continues in this direction, and meso-scale experiments are currently in planning for the Southern Ocean (Coale 1997). Notably, there are presently no serious suggestions from members of these scientific investigations to implement ocean fertilization for CO₂ sequestration, and implementation of full scale ocean fertilization does not appear to be on their agenda.

In contrast, the private sector has wholeheartedly adopted the concept of ocean fertilization. Typically, commercial proposals have tended to focus on the fish production potential of ocean fertilization (although they have recently been modified to incorporate carbon sequestration goals). International corporation Norsk Hydro has supported significant research into the commercial potential of fertilization through the Maricult Research Program (Hoell 1994; Hoell et al. 1995). Norsk Hydro have also been instrumental in gathering leading scientists together to discuss possibilities for enhancing marine harvest at the Ocean Harvest 97 Workshop (Shephard 1997). Fertilization featured heavily at these discussions. In addition, field experiments of various nutrient enhancement techniques including artificial upwelling and sea fertilization have been undertaken by the joint Japanese Government/Private research group known as ‘Marino Forum 21’ (Morimura 1997) (refer chapter 3).

A number of commercial projects for full scale implementation of ocean fertilization are already being planned. Ocean Farming Inc. (OFI) is one such newly established company, with start-up capital to develop and commercialize ocean fertilization technology. Markels - the CEO of this firm - holds patents for an ocean fertilizer and fertilization process in the United States and 14 other countries (Markels 1995; Markels 1996). OFI intend to fertilize the oceans with a nutrient mix comprised primarily of iron, with some phosphorus, in the hope of stimulating diatoms that have endosymbiotic cyanobacteria. OFI proposals rely on this cyanobacteria fixing sufficient atmospheric nitrogen to meet the nitrogen needs of the enhanced production. Some seed phytoplankton species and also filter feeding fish may also be added to the fertilizer mix.
Although primarily to be applied for harvesting fish, OFI have recently started investigating the commercialization of CO$_2$ sequestration as a by-product of this process (Markels 1997a; Markels 1997b), Markels, personal communication). Research scale experiments have been completed in the Gulf of Mexico, and will be continued later this year (Markels 1998). Full scale implementation of this proposal is intended to occur within a couple of years in the Marshall Islands.

An alternative commercial scheme has been proposed by Jones and colleagues at the University of Sydney, in Australia who advocate nitrogen fertilization of the oceans for both fish harvest and CO$_2$ sequestration (Jones 1996a; Jones 1996b; Jones and Otaegui 1997; Jones and Young 1997). Jones has patented a pipe-based fertilization process which provides reactive nitrogen, possibly in conjunction with trace nutrients, to increase biological production in the open oceans. This process now awaits commercialization and development (Jones and Otaegui 1997; Jones and Young 1997).

A SUMMARY OF FINDINGS

Although ocean fertilization has been the subject of intense interest and speculation, there appears to be limited assessment of whether it presents a practical and suitable means of achieving climate mitigation and food production goals. In this thesis I have attempted to undertake such an evaluation of ocean fertilization, with the following primary findings.

Climate Mitigation Potential

On a preliminary basis, I suggest that ocean fertilization offers a limited potential, but unproven means, of increasing the flux of CO$_2$ into the ocean, and thereby reducing atmospheric concentrations of CO$_2$ and mitigating climate. However, it’s implementation will entail substantial risk, and there is considerable associated uncertainty (Keith and Dowlatabadi 1992; Schelling 1996; Schneider 1996). There are also many more cost effective geoengineering schemes which might be considered, if such a mitigation strategy must be selected (Keith 1997; NAS 1992; Watts 1997) (refer chapter 7).
A number of models have assessed the climate mitigation potential of ocean fertilization (Joos et al. 1991; Kurz and Maier-Reimer 1993; Peng and Broecker 1991a; Sarmiento and Orr 1991). These have proven remarkably consistent and offer an upper limit of possible sequestration by fertilization. Predictions indicate that under optimum conditions only a 10-20% reduction in 2090 atmospheric CO₂ concentrations is possible after continuous fertilization of the oceans for 100 years. Models also suggest that sequestration by fertilization is most effective in the Southern Ocean, with only marginal effects in other regions. Net sequestration was maximized under continuous fertilization, and sequestration rates were found to be time dependent, dramatically declining from high initial uptake rates, after only a couple of years. (Sarmiento and Orr 1991). (refer chapter 4).

In practical terms there are a number of operational issues which need attention and seriously question the viability of ocean fertilization for climate mitigation. As part of this thesis I complete an estimate of the required scale of fertilization operations in order to achieve climate mitigation goals. This estimate is based on the model parameters and sequestration values predicted by Sarmiento and Orr (1991). It indicates that a total of 41,000 vessels will be required to disperse 4.1 million tons of fertilizer annually over 57 million square kilometers of ocean. An additional 2,700 tankers will be needed to supply these vessels with fuel and fertilizer to make continuous operation possible (Sarmiento and Orr 1991). The logistical problems of maintaining such an operation in the climatically difficult Southern Ocean (where sequestration will be maximized (Sarmiento and Orr 1991)), for over 100 years, are likely to be considerable (NAS 1992). Large quantities of iron fertilizer will also be required - although iron is typically available in vast supplies, pure quantities of iron fertilizer are needed and may be more difficult to obtain (NAS 1992). From a commercial perspective, CO₂ sequestration by ocean fertilization is not currently viable. This is because current international agreement does not recognize the use of the oceans as a permissible sink for CO₂ (UN 1997). Thus CO₂ quantities sequestered by this means are not a tradable commodity (refer chapter 4 for discussion of operational issues and chapter 6 for details of international legal constraints).
Global Politics is likely to introduce further practical difficulties into ocean fertilization schemes. The ability of the current global regime to sustain the long term, large scale, globally coordinated projects required for effective climate mitigation, without international incident, I think must be questioned (Schelling 1996). Climate mitigation projects violate international ‘polluter pays’ principles, providing a means for Nations to minimize the social and economic effects of emissions cutbacks by implementing fertilization activities outside of their State, and thereby spreading the risk of environmental harm to all users of the ocean. In addition large scale ocean fertilization schemes have high potential liability. It is conceivable that activities may attract damage claims if operations coincide with natural weather disasters - because we have limited understanding of ocean-climate processes it is possible that liability suits may be successful even where there is inconclusive evidence that weather changes are induced by ocean fertilization (Schneider 1996).

Legally, it has been difficult to determine whether ocean fertilization is subject to current international and regional regulation, largely because there is no precedent for such operations on the open seas. What does become clear from an investigation of existing legislation is that the law is incohesive, tends to be ambiguous, and different conventions can be inconsistent. As a result, much will ultimately depend on the chosen region of fertilizer application, as well as specific legal interpretation (refer chapter 6).

An assessment of the economic viability of ocean fertilization as a climate mitigation option was also undertaken as part of my evaluation, using optimistic assumptions. My calculations suggest a lower-limit cost of carbon sequestration of approximately $85/ton CO$_2$. This varies significantly from previous estimates, which range from $0.40/ton CO$_2$ to $7.50/ton CO$_2$. I suggest that the wide discrepancy between my estimate and previous values arises because the latter do not appear to consider physical ocean processes and the time-dependent effects of ocean fertilization$^1$. My calculations incorporate some of these effects by using output from Sarmiento

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$^1$ Refer to chapter 4 under ‘CLIMATE MITIGATION MODELS’ which describes model simulations and results by Sarmiento and Orr (1991) and others.
and Orr's (1991) three-dimensional ocean circulation model, and I have found that this substantially reduces the estimated cost effectiveness of operations (refer chapter 4).

**Fish Production Potential**

From a food production perspective, I suggest that ocean fertilization cannot be used to address the most urgent food shortage problems. These shortages arise primarily due to poor food distribution rather than an overall lack of supply (WB 1996), thus ocean fertilization has limited contribution other than as a commercial initiative in the short term. For now, it's implementation should be judged from a commercial rather than an altruistic perspective.

Ocean fertilization, provided it is successfully implemented, does have the potential to increase fish production, and thus, it is possible that ocean fertilization presents a partial solution to food supply shortages which may arise in the future. Again, it is but one of a spectrum of commercially attractive options available for increasing marine harvest and must be evaluated against these alternatives (refer chapter 7).

In contrast to climate mitigation proposals, much less rigorous scientific analysis has been undertaken for the fish production potential of ocean fertilization. My assessment of the cost effectiveness of fish production by fertilization reviews estimates from two commercial proposals, raising some serious questions about assumptions underlying these proposals (refer chapter 4). Ocean Farming Inc. (OFI) who propose an iron-fertilizer mix (refer details given above) estimate a yield of 200 kg of fish per kg of fertilizer (Markels 1997b). The commercial proposal by Jones (1996b) predicts a yield of 90 kg of fish per kg of nitrogen fertilizer. My separate assessment of the fish production potential of ocean fertilization was completed by adopting an iron mix similar in composition to that suggested by OFI. This calculation estimated a tenfold reduction in the OFI yield to about 20 kg of fish per kg of fertilizer (see chapter 4).

The assumptions and parameters underlying the fish production estimates by Jones and Markels are unclear. The calculations that I present are based on the assumption that fertilization was
100% successful (i.e. utilized all available nutrients), with some fertilizer dispersal losses. It was also assumed that fertilization reproduced conditions similar to those presently observed in highly productive zones, with consequent biomass production efficiency improvements. This assumption is not proven, but was adopted for the sake of consistency, to reflect similar assumptions made in commercial proposals. No consideration is made of secondary nutrient limitation, limitation by other biological or physical processes, harvesting and mortality losses, or yield constraints. The estimate would thus be expected to provide an upper limit value of fish production. It is clear that further attention is required to quantify some of these potential constraints to production and to better develop our understanding of the likely ecosystem response to fertilization (see chapter 4).

Operationally, fish production schemes utilizing ocean fertilization can be implemented at smaller scales, and in less difficult conditions than those required for ocean fertilization. They are therefore not subject to the massive logistical problems suggested under climate mitigation schemes. Nevertheless logistics of such a scheme should not be underestimated. Based on my calculation, a venture similar in scale to OFI's current commercial proposal will require 75 dispersing vessels to annually discharge 200,000 tons of iron-fertilizer mix over 100,000 km² of ocean. A total of 5 large tankers will be required to supply these vessels with fuel and fertilizer. In addition, harvesting of fish product will require a flotilla of fishing vessels of equivalent scale, doubling the size of operations (refer chapter 4).

Similar to climate mitigation proposals, fish production fertilization operations will tend to be sensitive to location and constrained to regions where biological growth is limited by the fertilizer supplied nutrients. Ideal conditions include deep and barren waters, benign currents, low winds, and high light intensity. Thus operations are most suitable, and largely limited to equatorial regions (Markels 1997b)(refer chapter 4). Perhaps of most practical concern however, is the limited control that operations will have on the form of organisms produced. There is no guarantee that enhanced production will comprise organisms of commercial interest, indeed evidence of nutrient enrichment processes in other ocean environments indicate that undesirable
species have been preferentially stimulated by nutrient loading (Cederwall and Elmgren 1990; Hansson and Rudstam 1990; Kideys 1993; Seliger et al. 1985). This raises some serious concerns about the commercial viability of fish production operations.

For fish production, global politics is not as great a concern as for climate mitigation schemes. However it would be naive to totally ignore political influences, and some reaction from environmental lobby groups should be expected. Fish production by ocean fertilization requires large scale operations and it is unlikely that capital-limited developing countries will be able to utilize this technology. Benefits to these nations will be indirect and minimal (or even negative), and thus fish production by these means is likely to contribute, rather than reduce, global inequity. It is simply incorrect to promulgate ocean fertilization as a solution for food shortage crises, especially because shortages are concentrated in the developing world where ocean fertilization is least able to be nationally implemented (refer chapter 6).

It is likely that fish production operations will be subject to harvesting control from regional fishery conventions and agencies. Otherwise, the legal considerations for ocean fertilization operations dedicated to fish production are similar to those whose purpose is climate mitigation. The same problems of incohesive and ambiguous legislation applies. Much will ultimately depend on the chosen region of fertilizer application, as well as specific legal interpretation (refer chapter 6).

From an economic perspective, commercial estimates of the cost of fish production using ocean fertilization have ranged from $0.13/kg (Markels 1997b) to $1.1/kg (not including fertilizer application, and harvesting costs)(Jones 1996b). My independent calculation, indicates that a lower limit cost for fish production (‘at the dock’) using an iron-mix fertilizer is about $0.30/kg. This is twice the cost predicted by OFI estimates (refer chapter 4).

When compared to other fish production strategies ocean fertilization may be commercially viable but only if theoretical yields are achieved, and potential profits must be weighted against
the high risks associated with this unproven technology (refer chapter 7). My separate estimate of the cost effectiveness of ocean fertilization raises some questions about the commercial viability of operations. The ‘at the dock price’ of commercial fish is between $0.66 - $0.88/kg (Markels 1997b). Although this suggests there is an adequate 60% margin for profit (c.f estimated $0.30/kg production cost), it should be remembered that estimates are based on upper limit yields, and lower limit costs. It is unlikely that either of these limits will be achieved, because operations cannot be expected to be 100% efficient. Given the significant commercial capital risks (approx $ 0.6 Billion/year) involved in such a proposal, you would expect operations to offer a higher potential return in order to attract investors.

**Combined Operations**

Proposals to undertake both CO₂ sequestration, and fish production will not be able to achieve both without efficiency compromises and some trade-offs. This is because ocean fertilization achieves optimum CO₂ sequestration rates only in the Southern Ocean (Sarmiento and Orr 1991), whereas fish production conditions are most suitable in equatorial regions (Markels 1997b). More intrinsically, some compromise will be required between the amount of carbon that is sedimented and thereby sequestered, and the amount of carbon that is used for biomass production. For these reasons, the feasibility of combining operations is uncertain. At the very minimum, cost of each activity under a combined operation will be increased, and this factor appears to have been overlooked in commercial proposals (refer chapter 4).

**Impacts and Unknowns**

Quantitative research on the impacts of ocean fertilization is limited, and there remain many scientific unknowns. The list of potential environmental impacts is long. This includes toxicological damage from inherent fertilizer impurities. Toxic effects might also be experienced as a result of the stimulation of toxic phytoplankton species (Devassy et al. 1978; Hawser and Codd 1992; Hawser et al. 1992; Turner and Tester 1997). Eutrophication has been experienced in some parts of the ocean as a result of nutrient loading, and fertilization might be expected to yield similar effects, including hypoxia, reduction of water quality and clarity, death of benthic organisms and shifts in species composition within the existing ecosystem (Valiela 1995).
In addition, the increased biomass of phytoplankton induced by fertilization may result in ‘shading’ and ultimately death of coral reefs (Genin et al. 1995). Experimental evidence indicates that fertilization will lead to shifts in species composition (Cavender-Bares et al. 1997; Coale et al. 1996), which is likely to result in a reduction of biodiversity and ecosystem changes. The introduction and growth of new species is to be encouraged under OFI’s commercial fish production proposals (Markels, personal communication), with unknown ecosystem consequences. Finally, natural degradation processes are likely to increase to match the increased quantities of organic matter generated during fertilization. This process consumes oxygen, and may also lead to the development of anoxia, which in turn, has the potential to kill organisms at all trophic levels and dramatically alter or even eliminate biological communities in the oceans (Hansson and Rudstam 1990; Seliger et al. 1985) (refer chapter 5).

There are some serious biogeochemical consequences which have been plausibly linked to ocean fertilization. An increase in the production of sulfide should be expected, as well as increased methanogenesis and increased production of nitrous oxide (Fuhrman and Capone 1991). These latter two gases are greenhouse gases with 21 and 200 times respectively, more global warming potential than CO₂ (Shine et al. 1990). There is the possibility that iron fertilization may result in the mobilization of naturally occurring iron, triggering a self-fertilizing mechanism. Although advantageous from an engineering point of view, this mechanism is uncontrollable, making effects difficult to reverse, and thus should be a cause of concern. Finally, it is suggested that dimethyl sulfide production will also be stimulated by fertilization. The climatic effects of this process are uncertain, but preliminary estimates indicate that the magnitude of this climatic influence is likely to be more significant than the iron-induced changes in the uptake of CO₂ (Fuhrman and Capone 1991). In short, the biogeochemical consequences of ocean fertilization are not known but have the potential to reverse any climate cooling benefit derived from CO₂ sequestration (refer chapter 5).
There remain several scientific unknowns relating to ocean fertilization. Although there is conclusive evidence that iron stimulates productivity in certain regions of the Equatorial Pacific (Coale et al. 1996; Martin et al. 1994), there is considerable uncertainty whether scientific results can be realistically extrapolated to other nutrients, and to other regions of the oceans. It should not be forgotten that the carbon sequestration and fish production potential of ocean fertilization are simply not proven (refer chapter 5).

In addition, physical limitations to ocean fertilization have tended to be overlooked. It has been suggested that these will impose additional constraints, particularly in relation to sequestration processes (Peng and Broecker 1991a; Peng and Broecker 1991b). Thus far, constraints to the rates of enhanced production, associated with the rates of fertilizer supply, rates of nutrient uptake by biota, and the rates of phytoplankton growth have been afforded little attention in commercial proposals; and the potential for secondary limitation is not adequately addressed. The influence of the microbial loop on biological production is also not considered, including the possibility that bacteria might compete against phytoplankton for iron (Tortell et al. 1996), and possibly other nutrient reducing the amount of production contributing to the food web and sedimentation. The long term fate of carbon is also unknown. Proposals that rely on natural surface water supplies of some nutrients also disregard the fact that the depletion of surface nutrients in one area of the ocean will have consequences well beyond the limits of this region. The ‘conveyor belt’ described in chapter 2 circulates nutrients through the ocean in a tightly locked, closed system. Depletion of surface nutrients in one area of the ocean, delivering them prematurely to ocean depths, will ultimately lead to a reduction of nutrients available through diffusion to other oceanic zones. Consequently, enhanced primary productivity in one location should be expected to give rise to a concomitant fall in productivity elsewhere - ‘there is no free lunch’.

**Uncertainty**

As illustrated in the above discussion, there are a wide range of indirect effects of ocean fertilization, and the positive effects of CO₂ sequestration and fish production have not been
conclusively proven. Given the formative nature of the science, and the unpredictability of physical and biological systems, it is highly likely that there are many more unidentified impacts, and that the unknowns are not fully realized. It is clear from a purely objective evaluation that further research is required and should be directed towards the critical unknowns, particularly focused on developing our understanding of the most likely environmental and biogeochemical impacts. This research is essential before committing to the implementation of ocean fertilization and it’s potentially long term consequences.

**Ethics**

But an objective evaluation, limited to practical, economic, and political constraints, still does not adequately address some of the broader ramifications of ocean fertilization. Certainly, it does not sufficiently address the question posed by this thesis - ‘Should we fertilize the oceans?’.

At a fundamental level, ocean fertilization presumes to meddle with basic ocean functions and processes we simply don’t understand. This assumption is based on human’s unfailing confidence that we can dominate nature directly, if only we know the laws that magically govern it (Ludwig 1993). Ocean fertilization represents a large scale manipulation of our global environment, and should be treated as such. For climate mitigation in particular, models predict that a doubling of existing levels of new production will be required to achieve even a nominal 10-20% reduction in atmospheric CO$_2$ concentrations in the year 2090. Fertilization for fish production is likely to occur at significantly smaller scales, but regional contortions of ecosystems should be expected to be equally substantial.

History clearly reflects human’s abysmal record of interference in natural systems. Man’s attempts at large scale resource management has universally failed for fisheries and forestry and similar attempts to improve land based agricultural productivity, although successful, have led to a long list of negative impacts. The similarities between ocean fertilization proposals and the processes underlying the growing international problem of marine eutrophication (Nixon 1990) are also startling. Concerns about the possible development of hypoxia, reduction of water
quality and clarity, death of benthic organisms and shifts in species composition as a result of nutrient enrichment has led to the promulgation of regional conventions controlling nutrient discharges to coastal marine waters and inland seas. It is somewhat ironic that in undertaking ocean fertilization, we will be replicating actions that are at this moment being banned in other marine zones (refer chapter 7).

A true assessment of the ethical concerns of ocean fertilization has not been done justice in this thesis. The main point is however, that an assessment of the future potential of ocean fertilization requires more than a scientifically based cost-benefit evaluation. It is important, that we complement such studies by questioning whether we are willing to accept the risks associated with this practice, and it’s potential consequences for what is one of the world’s only remaining pristine environments. Given the gravity of potential impacts, and our poor track record of interfering in natural systems, it would seem appropriate to select policies that are precautionary, so that we do not take a risk with our future.

CONCLUSIONS
At the completion of this evaluation we are faced with a number of fundamental questions. First of all, to answer the question - *Can we fertilize the oceans? And, is it an adequate means of achieving climate mitigation and food production goals?*

Based on the evaluation provided above, it is difficult to understand the current appeal of ocean fertilization schemes. The practical and operational obstacles to ocean fertilization are formidable; effectiveness of operations is not assured; there is a long list of potentially devastating environmental impacts; biogeochemical implications may negate or reverse desired climate effects; and there remain many scientific unknowns. Neither do proposals make tremendous economic sense. For climate mitigation, ocean fertilization is not currently commercially viable, or even cost effective when compared with other climate mitigation options. On the other hand ocean fertilization does appear to be a commercially acceptable
means of producing fish, but only if close to theoretical production values are maintained and costs are minimized.

To the more significant question - *should we fertilize the oceans?* - the answer must be ‘NO’, not now. Firstly, ocean fertilization only marginally addresses climate mitigation goals even under optimum conditions. It does little to address current food supply shortages, which arise from distribution-related, and not supply-related problems. We therefore do not have the ethical justification for considering ocean fertilization. Further given the uncertainties, our past failings, the magnitude of potential consequences, and it’s likely impact on one of the world’s few remaining ‘unperturbed’ resources, it would seem entirely rational to give the environment the benefit of the doubt and adopt a precautionary approach.

But the reality is that ocean fertilization does progress towards implementation. We must ask why private parties remain interested in ocean fertilization, and establish means of controlling these activities.

Firstly, the dichotomy between scientific and commercial interests is apparent, and this factor appears to be contributing to misconceptions regarding the potential of ocean fertilization. There has been limited coordination between private parties, who are interested predominantly in fish production, and the scientific sector who are presently independently pursuing climate research. It appears that the majority of scientists are either unaware or uninterested in private sector activities, despite some attempts from the private quarter to engage this attention. It is therefore not surprising that decisions are being made in the private sector without knowledge of the implications, full understanding of the uncertainties, and even the bottom line costs of these proposals. There is a real need to redirect research from the current emphasis on climate effects towards modeling of potential ecosystem impacts. Based on current proposals, it is reasonable to assume that ocean fertilization will be implemented for fish production well before it is investigated seriously for climate mitigation. At a fish production scale of operation ecosystem effects are the most significant concern, however thus far there has been limited research into the
implications of fertilization at this level, and our understanding of marine communities is limited. Ecosystem research should clearly become a priority.

The fact that commercial proposals have proceeded so far towards implementation without recall, is alarming. But to a large extent this is a reflection of the poor state of the current legal regime in the oceans. Ultimately, it should be expected that commercial interests will make their judgments based on economic cost. Regulation is therefore required to ensure that the environmental and ethical implications of ocean fertilization are incorporated in decisions. The current legal regime is contradictory in parts, regulation is not universal, and interpretation appears to be largely at the discretion of individual States. Nevertheless, with some dedicated effort, a number of existing legal instruments appear as if they might be applied to control ocean fertilization activities. These are listed below:

- Under Part XII of the United Nations Convention on the Law of the Sea (UNCLOS), for the Protection and Preservation of the marine environment, there appears to be a reasonable argument to control ocean fertilization in zones of coastal State jurisdiction (i.e. within the territorial sea, exclusive economic zone and the continental shelf). This requires scientific proof that operations cause 'harm to the marine life', 'hinders other marine activities' or has detrimental effects on 'on other States'. Burden of proof will lie with those who oppose fertilization activities. It is expected that more research will be required before this claim could be made.

- Under UNCLOS an Environmental Impact Assessment (EIA) can be demanded by the coastal State for ocean fertilization operations. The detail of this EIA is limited to what is 'practicable' and will largely be at the discretion of the State. This EIA could be significantly more detailed if parties are obliged to adopt UNEP standards, or if bound under the provisions of the Transboundary Convention.

- On the high seas fertilization operations can be controlled if they can be shown to violate the requirement for 'due regard' to other States. It is likely that transboundary impact will have to be scientifically established for this provision to be implemented.
• Ocean fertilization (by ship or pipe) does not strictly meet the UNCLOS definition of 'dumping', but may be able to be shown to be 'contrary to the aims of the (UNCLOS) convention'. Alternately, an appeal may be made to the International Maritime Organization to explicitly include ocean fertilization under its provisions. If it is recognized as 'dumping', then signatories of the London Convention, who adopt a precautionary approach to marine pollution, may legitimately ban ocean fertilization by nationals, and within areas of coastal jurisdiction. This ruling will rely on the composition of the fertilizer mix. If the fertilizer comprises additives other than naturally occurring nutrients, this provision could be readily enforced.

• MARPOL regulation may also control ship based full-scale ocean fertilization schemes, if marine harm can be demonstrated, however will have limited bearing on research scale experiments.

• The Biodiversity Convention will control ocean fertilization activities if operations can be shown to reduce ecosystem diversity. This effect has already been convincingly established from experiments. However, the application of the Biodiversity convention may be limited to ocean fertilization schemes for fish production. This is because a counter argument could be mounted for climate mitigation schemes - a case might be made that ocean fertilization reduces the biodiversity losses which are associated with climate change.

• The Kyoto Protocol (although somewhat in conflict with the earlier Framework Convention for Climate Change) does not ban ocean fertilization, in fact, it appears to encourage research into this climate mitigation strategy. It does however discount the use of the oceans as a sink of CO₂, and thus prevents sequestration by ocean fertilization from being commercially viable. Action should be taken to prevent the oceans from being re-considered as a potential sink in future FCCC discussions.

• There is some precedent for the control of nutrient (fertilizer) discharge in coastal marine waters through strongly enforced regional conventions such as OSPAR. It is conceivable that these may be extended to incorporate open ocean areas. However this would require negotiation, and at the very least, significant amendment to existing regulation.
• Governments and International Organizations also have a role in determining the acceptability of ocean fertilization practice, and may legitimately enforce constraints on its implementation.

• Any harvesting operation associated with ocean fertilization must obtain permission from Coastal States for fishing, and are also obliged not to over-exploit stocks. Fishing activities may require Regional as well as National permission where there are regional fishing conventions or agreements in place. Codes of Conduct are in place both in jurisdictional zones of the Coastal States, as well as on the high seas, and will require compliance.

Relevant requirements for future proposed fertilization experiments are as follows:

• Marine Scientific Research within zones of national jurisdiction require permission from the coastal State. On the high seas, no such permission is required. Ocean fertilization experiments with the specific goal of fish production may be legitimately refused under the provision that it is of direct significance for the exploitation of living natural resources LOS (Article 246(5)) (UN 1983). Experiments which involve pipe laying could also be refused. More generally, ocean fertilization experiments both within regions of jurisdiction, and on the high seas, could be banned if they are shown to cause harm to the marine environment.

Legally, there may also be merit in establishing specific regulation to control fertilization operations. This may either be incorporated within existing international and regional instruments, or could take the form of a new agreement to monitor fertilization and similar ocean development practices.

Ultimately, any regulation which may control ocean fertilization will only be effective if it can be appropriately enforced. Enforcement is likely to be more successful if regulation is monitored by responsible parties. As indicated by historical precedent and public opinion polls, there is definitely not a lack of public interest in the protection of the oceans. This might also be usefully directed towards controlling ocean fertilization practices.
RECOMMENDATIONS

In summary, the final recommendations of this thesis are as follows:

1. NO. We should not fertilize the oceans. Based on our limited current knowledge of this field, the tremendous uncertainties that still exist, the magnitude of potential impacts, the doubt associated with ocean fertilization effectiveness, and the considerable ethical concerns, we would be well advised to adopt a precautionary approach towards ocean fertilization. In the short term, the very minimum requires that we develop measures to control existing implementation proposals.

2. Improved coordination between private and scientific sectors is recommended. This should involve (i) information exchange, and (ii) a shift in research focus.

   I. Information exchange between private and scientific interests will assist the private sector in making more informed decisions regarding implementation. Ocean fertilization has little appeal on the basis of objective evaluation. But the private sector cannot be expected to reach this conclusion if not presented with all the available facts.

   II. A shift in research focus is desirable. Although fundamental research into climate science should continue, additional research is required into the ecosystem effects of ocean fertilization. Ecosystem impacts are the predominant concerns for fish based fertilization schemes. Given that ocean fertilization is more likely to be considered for fish production than for climate mitigation, it is essential that these effects become a research priority.

A better understanding of ecosystem effects is also important for the enforcement of existing laws and regulation. Many of the regulations which might be successfully used to control fertilization operations rely on scientific proof that harm is caused to marine life.
3. The establishment of a 'watchdog' body to monitor ocean fertilization experiments and implementation proposals is recommended. This is of particular urgency if interest in ocean fertilization continues to grow. This body should ideally comprise a partnership of scientific, government and private sector parties, to ensure all interests and issues are fairly represented. It is envisaged that this organization could also play an essential role in the enforcement and development of controlling regulation, in promoting information exchange between interested parties, and in generating public support for the protection of ocean resources.

Ocean fertilization is a fascinating field which generates some interesting scientific, economic and policy debate. And yet it perhaps marks only the beginning of a suite of 'ocean development' proposals. As mankind searches for new ways to deal with growing global problems, and as land-based alternatives for dealing with these problems are depleted, it is likely that the oceans will attract increasing attention, and enterprising means of harnessing it's yet untapped resources will be devised. Fundamentally, this must demand we question the sustainability of our current attitude towards our planet earth.

One of the greatest challenges presently facing mankind is accepting that we are subject to biological laws and therefore constrained by limits to natural resources. Today we either exceed, or will soon exceed, the limits of sustainable resource use. Not until we accept that these limits exist will we have a chance of creating a sustainable future. The reality is humbling - we are merely one small component of the giant experiment that is called planet earth - an experiment that has no controls, and will be run but once.
REFERENCES


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GLOSSARY

**Aquaculture**: mass production of aquatic organisms by human effort for commercial purposes. This includes the culture of bacteria, algae, small invertebrates, mollusks, crustaceans, and fish, both in freshwater and in seawater. (Although for the culture of marine organisms in seawater the term mariculture is commonly used).

**Autotrophs**: an organism that generates its own organic material from inorganic sources — it is independent of outside sources for organic food materials.

**Biomass**: the weight of living matter, including dead parts of living organisms. This is commonly expressed as grams per unit area (or unit volume).

**Bycatches**: this is defined as the unintended capture of marine animals, most of which is discarded, or dies.

**Coastal State jurisdiction**: this term is used to refer to all territory within the legal jurisdiction of the coastal State. This includes its territorial waters, exclusive economic zone, and the seabed of the continental shelf.

**Customary law**: consists of legal principles that have acquired international acceptance through common behavior and/or declaration.

**Ecosystem**: a discrete ecological unit consisting of all of its constituent organisms and its total environment.

**Euphotic zone**: the surface zone of the ocean within which net primary productivity occurs.

**Eutrophy**: refers to systems with a high macronutrient flux and a high biological production.

**Eutrophication**: a development towards a higher degree of eutrophy as a result of an increase supply of nutrients.

**Food web**: a successional network of ecosystem members based on food relationships. A food web diagram is useful for understanding how energy and matter are passed through the trophic levels of an ecosystem.

**Geoengineering**: the intentional large-scale manipulation of the global environment. Typically, the term geoengineering is applied to options that attempt to reduce the undesired climatic changes caused by humans.

**Gross primary production (GPP)**: the total fixating of energy by photosynthesis in a region.

**Heterotrophs**: an organism with a requirement for energy-rich organic molecules
High nutrient, low chlorophyll (HNLC) zones: zones where primary production (and thus chlorophyll levels) are low despite an abundant supply of nutrients. This anomaly is observed in the Southern Ocean and in regions of the Equatorial Pacific. Speculation about this anomaly led Martin to deduce the iron hypothesis.

Iron fertilization: includes all proposals to increase marine primary production through the addition of nutrients (see also ocean fertilization).

Iron hypothesis: this theory suggests that iron availability limits phytoplankton growth in nutrient rich seas.

Macronutrients: nutrients required by plants in relatively large quantities in order to photosynthesize and grow. Typically compounds that contain phosphorus, nitrogen and silica.

Mariculture: the culture of marine organisms in seawater (refer also aquaculture).

Micronutrients: chemical substances such as iron, copper, and zinc that are required in very small amounts by plants in order to photosynthesize and grow.

Microplankton: a size classification of plankton. The term applied to plankton in the size range 20-200 micron in diameter. Diatoms and dinoflagellates are common in this size range.

Mixing loss: a term used to refer to fertilizer losses due to physical mixing forces. It does not include additional losses that may be experienced due to chemical reaction or biological mechanisms.

Nanoplankton: a size classification of plankton. The term is applied to small plankton between 2 –20 micron in diameter. Includes diatoms and some other species.

Net community production (NCP): this represents the total net carbon fixed by an ecosystem, not lost to community respiration in any given region.

Net primary production (NPP): the amount of carbon fixed by photosynthesis that exceeds the respiration demands of the phytoplankton and thus contributes to growth.

New primary production: that portion of primary production that is based on newly incorporated nutrients in the euphotic zone (as opposed to regenerative production).

Nutrient Limitation: limitation of potential net primary production due to a lack of nutrients.

Ocean fertilization: term used to refer to schemes which propose to increase marine primary production through the addition of nutrients.

Oligotrophy: systems with small macronutrient flux and thus low biological production.
Picoplankton: a size classification of plankton. This term applies to all small plankton less than 2 micron in diameter. Comprises primarily bacteria, cyanobacteria, and small eukaryotic phytoplankton.

Polluter-pay principle: this principle seeks to shift all costs associated with pollution, including reduction, control and prevention to the polluter. This is considered equitable, because ultimately it is the polluter who benefits from the pollution generating activity.

Precautionary principle: this principle requires the use of preventative measures whenever there are reasonable grounds for believing that an activity will detrimentally impact the marine environment, whether or not causation can be shown.

Primary productivity: the rate at which biomass is produced per unit area by primary producers. Typically expressed as grams of carbon fixed per square meter of sea surface per unit of time (gC/m2/yr).

Regenerated primary production: primary production based on nutrients recycled in the euphotic zone.

Secondary productivity: the rate of production of new biomass by heterotrophic organisms.

Thermocline: layer in which temperature rapidly changes with depth.

Thermohaline circulation: circulation in the ocean that is driven by the density differences cause by temperature and salinity differences.

Trophic level: refers to the position in the food chain occupied by an organism. It is assessed by the number of energy transfer steps to reach that level.
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