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LETTER

Global negative emissions capacity of ocean macronutrient fertilization

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Abstract

In order to meet the goal of limiting global average temperature increase to less than 2 °C, it is increasingly apparent that negative emissions technologies of up to 10 Pg C yr^{-1} will be needed before the end of the century. Recent research indicates that fertilization of the ocean with the macronutrients nitrogen and phosphorus where they limit primary production, may have sequestration advantages over fertilizing iron limited regions. Utilizing global datasets of oceanographic field measurements, and output from a high resolution global circulation model, the current study provides the first comprehensive assessment of the global potential for carbon sequestration from ocean macronutrient fertilization (OMF). Sufficient excess phosphate exists outside the iron limited surface ocean to support once-off sequestration of up to 3.6 Pg C by fertilization with nitrogen. Ongoing maximum capacity of nitrogen only fertilization is estimated at 0.7 ± 0.4 Pg C yr^{-1}. Sequestration capacity is expected to decrease from the upper toward the lower bound over time under continued intense fertilization. If N and P were used in combination the capacity is ultimately limited by societies willingness to utilize phosphate resources. Doubling current phosphate production would allow an additional 0.9 Pg C yr^{-1} and consume 0.07% yr^{-1} of known global resources. Therefore offsetting up to around 15% (1.5 Pg C yr^{-1}) of annual global CO$_2$ emissions is assessed as being technically plausible. Environmental risks which to date have received little quantitative evaluation, could also limit the scale of implementation. These results reinforce the need to consider a multi-faceted approach to greenhouse gasses, including a reduction in emissions coupled with further research into negative emissions technologies.

1. Introduction

Since the industrial revolution 66% of the available 2 °C carbon budget has been consumed (IPCC 2013), while even the most recent international agreement the 'Paris Agreement' (UNFCCC 2015), provides for continued growth in annual emissions (Boyd *et al* 2015). Society has nearly run out of time to begin a practically plausible path to decarbonisation which limits globally averaged surface temperature rise to 2 °C (Anderson 2015). Even under optimistic paths of emission reduction, meeting this goal with an acceptable degree of confidence is predicted to require significant anthropogenic carbon sinks of

6 ± 4 Pg C yr^{-1} (20%–100% of current emissions) by mid century (e.g. Fuss *et al* 2014, Gasser *et al* 2015). However very few negative emissions technologies have been identified which could remove significant amounts of already released carbon dioxide from the atmosphere at an economically attractive cost (NAS 2015). Although many appear to be uncomfortable with deliberate human intervention in the climate system by humankind (e.g. Chisholm 2000, Schiermeier 2014, Zhang and Posch 2014), failure of the global community to avoid annual growth in CO$_2$ emissions imposes an onus on scientists to investigate carbon dioxide removal (CDR) technologies, so called 'geoengineering' (Jackson and Salzman 2010,

Long *et al* 2015, NAS 2015, Parson and Keith 2013, Royal Society 2009). Ocean Iron Fertilization (OIF) is one of few such proposed technologies which has received considerable scientific attention over the past two decades (Strong *et al* 2009). The capacity of OIF has been estimated to be the removal and storage of up to around 1 Pg C yr^{-1} globally (Aumont and Bopp 2006, Keith 2001, NAS 2015). However the location of the major High Nutrient Low Chlorophyll (HNLC) region in the Southern Ocean imposes difficulties for inducing, maintaining, and monitoring long term storage of carbon (Robinson *et al* 2014, Williamson *et al*, 2012; Zeebe and Archer 2005).

An alternative strategy to OIF is to provide the macronutrients missing from low nutrient low chlorophyll (LNLC) regions (Jones and Young 1997, Jones and Harrison 2013). Ocean Macronutrient Fertilization (OMF) is similar in principal to OIF, however the biogeochemical response has some important differences, which improve the potential for long-term carbon sequestration (ECOR 2011, Jones 2011). Macronutrient fertilization aims to sequester carbon from the atmosphere to the ocean by stimulating what's known as the 'ocean biological carbon pump' (Jones and Young 1997). This process, driven by the life cycle of marine phytoplankton is limited in ⌣70% of the oceans by a lack of nitrogen or by nitrogen and phosphorous. Relieving this limitation is expected to result in an increased net flux of C from atmosphere to the ocean (Lawrence 2014). Modeling macronutrient (N&P) enrichment of an oligotrophic gyre ecosystem Hardman-Mountford *et al* (2013) found that the enrichment 'showed a clear enhancement in gross primary production over respiration, a substantial shift in both phytoplankton and zooplankton community structure towards larger size classes, and an export of carbon below the deep chlorophyll maximum into the aphotic zone'. Lawrence (2014) considered the efficiency (C_{stored}/C_{fixed}) of carbon stored for more than 100 years, following addition of reactive nitrogen to LNLC regions where sufficient excess phosphate was present. The result was considerably better than Harrison (2013) found for the Southern Ocean OIF case, despite the obvious disadvantage of the much larger material (N and/or P) requirement to create planktonic biomass compared with Fe for OIF (Lampitt *et al* 2008, NAS 2015). Lenton and Vaughan (2009) presented a preliminary assessment of the radiative forcing potential of nitrogen and phosphate fertilization as independent case studies, however they only considered inadvertent addition of phosphate. The cost of OMF has recently been estimated by Jones (2014) to be as low as US\$ 20 t^{-1} CO$_2$ avoided, for regions where only nitrogen is needed to stimulate production. This cost is within the pricing range of emerging carbon markets (Kossoy *et al* 2014).

Given then that OMF may be a technically viable carbon dioxide removal technique, an important question not yet adequately addressed is: What is the negative emissions capacity, if macronutrients rather than iron were engaged to fertilize the oceans? The current study made use of global survey datasets, global circulation model (GCM) output, and simple 1 dimensional models to provide the first comprehensive and spatially explicit estimation of the sequestration potential of OMF, the results of which can inform policy debate, and future CDR research priorities.

2. Methodology

Biological productivity, and resultant carbon export from the surface ocean is often limited by a lack in availability of nutrients. In the oligotrophic low nutrient low chlorophyll (LNLC) regions, nitrogen is the most common proximate limiting nutrient, followed by phosphorus (Tyrrell 1999). A lack of reactive silica can limit the growth of diatoms, leaving other autotrophs to access the nitrogen and phosphorus pools (Moore *et al* 2013). Due to their typically fast sinking rates diatoms can move carbon to the deep ocean effectively, as observed for an iron-fertilized bloom by Smetacek *et al* (2012).
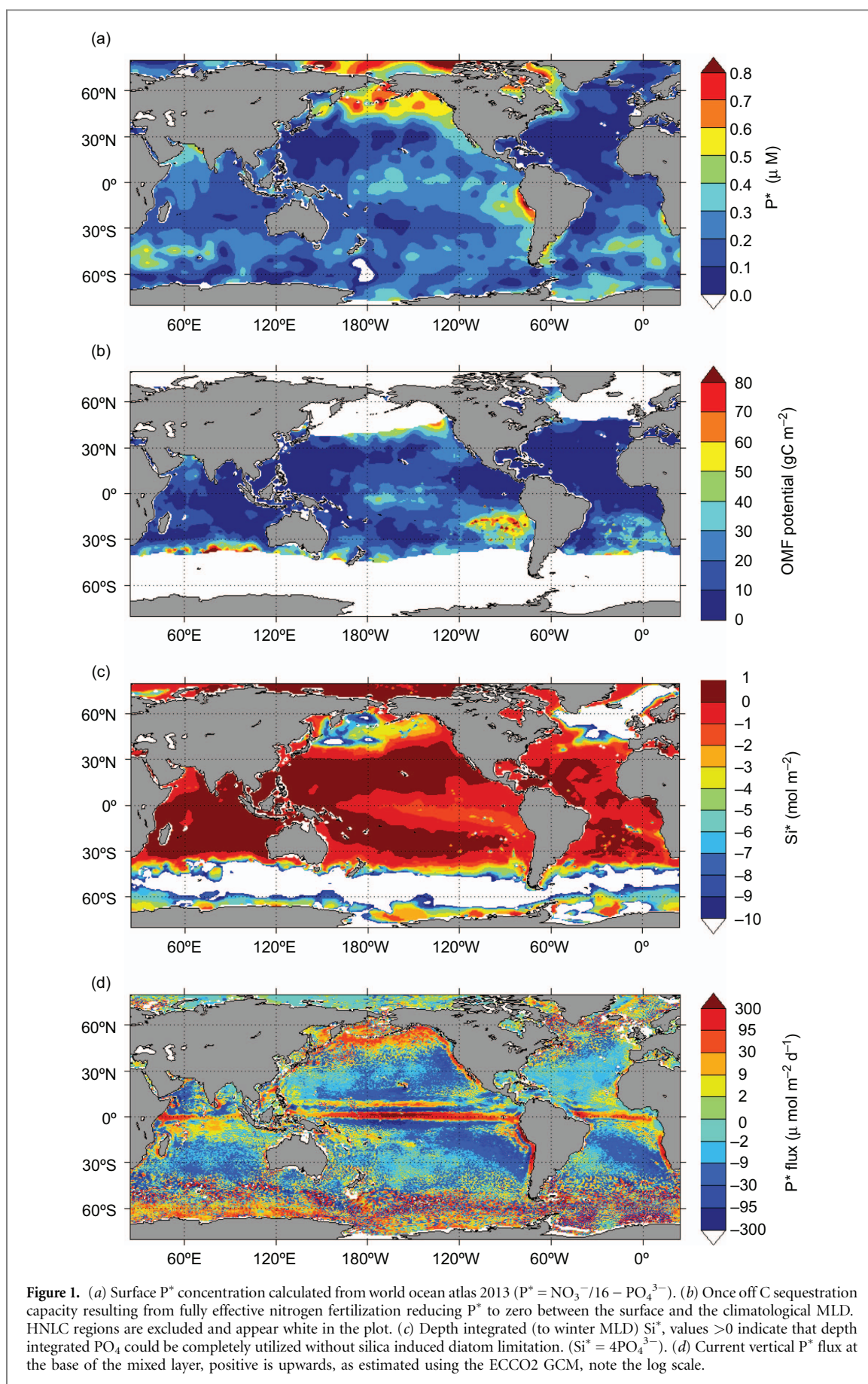
It is evident then that the CDR potential depends on which nutrients are used for fertilization and in what combinations. Three scenarios were considered:

1. Once off fertilization with N in regions of the surface ocean that have excess P.

2. Continuous fertilization with only N.

3. Continuous fertilization with N and P in combination.

Under all scenarios sufficient micronutrients and light are assumed to be present to enable incorporation of introduced macronutrient into organic matter. The exception to this assumption is iron, which is dealt with explicitly. On the likely basis that OMF would seek to promote diatoms within the assemblage, an assessment of available silica was also conducted. The second two scenarios are not mutually exclusive and could in theory be practiced simultaneously.

2.1. Once-off nitrogen fertilization utilizing available excess phosphate (P*)

In much of the global surface ocean the phosphate to nitrate ratio is in excess of the elemental Redfield (1934; 1958) molar ratio P:N of 1:16 (figure 1(*a*)). The excess of P over Redfield is defined as P* = NO$_3^-$/16 − PO$_4^{3-}$ (moles) following Deutsch *et al* (2007). This quantity represents P that will not be incorporated into primary production without the supply of additional N. By quantifying P* we can extrapolate using Redfield and published OMF efficiencies, the amount of carbon which can be sequestered by adding sufficient N to reduce P* to 0, at which point N&P are

Figure 1. (*a*) Surface P^* concentration calculated from world ocean atlas 2013 ($P^* = NO_3^-/16 - PO_4^{3-}$). (*b*) Once off C sequestration capacity resulting from fully effective nitrogen fertilization reducing P^* to zero between the surface and the climatological MLD. HNLC regions are excluded and appear white in the plot. (*c*) Depth integrated (to winter MLD) Si^*, values >0 indicate that depth integrated PO_4 could be completely utilized without silica induced diatom limitation. ($Si^* = 4PO_4^{3-}$). (*d*) Current vertical P^* flux at the base of the mixed layer, positive is upwards, as estimated using the ECCO2 GCM, note the log scale.

co-limiting. In order to examine silica availability a quantity $Si^* = Si - 4\ PO_4^{3-}$ (moles) is similarly defined based on the observation by Gilpin *et al* (2004)

that diatom growth begins to be inhibited at N:Si ratios of 4:1, but expressing in terms of P rather than N. An upper limit to sequestration for nitrogen only

fertilization, is the amount of C which could be sequestered in the case where N is added in sufficient quantity to reduce P^* to zero everywhere in the surface ocean. Si^* therefore indicates weather there is adequate silicate for this additional biomass (due to fertilization) to fully form with no restriction to diatom growth ($Si^* \geq 0$) or whether diatom growth is likely to become restricted ($Si^* < 0$). To exclude regions where the primary limiting nutrient is Fe rather than N, a threshold of 4 μM nitrate was applied (Okin *et al* 2011). It was not applied between 30°N and 30°S so as not to exclude intense upwelling regions of the Humboldt and Benguela current systems. This decision means P^* in the iron limited equatorial Pacific is included, however as pointed out by Watson *et al* (2008) waters in this region are generally resident at the surface for sufficiently long that they receive the necessary iron requirement before subduction. Fe could also be included inexpensively with the nitrogen fertilizer, increasing the capacity to access P^* within HNLC regions, thus a sensitivity analysis was conducted to examine the impact of varying the HNLC threshold.

Climatological nutrient concentration data and mixed layer depth (MLD) were obtained from the World Ocean Atlas 2013 (Garcia *et al* 2014) and 1995 (Monterey and Levitus 1997) respectively. P^* was integrated to the maximum monthly climatological MLD for each cell, the rationale being to include P^* that was at any time of the year accessible. Practicality was examined by considering the relationship between sequestration potential, and area of surface ocean required to achieve it. For estimation of total nutrient inventories, depths were taken from the General Bathymetric Chart of the Oceans (GEBCO) (IOC *et al* 2003).

2.2. Ongoing CDR potential of nitrogen fertilization

The ongoing carbon dioxide removal (CDR) capacity can be estimated by consideration of the net fluxes of N and P into the surface ocean. For fertilization with N alone, the net flux was determined for P in excess of the Redfield ratio to N (denoted by P^*) on an annual basis to the surface ocean, including riverine, upwelling, and aeolian inputs. The spatial distribution of vertical P^* flux into the surface ocean was examined by combining the monthly climatological fields of MLD, nitrate, and phosphate (as described in 2.1) with circulation output from Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2) global circulation model (GCM) (Menemenlis *et al* 2008). The ECCO2 GCM aims to provide an ocean synthesis of all available satellite and in-situ data, its high spatial resolution (0.25 degree) begins to resolve eddies and narrow current systems (www.ecco2.org, June 2015). Climatologies of the vertical velocity were calculated from 2 decades of monthly data (1992–2012). P^* flux was calculated as the product of vertical velocity at the depth of the monthly mixed layer and corresponding P^* concentration immediately below or above the MLD for upwards and downwards fluxes respectively.

2.3. Ongoing fertilization with N and P in combination

In low nutrient low chlorophyll (LNLC) regions phosphorus is the next proximate limiting nutrient after nitrogen, and has been argued as the ultimate limiting nutrient (Tyrrell 1999). If P is included with N to create a fertilizer mix, then primary production could be considerably increased. What then is the limit? Silica and micronutrients could also be included in the fertilizer mix if required. Light would be limiting in some regions of the ocean seasonally. It would be undesirable to increase concentrations of plankton to very high levels for the reasons outlined by Glibert *et al* (2008). Although it should be noted that these authors misread an OMF proposal to create 200 μg L^{-1} of phytoplankton biomass reported in Young (2007), which is equivalent to ⌣4, rather than 200 μg L^{-1} chl-a as was mistakenly assumed. Indeed Judd *et al* (2008) suggest nitrogen fertilization might be engineered to operate at a concentration of 4 μg L^{-1} chl-a. Due to the extremely vast areas of oligotrophic LNLC ocean, it would be possible to sequester large amounts of carbon without an overly high concentration of plankton in any one area. Reactive Nitrogen can be manufactured inexpensively using dinitrogen from the atmosphere, an inexhaustible supply for practical purposes, although fossil fuels are required in the process and create a carbon offset (Lawrence 2014). The approach has therefore been taken that the practical capacity of combined N&P fertilization is best considered in terms of the available non-renewable phosphate supply, putting aside for now considerations of environmental risk.

A simple model was employed predicting phosphate demand for the next 50 years under 2 scenarios. In the period 2000–2010 the per capita consumption of phosphate rock (PR) was variable but with no significant growth trend (Burt *et al* 2013). The current global per capita consumption of 30.4 kg PR yr^{-1} is predicted to increase to 34.1 kg PR yr^{-1} in 2018 (Burt *et al* 2013, United Nations 2013, USGS 2015a) although a balanced human diet requires only 22.5 kg PR yr^{-1} person^{-1} (Cordell 2010). In the baseline scenario, the predicted quantity of phosphate extraction is calculated at the 2018 per capita consumption using future population predictions from the United Nations (2013). In the second scenario N&P OMF amounting to 1 Pg C yr^{-1} sequestration, phased in linearly over 50 years, is superimposed. This is equivalent to one 'climate stabilization wedge' as proposed by Pacala and Socolow (2004).

2.4 Efficiency of Carbon Sequestration

The overall efficiency of nitrogen fertilization has been considered by Lawrence (2014), who concluded that around 75% of the photosynthesized nitrogen will lead
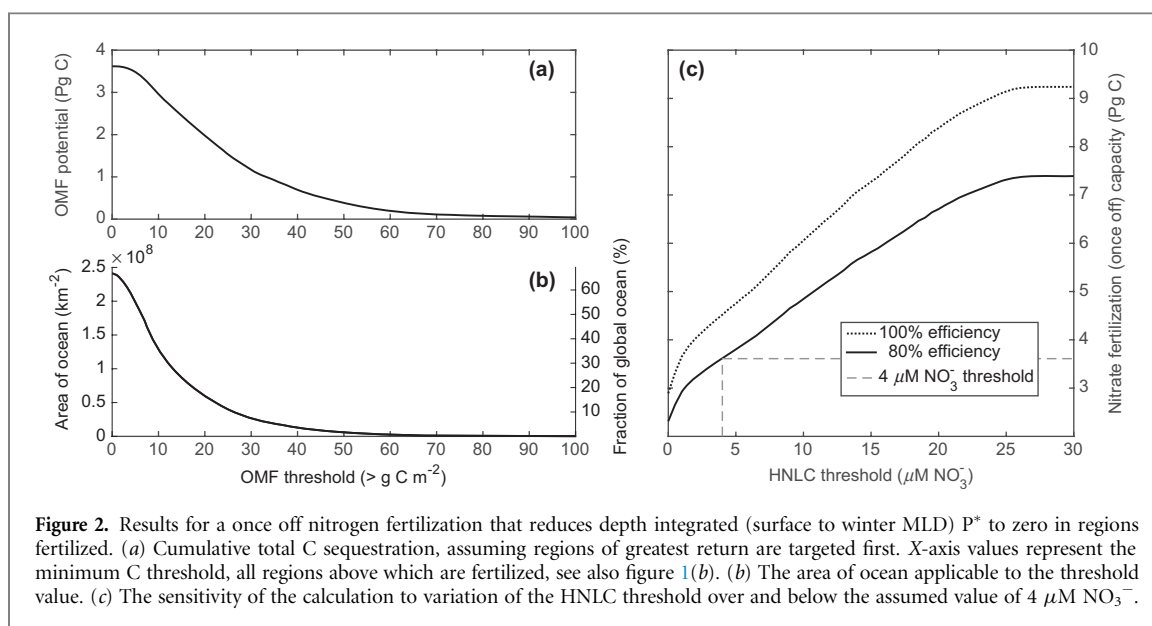
Figure 2. Results for a once off nitrogen fertilization that reduces depth integrated (surface to winter MLD) P* to zero in regions fertilized. (*a*) Cumulative total C sequestration, assuming regions of greatest return are targeted first. *X*-axis values represent the minimum C threshold, all regions above which are fertilized, see also figure 1(*b*). (*b*) The area of ocean applicable to the threshold value. (*c*) The sensitivity of the calculation to variation of the HNLC threshold over and below the assumed value of 4 μM NO_3^-.

to long-term sequestration of carbon (>100 years). Lawrence (2014) considered the offset due to greenhouse gasses (GHG) produced during the manufacture, transport, and distribution by ship of the fertilizer, as well as the effects of: denitrification, oceanic GHG production, air-sea transfer efficiency, alkalinity effect, fish effects, and production of calcium carbonate by calcifying organisms. Of the losses considered, manufacture of the reactive nitrogen had the largest efficiency impact of 10%–23% dependent on the form of nitrogen fertilizer. Some loss processes result from the removal of introduced reactive nitrogen from the ocean system. Nitrogen so lost will free up the concordant amount of phosphorus. Hence such efficiency losses impact the quantity of N required, and the cost, but not the calculation of ultimate storage capacity. Removal of losses meeting this criteria gives an adjusted efficiency of 80%, which is similar to the 78% estimated by Matear and Elliott (2004). If phosphate rock is mined for the purposes of OMF the efficiency will be further reduced. Single super phosphate is an economical P fertilizer, and contains 8.8% P by weight. Ledgard *et al* (2011) provides an average figure of 216 kg CO_{2-e} emissions t^{-1} fertilizer, including all associated emissions from mining, all forms of transport, and the fertilizer manufacturing processes, the lifecycle is considered from mining to delivery at a New Zealand port. Thus the additional OMF efficiency loss from incorporating phosphate fertilizer is estimated to be 1.63%, recalling that ship based emissions due to transport and distribution of the N fertilizer are already included. Further considerations, which could impact the effectiveness of OMF, but for various reasons did not directly influence the results of the current study, are briefly considered in the supplementary text S1 available at stacks.iop.org/ERL/12/035001/mmedia.

3. Results and Discussion

3.1. Once off fertilization potential by nitrogen fertilization

The quantity of phosphate in excess of Redfield ratio to nitrogen at any location in the surface ocean is set by the combination of P* concentration and MLD. Deeper MLDs often do not spatially co-occur with regions of higher surface P* concentration. Accordingly, regions of maximum potential carbon sequestration differ substantially from regions of highest surface P* concentration (figure 1). Should sufficient nitrogen be added to deplete P* to zero in all non HNLC regions of todays oceans, the carbon sequestration is found to be 3.6 Pg C after incorporating efficiency losses. However this represents the upper bound, and would require fertilization of the entire non-HNLC region (plus the equatorial HNLC region) as depicted in figure 1(*b*).

It is clear from figure 1(*b*) that depth integrated availability of P* is dominated by a few locations. Prioritizing fertilization to areas of highest accessible P* would minimize cost, effort, and the CO_2 offset from distribution. Additionally, should large scale ocean fertilization activities ever be permitted under international governance, the extent of ocean is likely to be limited due to operational considerations related to physical ocean circulation (Lampitt *et al* 2008), as well as socio-political and environmental considerations (Royal Society 2009).

The cumulative carbon storage potential, and area of surface ocean that must be utilized to achieve it are plotted in figures 2(*a*) and (*b*) respectively, assuming fertilization progresses from regions with higher to lower potential. Should nitrogen fertilization be confined to areas yielding >20 g C m^{-2} then the once off sequestration would be ⌣2 Pg C and an area of ⌣ 6×10^7 km^2 (around 16.5%) of the ocean surface would need to be enriched with nitrogen.

Table 1. Fluxes of P* to the surface ocean from various sources (Tmol yr^{-1}). Method refers to the method by which P* flux was calculated. W denotes flux of water, P*/P denotes ratio derived this study. Total anthropogenic contribution to the biosphere, and fertilizer production are shown for illustrative purposes, but are not included in the flux calculation. $^{\Psi}$GCM results show 55% of flux occurs outside HNLC regions.

Source	N	P	P*	—	Method	Reference
GCM vertical flux (a)			1.6		W × P*	This study, figure 1(d)
Upwelled non HNLC			0.88		0.55$^{\Psi}$ × (a)	
River	3.9	0.9	0.66			Mackenzie *et al* (2002)
	3.43	0.91	0.7			Boyer *et al* (2006) Tiessen (1995) (av. p 324)
			0.68 ± 0.2			
Aeolian	1.9	3.9 × 10^{-8}	−0.12		P − N/16	Vet *et al* (2014)
	4.5	0.01	−0.27		P − N/16	Okin *et al* (2011)
			−0.195 ± 0.075			
Nitrogen fixation	9.5		−0.59		P − N/16	Somes *et al* (2010)
	10.0		−0.625		P − N/16	Gruber and Galloway (2008)
	12.64		−0.79		P − N/16	Großkopf *et al* (2012)
			−0.668 ± 0.1			
Net P* flux—ocean			0.7 ± 0.4			
Fertilizer production	10.29	0.93	0.29		P − N/16	USGS (2015b), USGS (2015a)
Total anthropogenic	15	0.93	0		P − N/16	USGS (2015a), Fowler *et al* (2013)

The sensitivity study shows low variation for reasonable HNLC exclusion threshold values of 2–6 μM NO$_3^-$. However relaxing the threshold further, to in effect progressively include HNLC regions, shows a marked increase in sequestration capacity (figure 2(c)), indicating that around half of the surface ocean P* is contained within iron limited regions. An implication of this result is that models considering either natural or artificial OIF, in which the perturbation is provided by forcing a reduction in surface phosphate concentrations to zero may not adequately take into account an insufficient availability of nitrate (e.g. Marinov *et al* 2008, Sarmiento and Orr 1991).

Global spatial distributions of P* and Si* at depths of 50, 100, 500, & 1000 m are included as supplementary figures S1 & S2 respectively. The surface ocean shows an extreme shortage of Si relative to P at the ratio specified for unimpeded diatom growth. Figure 1(c) depicts the surface layer depth integrated Si*. Values of zero or greater indicate the entire depth integrated P* could support additional diatom growth, although this does not necessarily imply that diatoms will prosper over other autotrophs (Glibert *et al* 2008). These regions do not coincide well with regions of greatest nitrogen fertilization potential, except in the South Atlantic. Therefore if encouraging diatoms to prosper were a goal of fertilization, many regions may require additional silica.

3.2. Ongoing N fertilization

The total quantity of P* in the global ocean was estimated to be 10.19 Pg P*, and the total P to be 93.54 Pg P. The latter figure agrees well with Marinov *et al* (2008). Thus the average ratio of P*/P is 0.11 for the global ocean. The ratio is reduced in the surface ocean by nitrogen fixation and altered by N&P inputs which differ from the Redfield ratio, such as atmospheric deposition. In the deep ocean, denitrification acts to increase the ratio, apparent in the pronounced pool of high sub-surface P* in the equatorial East Pacific Ocean, which correlates spatially with the oxygen minimum zone (supplementary figure S1).

A summary of P* fluxes into the modern global surface ocean is given in table 1, along with the reduction of P* due to nitrogen fixation. Interestingly the total anthropogenic contribution of N&P to the environment is in almost exactly the Redfield ratio although some 28% of the terrestrial N flux is estimated to be de-nitrified (Bouwman *et al* 2013) partially accounting for the imbalance evident in the riverine contribution. Nitrogen fertilizer production may be increasing relative to phosphate (Glibert *et al* 2014), if this imbalance permeates into the ocean less P* may be available for OMF, due to increased inadvertent N fertilization. Model results (GCM) indicate that 40%–50% of the flux occurs within non-equatorial HNLC regions, thus the upwelling contribution is reduced by this amount. Net flux of available P*, 0.7 ± 0.4 Tmol P yr^{-1} is equivalent to 0.7 ± 0.4 Pg C yr^{-1} at 80% efficiency, a value consistent with that estimated by Lenton and Vaughan (2009). As surface and near-surface P* pools are depleted the vertical distribution of P in the near surface ocean will be altered and the flux is likely to be reduced. Thus initially carbon sequestration can be expected near the upper bound of this estimate but if large scale N only fertilization progresses over time, the capacity will fall towards the lower bound. A first order indication of the transition time is the average residence time of the surface ocean, ∼6 years in the mid Pacific (Broecker and Peng 1982). Additionally it is unclear what portion of excess phosphate upwelled in HNLC regions is subsequently advected into regions with sufficient iron supply, by excluding this portion completely the calculation is conservative. These

issues introduce some uncertainty in the long term estimate for N only fertilization, which could best be resolved through future application of global biogeochemical models.
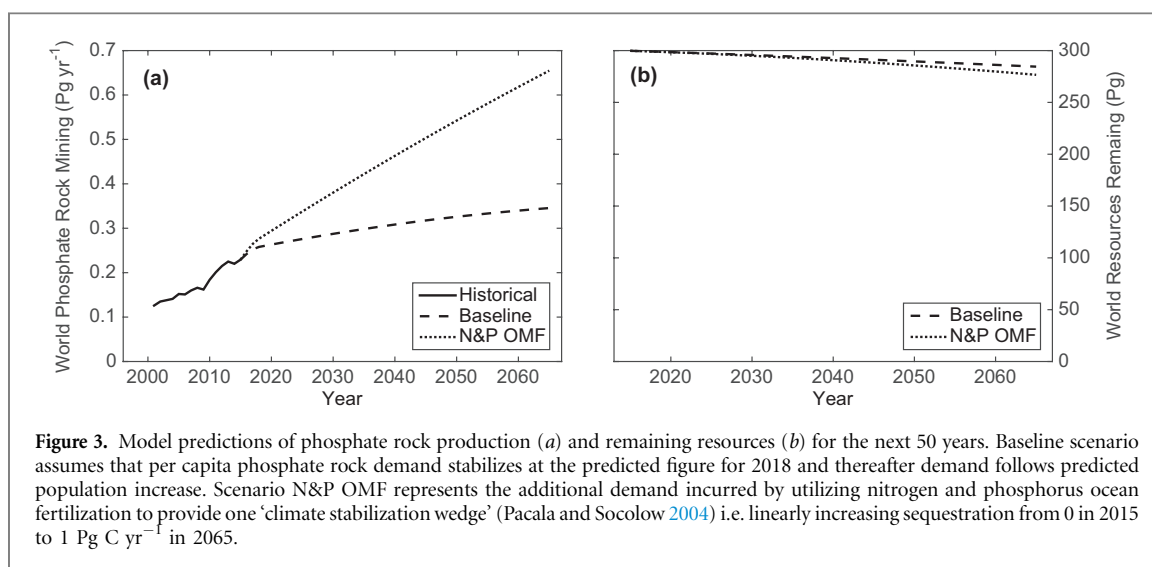
3.3. N&P fertilization

Phosphate is a non renewable resource essential for industrialized agriculture and global food supply, the only alternative to mined phosphate is recycling (Cordell *et al* 2009). Current world reserves (economically extractable at the current time, and held by production companies under lease) of phosphate rock are 67 Pg, current production levels of 0.22 Pg PR yr^{-1} give a static lifetime of >300 years (USGS 2015a). However global resources (economic extraction is regarded as feasible either at the current or some future time) are in excess of 300 Pg PR (USGS 2015a), giving a potential static lifetime >1300 years, almost certainly an underestimate as mining and exploration companies generally have a 15–20 year outlook and fears of impending 'peak' phosphorus are misplaced (Heckenmüller *et al* 2014). Phosphate mining is also associated with negative environmental impacts including de-vegetation, ecosystem alteration, geohazards, contamination of soils or water, and erosion (Yang *et al* 2014), which can leave a lasting legacy after the phosphate is exhausted (Anderson 1992). However with appropriate management former phosphate mines can also be successfully rehabilitated (Yang *et al* 2014). So although resources are currently abundant, the environmental considerations, ultimately finite supply, and essential role of phosphorus in food production nessecitates that any decision to direct significant supply to new purposes, should give careful consideration to the long term opportunity costs vs benefits. Such an analysis is beyond the scope of this study, here the relatively modest goal of utilising N&P OMF to achieve 1 climate stabilization 'wedge' (Pacala and Socolow 2004) is modelled. This involves a linear increase to 1 Pg C yr^{-1} CDR over the next 50 years. The baseline model result is consistant with published estimates of a 50%–100% increase in phsosphate mining by 2050 relative to 2009 levels (Cordell *et al* 2009). The current analysis shows that the impact of OMF on global phosphate resources would be minimal for a 1 wedge approach (figure 3(*b*)). The increase in mining effort required is more significant, with an increase over the baseline scenario by 2065 slightly greater than current levels of extraction.

Current world phosphate rock mining of 220 Tg PR yr^{-1} is equivalent to around 28.8 Tg yr^{-1} P, which could sequester (if used in OMF) 0.94 Pg C yr^{-1} assuming 80% efficiency. Also required would be 14.9 Tmol N which would represent greater than doubling of current nitrogen production (table 1). Current nitrogen production accounts for ∽1.2% of global energy demand (IFA 2014), although it is possible to manufacture ammonia with renewable energy using

water as the hydrogen feedstock, a process which may become economically viable in the future (Du *et al* 2015). For a negative emissions technology to make a significant difference relative to anthropogenic output of CO$_2$ it is reasonable to expect operations on a physical scale commensurate with technologies creating the emissions. Present day coal mining alone is responsible for the extraction of 7.2 Pg coal yr^{-1} (World Coal Association, www.worldcoal.org) and around 40% of anthropogenic CO$_2$ emissions (IEA 2014). Therefore sequestering 25% of global coal emissions with N&P OMF would require 3% of physical coal mining activity.

Ultimately the maximum capacity of OMF would be set by the willingness to employ phosphate resources for ocean fertilization. This would likely be a controversial debate, numerous authors have already expressed concerns over future phosphate scarcity e.g. (Cordell *et al* 2009), as well as concern that control of the majority of phosphate resources rest with just a few countries. Jones and Young (1997) speculated that OMF would lead to increased fisheries production as a flow-on effect of enhancing primary productivity, potentially retaining some of the food production potential of the phosphate. Attempting to offset the entirety of anthropogenic emissions would require an approximate doubling of primary productivity in the ocean and around 10 times the current rate of phosphate mining, using 0.7% of known resources per year, a proposition unlikely to be acceptable to global society. Environmental considerations may also limit; the intensity, CDR extent, and appropriate regions of OMF. There are numerous potential environmental risks associated with ocean fertilization (Fuhrman and Capone 1991, Glibert *et al* 2008, NAS 2015, Williamson *et al* 2012), and the level of risk can be reasonably expected to increase with the scale of fertilization (SCBD 2009).

One issue is consumption of oxygen by OMF. According to Jones (2014) one wedge (25 P g C) of OMF would in total consume 23.75 Pg O. Matear and Elliott (2004) simulated 1.2 Pg C yr^{-1} OMF for 80 years (96 Pg C) between latitudes 18–50 S, with the result that the global volume of anoxic water increased 17.5%, by thickening and extending existing anoxic regions mainly in the central Pacific and Indian Oceans. They also considered the effect on ocean acidity and found that the immediate effect depended on the form of nitrogen used, as did Lawrence (2014) who found the effect could be positive or negative. Matear and Elliot (2004) described how differential depths in the dissolution of carbonate and the remineralization of organic carbon could amplify the efficiency loss due to enhanced production of calcifying organisms to be up to 25%. Neither study estimated the net benefit to ocean acidity due to the associated atmospheric carbon reduction, which has relevance to biogeochemical cycles (Matear and Lenton 2014). The efficiency estimates used herein

Figure 3. Model predictions of phosphate rock production (*a*) and remaining resources (*b*) for the next 50 years. Baseline scenario assumes that per capita phosphate rock demand stabilizes at the predicted figure for 2018 and thereafter demand follows predicted population increase. Scenario N&P OMF represents the additional demand incurred by utilizing nitrogen and phosphorus ocean fertilization to provide one 'climate stabilization wedge' (Pacala and Socolow 2004) i.e. linearly increasing sequestration from 0 in 2015 to 1 Pg C yr^{-1} in 2065.

are largely based on rates and proportions in the current ocean. Fertilization would represent a perturbation which, if performed on a large scale, has the potential to alter physical and biogeochemical processes, including those on which these calculations are based, e.g. Bopp *et al* (2013). The extent of OMF should it ever be undertaken, will ultimately require comprehensive evaluation of risks verses benefits, the outcome of which may constrain OMF to less than the maximum technical potential (Matear and Elliott 2004).

4. Conclusion

Sufficient P* exists in the surface ocean to sequester up to 3.6 Pg C by ocean nitrogen fertilization as a 'once off' activity. It would not be practical to fertilize the entire surface ocean; however depth integrated P* is concentrated in several regions, such that 2 Pg C sequestration could be achieved by fertilization of 16.5% of the ocean surface area, representing a very large industrialization of the ocean commons. The ongoing maximum sequestration potential of nitrogen fertilization is estimated to be 0.7 ± 0.4 Pg C yr^{-1}, and is the least certain estimate. To achieve additional ongoing carbon removal, OMF would need to include mined phosphate, a non-renewable but abundant resource. The potential capacity for OMF to provide negative emissions depends on society's willingness to utilize phosphate resources for the purpose, and the associated political and environmental implications. Offsetting the entirety of anthropogenic emissions with OMF would place an unacceptably high demand on phosphate rock. However a doubling of current phosphate mining would allow an additional 0.9 Pg C yr^{-1} sequestration, and consume 0.07% yr^{-1} of known phosphate resources. Therefore it is technically plausible that OMF could contribute up to 1.5 climate stabilization wedges, equal to 1.5 Pg C yr^{-1} of anthropogenic emissions in 50 years time. These findings support the concept that there is unlikely to

be a single technological solution to greenhouse gas mitigation. Effective action is likely to require a multifaceted approach, combining a reduction in emissions with further focused research into negative emissions technologies.

Acknowledgments

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