Supporting Information for

Global negative emissions capacity of ocean macronutrient fertilization

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Contents of this file

Text S1
Figures S1 to S3

Introduction

The supporting textual information contains an extension of the methodology considering several factors, which could potentially affect the efficiency of the model, but were not incorporated, and the reasons for exclusion. The first and second supporting figures provide a description of the distribution of $P^*$ and $S^*$ in the global ocean, which goes beyond the mixed layer depth integrated values presented in the main text. These are in the form of a set of discrete horizontal global depth planes. Figure S3 reveals the seasonal component to the GCM modeled $P^*$ flux in the form of climatological output by month.

Text S1: Further efficiency considerations not incorporated into the modeling

1. Cyanobacteria

Large scale, nitrogen fertilization, such as postulated under a maximum capacity scenario is likely to reduce the global contribution of nitrogen fixation by cyanobacteria. Phosphorus availability is believed to be important for nitrogen fixation (Sanudo-Wilhelmy et al., 2001). A reduction in N fixation is an OMF
efficiency loss not quantified by Lawrence (2014) in his analysis. However a reduction in ‘naturally’ fixed nitrogen does not impact the capacity. A reduction in nitrogen fixation could be overcome by supplying more reactive nitrogen, which would affect the cost, and to a degree the CO₂ offset for nitrogen manufacture and distribution.

2. Nutrient Stealing

When productivity in the ocean is increased, the resulting biological processes will consume micro and macro nutrients in addition to the proximate limiting nutrient/s added. As has been pointed out in the case of OIF, exporting nutrients in one location may reduce production elsewhere, creating an efficiency loss for sequestration (Dutkiewicz et al., 2005; Gnanadesikan et al., 2003; Sarmiento and Orr, 1991). Numerous micronutrients are also utilized by phytoplankton so it is conceivable that enhancing their uptake by OMF may cause them to become limiting either at the fertilization site or elsewhere downstream. Culture bottle studies in various oceans have demonstrated significant increases to primary production by addition of macronutrient alone, providing evidence that micronutrients (with the exception of iron) are generally present in sufficient quantities to support additional primary production (DiTullio et al., 1993; Menzel and Ryther, 1961; Thomas, 1969; 1970; Wu et al., 2003). It is beyond the scope of this study to consider micronutrient availability further, except to note that micronutrients could be included, as is common practice in agriculture, thus the issue does not directly impact the calculation of capacity. Potential implications of OMF on micronutrient availability, and the inverse is a topic requiring further research. Should fertilization be conducted with N but not P, there is the
potential to cause reduced production elsewhere. However since N rather than P is limiting in most of the LNLC surface ocean, the effect on capacity is expected to be small. Nutrient stealing by OMF could be considered in greater detail by making use of global biogeochemical modeling techniques.

3. Nitrogen vs Phosphorus limitation

Modeling results by Tyrrell (1999) suggest that surface waters are more deficient in nitrate than phosphate in the steady state, but with external phosphate inputs controlling longer-term (1000s of years) primary production in the global ocean. Lenton and Watson (2000) suggest that nitrogen fixation tends to maintain nitrate close to Redfield ratio with phosphate, while denitrification tends to keep nitrate as the proximate limiting nutrient. Thus over very long timescales fertilization with nitrogen alone may ‘leak’ due to the readjustment of biologically mediated nitrogen fluxes. The timescales involved are large compared with a 100 year time horizon typically applied to sequestration calculations (see discussion in Harrison (2013)), thus for this study only the current ocean nutrient limitations were considered.

4. Stoichiometry

The Redfield ratio (Redfield, 1958) of P:N:C has been used throughout for stoichiometric calculations. Of course the Redfield ratio is known to vary regionally, and amongst phytoplankton types (Geider and La Roche, 2002). However for global calculations such as those in the current study the Redfield ratio provides a robust average. It has been observed that during export of organic material, nitrogen and phosphorus are remineralized more rapidly than
the associated carbon. Dependent on the location where OMF was employed portions of the receiving water mass may return to the surface in considerably less than 100 years, as been observed in modeling studies for OIF (Aumont and Bopp, 2006; Robinson et al., 2014; Sarmiento and Orr, 1991; Zeebe and Archer, 2005). However unlike OIF the associated ‘new’ macronutrients are also returned to the surface, possibly in greater proportions than the associated carbon, thus potentially leading to increased sequestration. As the models used in the current study do not evolve with time this proposition has not been evaluated.

Calculations of P* used NO$_3^-$ and PO$_4^{3-}$ data from the world ocean atlas, and thus do not include particulate N & P, other dissolved inorganic forms of N, or organic dissolved N & P. In the deep ocean the vast majority of reactive N is in the form of nitrate (Tyrrell and Law, 1997). In the surface ocean there is greater potential for an affect on the calculation of P*. To the first order, remineralised N&P as well as organic forms of N&P can be expected to be on average in the Redfield ratio, and thus not contribute to P*. This is supported by the observation in this study that the ratio of P/P* is the same for the deep ocean as the surface ocean, therefore while it is acknowledged that there may be some error due to the reliance on nitrate and phosphate measurements it is assumed to be negligible within the context of the broad calculations considered here.
5. References

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**Figure S1.** Distribution of $P^*$ ($= \text{PO}_4^{3-} - \text{NO}_3^-$/16, moles) in the global ocean at 12 horizontal depth planes. Calculated using data from the world ocean atlas 2013 (Garcia et al., 2014).

**Figure S2.** Distribution of $\text{Si}^*$ ($= \text{SiO}_2 - 4\text{PO}_4^{3-}$, moles) in the global ocean at 12 horizontal depth planes. $\text{Si}^*$ represents the ratio above which diatom growth is unimpeded by silica limitation. Calculated using data from the world ocean atlas 2013 (Garcia et al., 2014).
Figure S3. Monthly climatology of the vertical flux of $P^*$ ($= \text{PO}_4^{3-} - \text{NO}_3^- / 16$, moles) through the base of the mixed layer as calculated using output from the world ocean atlas and ECCO2 global circulation model. Seasonal variation in the vertical flux of $P^*$ is apparent in many of the major upwelling zones. Positive is upwards.