Ocean fertilization and biological productivity

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Abstract

Ocean fertilization through the addition of micronutrients has been proposed as a means of offsetting anthropogenic emissions of carbon dioxide to the atmosphere. In regions such as the North Pacific, Equatorial Pacific and Southern Ocean, macronutrients such as phosphate and nitrate are found throughout the year at the surface. It has been suggested that adding iron to these waters would allow for these nutrients to be taken up by plankton and exported. One would expect this nutrient reduction to enhance biological productivity while removing carbon from the atmosphere. We demonstrate, however, that this is not necessarily the case. Removing nutrients from the low-latitude pycnocline by exporting them to great depth could also have a a negative impact on tropical production. Depleting nutrients in the Southern Ocean could result in a shift of production from the low latitudes to the Southern Ocean, with potentially large effects on tropical oceanic ecosystems. In both cases, the reduction in tropical biological productivity over time scales of a century or more is significantly larger than the carbon removed from the atmosphere.

1. Introduction

Fertilizing the ocean with micronutrients has been proposed as a means of offsetting anthropogenic emissions of carbon dioxide. A significant fraction of the surface waters of the world ocean are high in nutrients such as phosphate and nitrate throughout the year (Cullen, 1991). The emerging consensus about why this is the case is that these regions lack enough dissolved iron for large phytoplankton to grow (Martin et al., 1991). In the absence of these large plankton, nutrients cycle rapidly between small phytoplankton zooplankton and bacteria with a relatively small fraction being exported to the deep ocean (Laws et al., 2000). Were these nutrients to be taken up by large plankton instead, a substantial fraction of the uptake could end up being exported to depth as particulate organic matter. In general, organic matter has roughly the same density as seawater, so that ballast is required to make it sink. Large plankton appear to be a major source of such ballast (Armstrong et al., 2001). Increasing the growth of large plankton would be expected to increase the flux of carbon to the deep ocean. Insofar as this would reduce dissolved inorganic carbon concentrations in the surface ocean a further consequence of fertilization would be to increase the flux of carbon from from the atmosphere to the ocean.

Recent experiments in the Equatorial Pacific (Coale et al., 1996) and in the Southern Ocean (Boyd et al., 2000) have demonstrated that the addition of iron to surface waters does permit the growth of large phytoplankton. Although these experiments have yet to show conclusively a concommitant increase in the export of organic matter to the deep ocean, this may at least be in part due to the fact that measuring such flux requires a much longer-duration experiment than has been undertaken up to the present time. Assuming that such a flux would occur, iron fertilization would seem to have the consequence of enhancing oceanic biological productivity while removing carbon dioxide from the atmosphere.

This paper argues that the picture may not be so simple. It demonstrates that under certain conditions fertilization could result in a decline in global or regional net primary production by reducing the supply of nutrients to the tropical surface ocean. In some cases these declines could greatly exceed the additional uptake of carbon associated with fertilization. We argue that such effects must be considered in evaluating the overall impact of fertilization.

2. Approach

Our approach follows that of Sarmiento and Orr (1991) who simulated the effects of micronutrient fertilization using a simple parameterization of the effects of biology in an ocean general circulation model. Ocean general circulation models assume the dynamics of the ocean can be captured with a somewhat limited set of physics (see Griffies et al., 2001 for a more complete description of these models). The physics which are included are 1. Geostrophic balance between pressure gradient and Coriolis forces in the ocean interior. 2. Ekman balance between wind stress and Coriolis forces in the surface layer. 3. Eddy homogenization of tracers (temperature, salinity, nutrients, carbon) along surfaces of constant density. 4. Diffusive transport of tracers across surfaces of constant density. 5. Lateral friction (which becomes most important near boundaries). 6. Advection of tracers by the mean flow. 7. Convective homogenization of tracers. Coarse-resolution models such as those presented here implicitly assume that the details of eddy-topography interaction and resolution of the coastal and equatorial waveguide are not of primary importance.

In the circulation models described in this paper, the surface flux of momentum is prescribed, while the surface flux of heat and freshwater are a combination of a "first-guess" based on observations, and a diagnosed flux required to keep the surface temperatures and salinities near their observed values. The reason for this procedure is that far more high-quality measurements of temperature and salinity than heat and freshwater flux have been made at sea. The model then calculates the circulation which is consistent with the reduced set of physics.

The effects of biological cycling within the model are also diagnosed. Following previous work (Sarmiento and Orr, 1991; Najjar et al., 1992; Gnanadesikan et al., 2001) biological cycling is calculated implicitly, balancing physical transport so as to maintain surface nutrients near their observed values. The restoring production $Jprod$ is parameterized as

$$Jprod = \frac{1}{T}(PO_4 - PO_4^{obs}) \quad PO_4 > PO_4^{obs} \tag{1}$$

where PO_4 is the modeled concentration, PO_4^{obs} is the observed concentration and T is the restoring time. The new production is instantaneously converted into nonliving organic matter, a reasonable assumption given that the standing stock of phytoplankton rarely reflects more than a few days production (Longhurst, 1998). Two-thirds of this organic matter is dissolved organic matter, which is advected and diffused with the ambient water and remineralized back

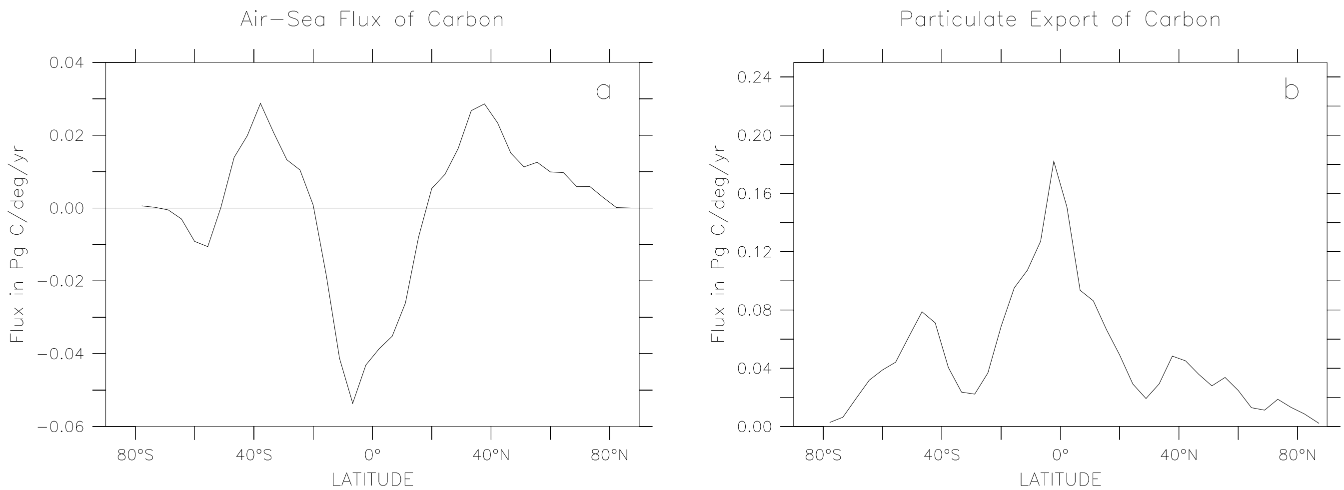

Figure 1: Key diagnostics of the carbon cycle in a general circulation model at equilibrium. (a) Air-sea flux of carbon dioxide. Note that carbon dioxide tends to invade the ocean at high latitudes and to escape from the ocean at low latitudes. (b) Export flux of carbon across the base of the euphotic zone.

to phosphate using first-order kinetics and a time constant of six months. The remaining one-third is immediately converted to particulate organic matter, which sinks and is immediately remineralized back to PO_4 within the water column. The remineralization results in a source of phosphate of

$$JPO_4 = \left(\int_{z=-z_c}^{0} Jprod \cdot dz\right) \frac{\beta}{z_c} \left(\frac{z}{z_c}\right)^{\beta-1} \qquad (2)$$

where, following Yamanaka and Tajika (1996), $z_c = 75$ m and $\beta = -0.9$.

Figure 1 shows the zonally averaged pattern of air-sea carbon flux and export production in the circulation model. Both patterns reflect the large-scale wind driven circulation, which produces upwelling in the tropics and downwelling in mid-latitudes (Murnane et al., 1999; Sarmiento et al., 2000). The wind-driven upwelling of cool intermediate waters rich in carbon and nutrients within the tropics is associated with an outgassing flux of carbon. This flux is driven largely by the fact that warm waters hold less carbon dioxide. Carbon is driven out of the surface layer as the intermediate waters are upwelled and warmed in the tropics. This flux out of the ocean is opposed by the fact that nutrients are simultaneously being stripped out of these waters and exported to depth. As tropical water moves polewards, it cools and the carbon is taken back out of the atmosphere. In high latitudes, deep waters rich in nutrients and carbon are brought through the surface as a result of convection, vertical diffusion, and upwelling. This results in a weak source of carbon to the atmosphere in these latitudes.

3. Results

3.1 Fertilizing a patch of the tropical ocean

The first experiment which we consider is one in which PO_4^{obs} is set to zero within one box of

Time	Carbon Export (Site)	Carbon Export (Local)	Carbon Export (Global)	Carbon Uptake (Site)	Carbon Uptake (Local)	Carbon Uptake (Global)	Efficiency (percent)
1mo	4.15	3.84	3.91	0.23	0.45	0.40	9.7
1yr	2.68	1.28	-0.44	0.41	1.21	0.76	28.2
5yr	2.67	1.00	-3.91	0.41	1.25	0.56	20.8
10yr	2.65	0.90	-5.61	0.41	1.26	0.50	18.9
50yr	2.60	0.46	-12.23	0.42	1.30	0.49	18.9
100yr	2.58	0.22	-15.97	0.42	1.31	0.48	18.6

Table 1: Summary of cumulative change in export and uptake (in Mt C) due to fertilization. Note that while local changes in fluxes occur over 1 year, globally integrated changes take much longer. Efficiency is defined as the percentage of the additional carbon export at the fertilization site which ends up coming out of the atmosphere.

the tropical ocean (at 2.2S, 110W) for one month. The particulate organic carbon produced by this fertilization is allowed to sink all the way to the bottom of the ocean before remineralizing. Figure 2 shows a summary of the results over the first ten years and Table 1 summarizes the changes in POC and DIC flux over 100 years. A number of important lessons emerge from this run.

- Although fertilization does result in an increase in particulate organic carbon flux to the deep ocean at the fertilization site, during the period of fertilization, it can result in a decrease in production during the months following fertilization. It is unclear to what extent this is an artifact of the simplistic biological model used in this paper. Following fertilization, PO_4 is less than PO_4^{obs} so production is zero. This condition persists until sufficient nutrient is advected into the box to raise the concentration sufficiently and restart production. Whether this is realistic depends on how the rate of production is regulated. Nutrient uptake rates are often modelled as being dependent on the concentration of inorganic nutrient when the concentration is low (Laws et al. 2000). If this is the case in the tropical Pacific, removing nutrients would reduce the rate of production in subsequent months, so that the decline in production following a bloom would be realistic. However, it is possible that the factor controlling the rate of production in the tropical Pacific is the external supply of iron. If this is returned to pre-existing levels following fertilization, production might simply continue at the same rate as before. In this case, the model presented here would overestimate the impact of fertilization on biological production.

- Fertilization results in a decrease in the production at surrounding sites. This occurs because nutrients which have been exported as a result of fertilization are unable to supply export production elsewhere. At the site, the additional export of 4.1 Mt C during the month of fertilization is offset by 1.3 Mt C of decreased flux during subsequent months. Over surrounding regions the decreases are even larger, and when the global integral is taken, the result is to decrease the total particulate flux of carbon to the deep ocean.

- Although fertilization does result in an increase in carbon flux to the ocean in an area around the fertilization site, this flux is balanced by a flux out of the ocean on larger scales

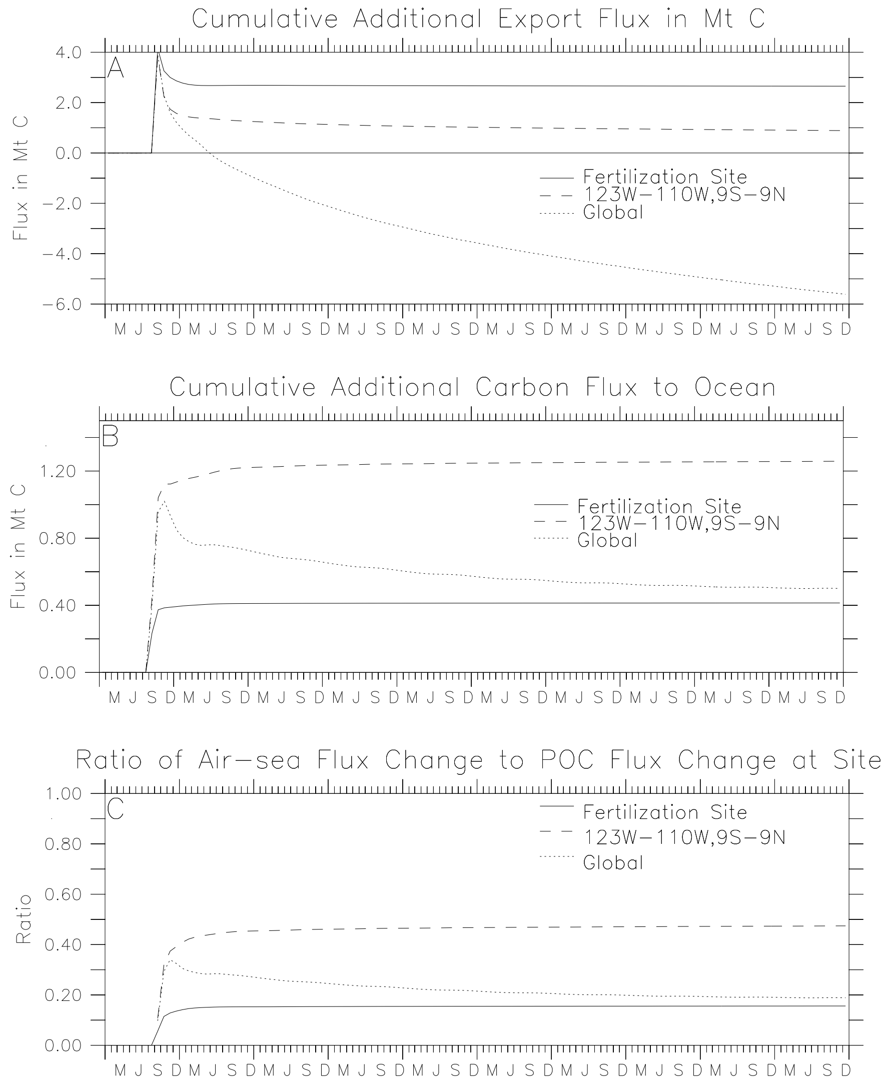

Figure 2: Summary of changes resulting from a single fertilization event where nutrients are restored to zero for one month in a box centered at 2.2S, 110W. Curves are shown for three regions, the site itself, a region including the site and an adjoining patch of ocean to the west, south, and north, and the entire globe. (a) Change in the export of carbon across the base of the euphotic zone. (b) Change in the flux of carbon to the ocean. (c) Change in the flux of carbon to the ocean divided by the change in the flux of carbon across the base of the euphotic zone at the site (efficiency as defined in equation 3).

spatial scales over time scales of several years. If one defines the efficiency of fertilization as

$$Efficiency = \frac{Cumulative\ additional\ globally-integrated\ air-sea\ carbon\ flux}{Cumulative\ additional\ export\ flux\ at\ site} \quad (3)$$

(as shown in Figure 2c), the efficiency is very low (only about 19%). If the efficiency is defined as

$$Efficiency = \frac{Cumulative\ additional\ globally-integrated\ air-sea\ carbon\ flux}{Additional\ export\ flux\ at\ site\ during\ fertilization} \quad (4)$$

the efficiency is even lower (about 12%).

- Over a period of a century, the cumulative decline in new production (16 MtC) is much larger than the carbon removed from the atmosphere (0.48 Mt C). The decreases in export production continue over a much longer period of time as well, so that the decrease in export production over 50 to 100 years after sequestration (3.76 MtC) is almost an order of magnitude larger than the uptake of carbon over the entire 100 year time scale.

It should be emphasized that the above is a *worst* case as regards export flux but that it may be a *best* case as regards efficiency. We ran a separate simulation in which carbon and nutrients were remineralized following equation (2). In this simulation the impacts on export production were much less serious. However, this run assumed that the iron added to the system was lost after remineralization. As a result, when the nutrients returned to the surface, they carried the additional carbon with them. This carbon was then released to the atmosphere, resulting in an efficiency of only 1-2%.

3.2 Fertilizing the entire Southern Ocean

A second set of runs was carried out in which nutrients were drawn down to zero within the entire Southern Ocean south of 30S. Figure 3 and Table 2 summarize the results of this simulation. Initially, the fertilization produces a large increase in export over the Southern Ocean, and a corresponding uptake of carbon from the atmosphere. The scale of the effect is naturally much larger than from the spot fertilization, being measured in gigatons rather than megatons of carbon. Initially, approximately half of the carbon export comes from the atmosphere and there are no major effects away from the fertilization site. As in the case with the spot fertilization, however, over time remote effects develop.

The change on which to focus is the reduction of export flux in the tropics. After 100 years of fertilization, this flux has declined by 40%. After 500 years, it has declined by 70%. The reason for this decline is that the water which supplies nutrients to the tropics in this model comes from the Southern Ocean. As nutrients are drawn down in the Southern Ocean, this supply is greatly reduced and the export production decreases. The effect is more pronounced in the model shown in Figure 3 than in other versions of the POBM (in particular the model of Sarmiento and Orr, 1991) because the diapycnal diffusion is much weaker (and we believe more realistic) in the present model. As shown by Gnanadesikan (1999) and Gnanadesikan et al. (2001), lowering the diapycnal diffusion shifts the dominant location of upwelling deep water from the low-latitude pycnocline to the Southern Ocean. As a result, the remote effects of

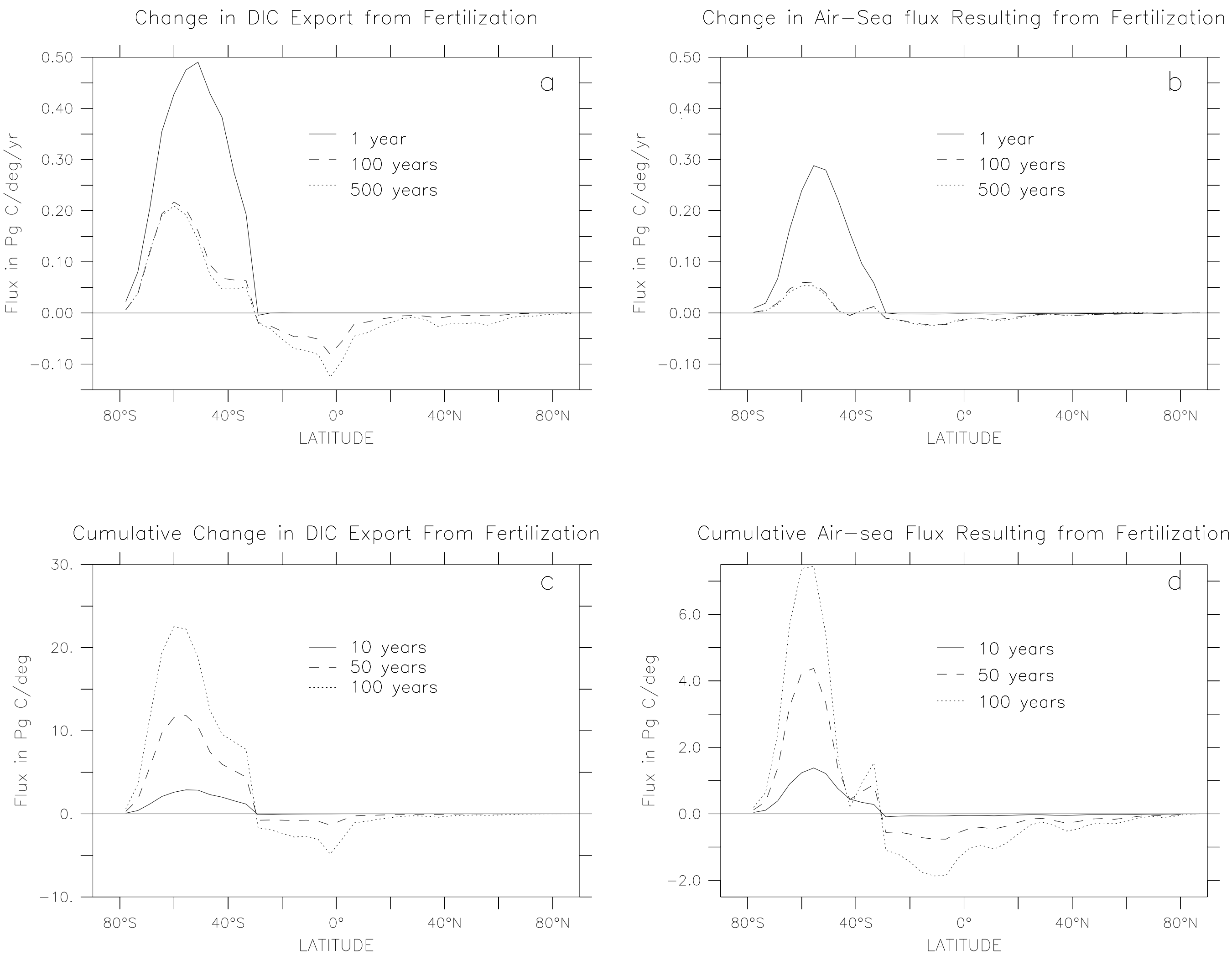

Figure 3: Summary of changes resulting from fertilization of the entire Southern Ocean. (a) Change in DIC export from fertilization, integrated zonally. Note that after 500 years the increase in export flux in the Southern Ocean is compensated by a reduction in the export flux of carbon away from the Southern Ocean. (b) Change in air-sea flux resulting from fertilization, zonally integrated. Note that after 100 years, increased ingassing in the Southern Ocean is balanced by increased outgassing away from the Southern Ocean. (c) Cumulative change in DIC export. (d) Cumulative change in air-sea flux.

Time	Carbon Export (SO)	Carbon Export (Trop.)	Carbon Export (Global)	Carbon Uptake (SO)	Carbon Uptake (Trop.)	Carbon Uptake (Global)	Fert. Effic. (%)	Change in Trop. Prod (%)
1yr	14.8	-0.01	14.8	7.1	-0.1	7.0	47.0	-0.3
5yr	49.0	-0.26	48.7	20.2	-1.2	18.6	37.9	-1.9
10yr	85.1	-1.07	84.0	31.5	-3.2	27.1	31.9	-4.7
50yr	329.6	-33.1	295.6	90.1	-29.1	54.1	16.4	-26.6
100yr	608.2	-113.3	487.1	148.0	-68.2	66.9	11.0	-40.4

Table 2: Summary of cumulative change in export and uptake (in Gt C), efficiency of fertilization, and percentage reduction in tropical production due to drawing nutrients down to zero in the entire Southern Ocean. Note that there are delayed effects in the tropics. After 100 years, the reduction in tropical export production exceeds the increase in global carbon uptake.

Southern Ocean fertilization are much more pronounced in models with realistically low levels of vertical mixing.

In addition to the remote decline in production there are also significant changes in air-sea carbon flux away from the fertilization region. Within the Southern Ocean, fertilization resulted in a region which acted as a weak source of carbon to the atmosphere (Figure 1a) becoming a weak sink. Away from the Southern Ocean, fertilization results in decreased ingassing in the subtropical gyre and increased outgassing in the tropics.

4. Conclusions and Future Activities

In order for ocean fertilization to remove carbon from the atmosphere, it must increase the carbon content of the deep ocean. This can happen if fertilization results in an enhanced flux of nutrients from light surface waters to deep waters. However, removing nutrients from surface waters may have potentially significant effects on the magnitude of tropical production insofar as it would result in a decrease in the supply of nutrient to the tropical surface ocean. In two cases, we show that the potential reduction in tropical export production exceeds the uptake of carbon from the atmosphere by a large factor.

This reduction in tropical export production is significant, because the tropics are the location of many of the ocean's most productive fisheries and much of its biodiversity. High-latitude ecosystems in which export production is high tend to be characterized by low biodiversity with a large fraction of primary production being exported. By contrast, ecosystems where nutrients are scarce tend to have higher biodiversity and ecosystems tend to recycle nutrients relatively efficiently (Longhurst, 1998). The Southeast Pacific region, where a significant portion of the impacts are found in the present study, accounts for almost 20% of global fisheries landings (FAO, 1997), with some 15-20 million tons of fish caught each year and a first sale value in the $10-20 billion range. Subsequent processing would raise the value of this catch substantially. The total export flux predicted by the GCM in this region is round 2 GtC/yr. Making the (undoubtedly oversimplified) assumption that any change in export flux would result in a proportional change in fisheries landings, the impact of reducing tropical export production in the Pacific is at a minimum $5/ton export production. Insofar as the model runs presented in Section 3.1 are accurate, the cost to fisheries over 100 years of sequestering a ton of carbon through micronutrient fertilization of the tropical ocean would be 30 times this or around \$150/ton C sequestered. While it should be recognized that there are huge uncertainties surrounding this estimate, it is important to note that this cost is significant. The cost of separating and capturing carbon dioxide from flue gasses using currently available technology ranges from \$35-\$264/ton C (DOE, 1999), so that fisheries impacts could make micronutrient fertilization unfeasible.

By contrast, the value of fisheries in the Southern Ocean is much smaller, with the FAO estimating that potential fisheries are less than 1 million tons. Our model estimates an export production of 0.8 Gt C/yr south of 50S, so that the "efficiency" of Southern Ocean ecosystems in producing fish is only about 10% that of the tropics. A shift in production from tropical latitudes to the Southern Ocean would be expected to result in a significant decline in the abundance of those fishes currently exploited by human beings as food sources.

While this study suggests that fertilization could result in significant impacts on tropical biology, it leaves a number of questions unanswered. The first is what exactly sets the efficiency of fertilization. Why is the efficiency only 20% for the first case rather than 5 or 50%? What are the relative roles of circulation and biology in determining this efficiency? A second question is the role of fertilization in changing biological production. What really would be the effects of removing adding iron and removing nutrients from some point in the tropical Pacific? Would the production in subsequent months drop at at the site and in the vicinity of the site? What is the true impact of taking phosphate which would have been remineralized within the upper ocean away from the equator and remineralizing it at great depth on the supply of nutrients to the surface waters? In order to better answer such questions, it will be necessary to consider models of ocean circulation with higher spatial resolution to provide a better representation of the true physical structure of the Tropical Pacific. Additionally, observations of how iron affects tropical ecosystems and how it cycles through these ecosystems are needed. Only if these become available will it be possible to develop more realistic biological models capable of directly simulating the impact of iron fertilization on marine ecosystems and carbon cycling.

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