Impacts of light shading and nutrient enrichment geo-engineering approaches on the productivity of a stratified, oligotrophic ocean ecosystem

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Geo-engineering proposals to mitigate global warming have focused either on methods of carbon dioxide removal, particularly nutrient fertilization of plant growth, or on cooling the Earth’s surface by reducing incoming solar radiation (shading). Marine phytoplankton contribute half the Earth’s biological carbon fixation and carbon export in the ocean is modulated by the actions of microbes and grazing communities in recycling nutrients. Both nutrients and light are essential for photosynthesis, so understanding the relative influence of both these geo-engineering approaches on ocean ecosystem production and processes is critical to the evaluation of their effectiveness. In this paper, we investigate the relationship between light and nutrient availability on productivity in a stratified, oligotrophic subtropical ocean ecosystem using a one-dimensional water column model coupled to a multi-plankton ecosystem model, with the goal of elucidating potential impacts of these geo-engineering approaches on ecosystem production. We find that solar shading approaches can redistribute productivity in the water column but do not change total production. Macronutrient enrichment is able to enhance the export of carbon, although heterotrophic recycling reduces the efficiency of carbon export substantially over time. Our results highlight the requirement for a fuller consideration of marine ecosystem interactions and feedbacks, beyond simply the stimulation of surface blooms, in the evaluation of putative geo-engineering approaches.

1. Introduction

The urgent need to rectify the effects of climate change from enhanced atmospheric CO₂ concentrations has led to the proposal of geo-engineering ‘solutions’ aimed at mitigating global warming through manipulation of the natural environment. Approaches proposed to date have focused on methods of carbon dioxide removal (CDR), particularly (although not exclusively) through nutrient fertilization of plant growth, or on cooling the Earth’s surface by reducing incoming solar radiation (shading), with the different approaches considered in isolation from each other.

Marine phytoplankton contribute half the Earth’s biological carbon fixation [1] with their photosynthesis directly controlled by the availability of both nutrients and light. Phytoplankton exist as the basis of all marine food webs with photosynthetic production driving marine ecosystem production. Knowledge of the dynamic response of ocean ecosystems to perturbations in light and nutrient controls is immature when compared with our comprehension of physical ocean dynamics. Therefore, understanding the relative influence of different geo-engineering approaches on the processes driving ocean ecosystem
production represents a critical knowledge gap and impediment to evaluation of their effectiveness.

The prospects for fertilization of low-productivity waters in the ocean to increase their productivity have been the subject of intense scientific interest and commercial speculation [2,3]. Such approaches belong to the CDR category of putative climate geo-engineering solutions [4]. Most of the research to date has focused on fertilization of regions deplete in the micronutrient iron (termed high nutrient, low chlorophyll, HLNC, e.g. Southern Ocean, subpolar North Pacific, equatorial Pacific [5]), with only limited modelling [6] and field experiments [3,7–9] into fertilization of the macronutrient-limited regions (termed low nutrient, low chlorophyll, LNLC, [5]), such as the subtropical oceanic gyres that dominate all the non-polar ocean basins. Macronutrient fertilization has nonetheless been the subject of academic discussion [10,11] associated with commercial interest [12,13], highlighting the importance of research into these regions.

The subtropical gyres have very low net primary production per unit area owing to their characteristic paucity of macronutrients (i.e. are oligotrophic [14–16]), a consequence of their stable upper water column being permanently separated from deeper waters by strong, thermal stratification. Yet, they are still major contributors to biological carbon cycling in the ocean [17,18] owing to their vast area, approximately 70% of the ocean’s surface. It is predicted that the productivity of these regions will decline further as climate warming increases and the thermal stability of the upper water column strengthens, reducing the already limited flux of nutrients from below [19]. Recent observations suggest that such impacts may already be detectable, with the area of lowest productivity waters increasing [20]. Such a decline in productivity would be expected to result in a decrease in the size distribution of phytoplankton cells [21]. However, the ability of marine ecosystems to adapt to such changes is largely unknown and the available evidence for any long-term change in phytoplankton production is inconsistent [22,23], emphasizing the need for greater process understanding of marine ecosystem dynamics.

While the subtropical gyres are normally light replete all year round, a second category of geo-engineering approaches, solar radiation management (SRM), could change this through proposals to shade the Earth’s surface as a means of reducing global temperatures [4,24]. Although phytoplankton are able to acclimate to variations in light levels by adjusting their pigment concentrations, reductions in irradiance will directly reduce photosynthetic rates. The implications of such solar shading for ocean productivity and carbon cycling have, so far, not been explicitly investigated [25].

While photosynthesis drives productivity in the ocean, it is the balance between gross primary production (GPP) and community respiration (R) that determines the trophic status of an oceanic ecosystem, and consequently its biological potential as a source or sink of atmospheric CO₂ [26]. The ratio of GPP : R is termed as the metabolic balance and is representative of the net community production (NCP, defined as GPP – R). A surface GPP : R in equilibrium indicates that all the organic matter produced is locally respired with no export to the interior ocean and no potential for alteration of the net sea–air CO₂ flux. Conversely, a GPP : R > 1, termed net autotrophic, would imply a net export of organic carbon to deeper layers, depleting CO₂ in surface waters, perturbing the equilibrium with the atmosphere and leading to net influx of CO₂ to the surface ocean.

In this paper, we investigate the process relationship between light, nutrient availability and planktonic ecosystem productivity in the subtropical gyres using a one-dimensional coupled physical ecosystem model, with the goal of elucidating the potential impacts of geo-engineering approaches on ecosystem dynamics in these largest of ocean biomes. We do not undertake an assessment of geo-engineering approaches per se, as this is has been published elsewhere [4,27–29]. Neither do we consider the global carbon sequestration or cooling potential of these approaches nor feedbacks of geo-engineering approaches on ocean physics as these would require an alternative modelling framework (fully coupled, three-dimensional ocean–atmosphere–ecosystem model, e.g. [30,31]). Rather, we exploit the advanced ecological dynamics of a well-tested multi-plankton ecosystem model constrained by a one-dimensional water column with realistic physics and seasonal forcing to address the question: how do light shading and nutrient enrichment at the ocean’s surface influence ecosystem productivity, hence the biological contribution to atmospheric CO₂ uptake, in a nutrient-limited, stratified ocean?

2. Choice of study site

As described above, the subtropical gyres represent the largest areas of nutrient limitation in the ocean. As our focus is on the response of phytoplankton to external perturbation through geo-engineering, we require a location with relatively simple physics but that exemplifies the hydrodynamic requirements for nutrient fertilization to be effective, namely a well-mixed surface layer overlying a strong density gradient (pycnocline) which restricts the flux of nutrients and inorganic carbon from the ocean interior to surface waters and through which exported organic carbon is removed to the deep ocean out of contact with the atmosphere. Such stratification occurs seasonally in mid-high latitudes but is terminated through the subsequent deep winter mixing that also returns remineralized carbon from the deep ocean to surface waters where they can again equilibrate with the atmosphere. The permanently stratified subtropical gyres, on the other hand, are not limited in this way, so theoretically provide the potential to sustain export of carbon over longer than annual periods. Thus, they provide an ideal environment to test the ecosystem effects of nutrient enrichment experiments. As such, we have chosen a typical subtropical gyre region for our study site.

With regard to their biological carbon dynamics, the subtropical gyres have generally been thought of as being in trophic balance or weakly net heterotrophic (GPP : R < 1), explained by factors such as lateral advection and slow remineralization of refractory organic carbon over interannual timescales [32,33]. However, Emerson et al. [34] measured significant rates of carbon export in the North Pacific subtropical gyre, implying net autotrophy. Gist et al. [35] showed the North Atlantic gyre to be weakly net heterotrophic, with net heterotrophy decreasing towards the centre of the gyre and suggested lateral advection from the gyre margins as a mechanism to explain this net heterotrophy. By contrast, these authors found the South Atlantic gyre to be in trophic balance, at least between the spring and autumn seasons. One-dimensional modelling studies, by design, do not include lateral advection, so mass-balance in the model will result in trophic balance of the ecosystem. For this reason, we have chosen to force the model with surface data and seasonal
profiles for the South Atlantic subtropical gyre region. However, the model captures the major processes relevant to biological carbon cycling that hold for any of the major subtropical gyres, hence the results should be considered to have wider application to subtropical gyre ecosystems in general.

3. Model description and set-up

3.1. Choice of ecosystem model

We have chosen to use European Regional Sea Ecosystem Model (ERSEM [36,37]) for this study as it presents a relatively complex representation of the plankton community structure which we consider to be crucial for a realistic assessment of the ecosystem production/respiration budget, hence CO2 dynamics. Indeed, ERSEM has been used substantially to address a range of questions in marine carbon cycle and biogeochemical research in a range of regions, such as the NW European Shelf, the Arabian Sea and the Sargasso Sea of the subtropical North Atlantic gyre, e.g. [37–45]. In all of these papers, model simulations were compared with SeaSonde profiles for the South Atlantic subtropical gyre region. Howev-
er, the model captures the major processes relevant to any of the major subtropical gyres, hence the results should be considered to have wider application to subtropical gyre ecosystems in general.

3.2. Biogeochemical model description

ERSEM is a biomass and functional group-based biogeochemical/ecosystem model describing nutrient and carbon cycling within the lower trophic levels of the marine ecosystem (up to mesozooplankton). Model state variables include living organisms, dissolved nutrients, organic detritus, oxygen and carbon dioxide. Model living organisms are divided into three functional groups describing the planktonic trophic chain: primary producers, consumers and decomposers. Primary producers and consumers are further subdivided into size-based functional types (four primary producers and three consumers), while decomposers are modelled through only one functional type. More specifically, the phytoplankton community consists of picophytoplankton, autotrophic nanoflagellates, dinoflagellates and diatoms. The zooplankton community includes mesozooplankton, microzooplankton and heterotrophic nanoflagellates. Decomposers are modelled by one type of heterotrophic bacteria. Functional types belonging to the same group share common process descriptions but different parameterizations. General parametrizations used in ERSEM are listed in [37] with the bacterial submodel described in [48].

A key feature of ERSEM is the decoupling between carbon and nutrient dynamics allowing the simulation of variable stoichiometry within the modelled organisms [49]. Chlorophyll is also treated as an independent state variable following the formulation proposed by Geider et al. [50]. Consequently, each plankton functional type is modelled via up to five state variables describing each cellular component (C, N, P, Si and Chl-a).

Photosynthesis is dependent on cell internal nutrient quotas rather than directly on external nutrient availability. Active dissolved organic carbon (DOC) exudation is accounted in order to re-equilibrate cells’ internal stoichiometry. This mechanism allows for a more accurate description of the nutrient limitation also ensuring an adequate production of DOC to fuel the bacterial pool. The ‘classic’ Redfield ratio of 106C:16N : 1P [51] is not used to constrain the cellular stoichiometry but is applied to discriminate between nutrient-replete and nutrient-stressed conditions (the actual nutrient to carbon ratio is free to vary around the Redfield ratio).

Dissolved organic matter (DOM) is produced by different processes involving phytoplankton, bacteria and zooplankton while its consumption is exclusively regulated by bacterial uptake. DOM is subdivided into labile and semilabile components, in order to provide a representation of the range of organic compounds present in marine DOM and their different degrees of degradability. We have used the bacterial submodel proposed by Polimene et al. [48], as previously applied for the Sargasso Sea [44]. This submodel implies a semilabile carbon release by bacteria in order to re-equilibrate the internal stoichiometry in case of nutrient limitation.

Particulate organic matter is assumed to be produced by phytoplankton and zooplankton and is divided into three size-based categories (depending on the producing organism), corresponding to different sedimentation rates.

3.3. Model set-up

For this study, we used the previously published ERSEM-GOTM system [37,39,44]. The General Ocean Turbulence Model (GOTM [52]) is a one-dimensional water column model which dynamically simulates the evolution of temperature, density and vertical mixing. Turbulent kinetic energy, shear production, buoyancy and eddy diffusivity were modelled as described in Allen et al. [39].

The model was set up to resolve the top 250 m of a water column. This is well below the depth of the euphotic zone and upper pycnocline so is adequate to incorporate the dynamics of our simulation. The model was located in the middle of the South Atlantic gyre (18.53°S, 25.1°W), forced by local environmental variables (ECMWF-ERA 40 reanalysis data [53]) with assimilation of local temperature profile data from the Smith & Haines reanalysis [54] to realistically reproduce seasonality of the vertical structure.

Because the focus of this study was the response of the planktonic ecosystem, we constrain the impact of the geo-engineering perturbations on the physical ocean structure through the assimilation of local temperature and salinity profiles as described above, thereby only considering the direct response of the biological components of the ecosystem. Therefore, the impact of surface light shading on the vertical structure of the model was negligible, with average annual reduction of −0.6 K in the first 80 m and 0.01 K in deeper layers (80–150 m). This was insufficient to perturb the thermal stratification of the water column, characterized by a greater than 3 K difference between the surface layer and deeper waters.

Carbon export was calculated from the loss of particulate organic carbon through the lower boundary of the model (250 m). A simple remineralization closure was applied at this lower boundary to re-ject the sinking detritus into the water column as dissolved inorganic nutrients at a fixed rate of 50% per day. Note that this re-injection is only used to provide closure on the inorganic nutrient inventory of the lower water column and has no detectable impact on
the nutrient budget of the upper 150 m of the water column, hence on primary production. Previous use of this same scheme and rate by Polimene et al. [44] were shown to realistically reproduce the vertical profile of PO₄ at BATS (where P is the limiting nutrient).

The model was run for the period 1995–2005, with the first 2 years (spin-up) excluded from the analyses of the simulations. The 2 years of spin-up allow the model to reproduce a nutrient vertical structure (with a nutricline at around 100 m depth) starting from a vertically constant initial condition (0.02 and 0.2 mmol m⁻³ for phosphate and nitrate, respectively).

Simulations of geo-engineering experiments were compared with a control run. In the light-shading experiments, surface irradiance was reduced by between 10 and 90% of ambient solar insolation for 1 year from June 2000 to June 2001. For the nutrient fertilization experiment, P and N (0.16 and 2.4 mol m⁻², respectively) were added to the ocean surface at the beginning of June 2000. These concentrations were based on the quantity of anhydrous monosodium phosphate added during the 2004 UK Phosphate and Iron Enrichment Experiment (FeeP [55]) in the subtropical gyre of the North Atlantic (approx. 20 tonnes). The concentration of PO₄³⁻ in our study approximates this mass added to approximately 1 km² of the surface ocean and is equivalent to increasing the mixed layer nutrient inventory by a factor of 10⁸. The concentration of NO₃⁻ was calculated from that of PO₄³⁻ at a ratio slightly less than Redfield (15:1) to maintain an excess of P, hence N limitation of the system.

4. Results

Figure 1 shows the chlorophyll and thermal structure of the unperturbed model run. Comparison with satellite ocean colour data (SeaWiFS) showed the model to reproduce the seasonal phase and amplitude of surface chlorophyll-a concentration well ($r^2 = 0.819$, $p = 0.002$), although with a small negative bias relative to the satellite data of approximately 0.02 mg m⁻² that is within the expected range of uncertainty. Metabolic balance of the water column was in equilibrium (GPP = R) over the annual cycle, consistent with evidence for the South Atlantic gyre [35], with no export of carbon from the surface to deeper waters (i.e. below 250 m) and, by implication, no metabolic contribution to the net exchange of CO₂ between the water column and the atmosphere. Pico-sized phytoplankton dominated the surface autotrophic community (data not shown), with primary production being supported by nutrients regenerated via the ‘microbial loop’. Higher levels of primary production were seen deeper in the water column, within a deep chlorophyll maximum (DCM) layer. The DCM was located in the upper thermocline at the top of the nutricline. Primary production in the DCM was light limited and in equilibrium with community respiration, implying that all the organic matter produced was respired locally. Pico-sized phytoplankton again dominated the autotrophic community, but with a greater proportion of the total biomass contributed by larger phytoplankton size classes. This was also reflected by the higher chlorophyll concentration (consistent with global-scale pigment analyses; [56–58]).

In order to assess the effect of light shading and nutrient fertilization on the metabolic balance, the water column was divided into three idealized regions based on chlorophyll structure. The first (zone X) covers the upper 80 m and is a nutrient-limited zone characterized by low chlorophyll concentration (less than 0.1 mg Chl m⁻²), in contact with the atmosphere at its upper surface, consistent with the surface mixed layer (SML). The second zone (zone Y) spans from 80 to 150 m and includes the DCM, is light limited and characterized by (relatively) high chlorophyll concentration (up to 0.7 mg m⁻²). It is only seasonally (and weakly) connected to the surface by vertical mixing (figure 1b). The third zone (zone Z) is almost aphotic and permanently below the DCM, with no direct connection with the surface. Conceptual diagrams describing the simulated relative and absolute carbon exchanges between the three zones under unperturbed conditions, during solar shading and following nutrient fertilization, are provided in figure 2. The values reported in the figure refer to values averaged over the 12 month period from June 2000 to June 2001.

Reducing surface irradiance by 90% reduced GPP in the DCM (zone Y), however, depth-integrated GPP was maintained throughout the water column, with the maxima of production and biomass shoaling into the SML (zone Z; figure 3). The increase in GPP in zone X was balanced by a concomitant increase in community respiration, leading to only 2% of GPP being exported to zone Y and a net zero export of GPP to zone Z (figure 2). No changes in the phyto- or zooplankton community composition were simulated by the model during this experiment. Furthermore, after the light was fully restored to ambient, GPP in the surface bloom was sustained briefly, relaxing within one month to preperturbation conditions as the light flux penetrated deeper, reviving production in the DCM. Reducing surface irradiance by 80, 50 or 10% produced
5. Discussion

In this paper, we have considered the potential impact of proposed geo-engineering approaches on the efficacy of the ocean’s biological carbon pump at the ecosystem process scale. These approaches propose to either limit light availability or to enhance nutrient availability, both of which are essential for phytoplankton growth. The focus of the study was on how manipulations of nutrient supply and irradiance can influence the metabolic balance of the water column, hence atmospheric CO$_2$ uptake, in an oligotrophic, stratified ocean. To this end, we ran simulations using a complex...

proportionally lesser responses. Varying the period of shading from a few weeks to several years and implementing it for different seasons made little difference to the experimental outcomes, with a full return to preperturbation conditions following the restoration of full light fluxes.

Nutrient addition stimulated high production at the surface and deeper as nutrients were mixed down; see figures 4 and 5a. Surface chlorophyll concentrations exceeded 10 mg m$^{-2}$ and GPP rates exceeded 13 g C m$^{-2}$ d$^{-1}$, indicating an intense phytoplankton bloom. Export of carbon below the bottom boundary of the model (zone Z) peaked initially (up to 0.45 g C m$^{-2}$ d$^{-1}$; figure 5b), although this rate of export dropped off rapidly. Heterotrophic activity (bacteria and zooplankton) continued to recycle some of the added nutrients within the SML for several months after the fertilization, sustaining high surface production for a prolonged period (up to nine months), after which the system returned to the unperturbed condition. Significantly, during the first 12 months after fertilization, the simulated metabolic balance was altered with GPP exceeding community respiration (GPP : R > 1) in the surface layer (zone X). This excess of production led to an increase in biomass and a shift in the planktonic community towards larger phyto- and zoo-plankton (figure 4c,d), producing larger, faster sinking detritus. Not all of this detritus was respired in the euphotic zone (zones X and Y), resulting in an overall net export below the deepest layer (zone Z) of approximately 35% of NCP but only approximately 3% of GPP during the year after the nutrient addition. Increased plankton biomass in zone X accounted for the remaining 65% of NCP. Both the total plankton biomass and the fraction associated with larger size classes remained elevated above preperturbation conditions for the remaining years of the simulation.

A quantitative comparison between the simulated solar shading and nutrient fertilization experiment is shown by the temporal evolution of the difference between GPP and R (figure 6). During the solar shading, GPP–R remained close to 0 (GPP : R ∼ 1), similar to the unperturbed system. After fertilization, the GPP reached an excess of 3000 mg C m$^{-2}$ d$^{-1}$ over R and was only partially balanced by the subsequent excess of respiration over GPP, resulting from the decline of the bloom.

Figure 2. Comparison of (a) relative proportion (%) and (b) absolute values (g C m$^{-2}$ d$^{-1}$) of gross primary production (GPP), either respired (R) or transported through the different water column compartments (zones X, Y and Z) under unperturbed conditions (left), 90% solar shading (middle) and nutrient fertilization (right) experiments, calculated for the 12-month period following the initiation of each experiment (June 2000–June 2001).

Figure 3. Monthly mean vertical profiles from 0 to 250 m showing (a) chlorophyll concentration (mg Chl m$^{-2}$) and (b) phytoplankton biomass (mg C m$^{-2}$) for model simulations of a 90% reduction in surface irradiance during June 2000–June 2001.
Our results suggest firstly that solar shading is unlikely to have a negative impact on the productivity of subtropical gyre ecosystems. The range of solar shading scenarios we ran showed that a 90% reduction in surface irradiance was required to have any notable effect and this increased surface primary production. This counterintuitive result can be

Figure 4. Monthly mean vertical profiles from 0 to 250 m showing (a) chlorophyll concentration (mg Chl m\(^{-3}\)), (b) phytoplankton biomass (mg C m\(^{-3}\)), (c) large phytoplankton biomass (mg C m\(^{-3}\)) and (d) mesozooplankton biomass (mg C m\(^{-3}\)) for model simulation of nutrient enrichment at the surface during June 2000.

Figure 5. Time series from the model simulation of nutrient enrichment showing (a) GPP within the surface zone X and (b) export of carbon through the bottom boundary layer of the model (250 m). Both plots show mean daily rates (mg C m\(^{-2}\) d\(^{-1}\)) for each month of the simulation.

Figure 6. Net community production (NCP = GPP − respiration) in surface zone X (mg C m\(^{-2}\) d\(^{-1}\)), comparing results from the model simulations of a 90% reduction in surface irradiance (solid line) and nutrient fertilization (dashed line). The period of shading (June 2000–June 2001) is indicated by a dot–dash line. Nutrient enrichment occurred during June 2000.

(multi-plankton) ecosystem water column model of a permanently stratified oligotrophic gyre in metabolic balance (GPP = R, geographically representative of the South Atlantic subtropical gyre ecosystem).

Our results suggest firstly that solar shading is unlikely to have a negative impact on the productivity of subtropical gyre ecosystems. The range of solar shading scenarios we ran showed that a 90% reduction in surface irradiance was required to have any notable effect and this increased surface primary production. This counterintuitive result can be
explained by a feedback process described by Taylor et al. [59]. Using a one-dimensional time-dependent advection–diffusion model, these authors showed that under enhanced surface irradiance, phytoplankton growth was enhanced in the DCM, reducing the flux of nutrients from below the nutricline to the surface waters, thereby decreasing surface productivity and biomass. Conversely, a reduction in surface irradiance reduced phytoplankton growth in the DCM, enhancing the flux of nutrients from below the nutricline to surface waters, thereby stimulating productivity and increasing biomass in the SML. While not affecting the overall productivity of the system, this redistribution of productivity throughout the water column could have other knock-on effects for the ecosystem, e.g. through enhanced plankton availability to fish in the upper layers of the ocean. Such effects are outside of the scope of this paper to evaluate, suggesting a need for further research into ecosystem responses to SRM approaches.

Following removal of the shading, the ecosystem returned to its former state relatively rapidly (less than one month), showing the effects of light shading on marine productivity to be fully reversible. The highest (90%) level of shading applied can occur naturally, through heavy cloud cover, and may be representative of the localized effects expected from a cloud albedo enhancement geo-engineering approach, e.g. [24]. At the lower level of 10% reduction in irradiance, closer to expected impacts of stratospheric aerosol injection [60], we detect no notable effect of light shading on productivity of the South Atlantic subtropical gyre.

A further consideration of this result is whether light shading may have a positive effect on atmospheric CO2 uptake. While the results of the light-shading simulations showed a redistribution of primary production in the water column, there was no net increase across zones X and Y and GPP continued to be balanced by an increase in community respiration, with no change in the phytoplankton community structure. Only 2% of the GPP was exported below the SML into the upper thermocline/DCM region and there was no increase in export of carbon to deeper waters. Carbon exported to the upper thermocline is only removed from atmospheric exchange over seasonal timescales, so would not constitute long-term sequestration.

On the other hand, this concentration of productivity in the SML should itself enhance the uptake efficiency of atmospheric CO2 by the bloom. This has been demonstrated through the study of Jin et al. [61], which simulated the influence of surface iron fertilization on the productivity of HNLC regions in the equatorial Pacific. They showed surface fertilization to give rise to far higher atmospheric uptake efficiencies than fertilization deeper in the water column. Additionally, they showed that increasing the light penetration depth by reducing the attenuation coefficient of phytoplankton strengthened primary production in the DCM and reduced the atmospheric uptake efficiency of CO2, a result that simulates the opposite extreme of the shading results shown here. Thus, they deduced that the distribution of productivity in the water column was important for determining the atmospheric uptake efficiency of phytoplankton blooms. Although air–sea gas exchange was not explicitly parametrized in this study, our results imply that the effect of light shading in concentrating productivity in the SML should increase the atmospheric uptake efficiency of CO2 by the ocean. Nonetheless, higher atmospheric uptake efficiency in the absence of carbon export will not increase CO2 sequestration.

The results of surface nutrient enrichment on NCP were much more pronounced. They showed a clear enhancement in GPP over R, a substantial shift in both phyto- and zooplankton community structure towards larger size classes and an export of carbon below the DCM into the aphotic zone. Indeed, larger organisms produce larger, fast-sinking detritus and are essential to mediate carbon export from the surface layer to the deep ocean [62]. This coupling between enhanced productivity following nutrient enrichment, increase in plankton size and enhanced export is in agreement with observations from open ocean iron fertilization experiments [5]. The role of grazers was also important in recycling nutrients within surface waters. This helped to sustain the bloom but additionally returned inorganic carbon to the surface, reducing its net export to depth. Thus, while the 35% export rate was a significant fraction of surface NCP, only 3% of the GPP was exported after 12 months. These rates are within the range of iron enrichment field experiments [63].

Although NCP returned to near-equilibrium conditions after 12 months, the longer term elevation of the plankton community biomass and their proportion associated with larger size fractions, for several years following enrichment, suggests that longer term responses of the ecosystem to nutrient enrichment also need to be considered. This requires a fuller evaluation of impacts to the oceanic nutrient inventory than can be evaluated within a one-dimensional modelling framework. The role of zooplankton migration in actively transporting carbon throughout the water column may also be significant [64] and is a current limitation of our model that requires further research.

In this study, we have undertaken an initial investigation into the response of ecosystem production in the oceans over annual timescales to proposed geo-engineering solutions, within the context of atmospheric carbon sequestration. Both scenarios investigated were short-term rather than long-term sustained perturbations (such as might be imposed in practice), so the consequences of such long-term interventions have not been estimated here. A full consideration of the impact of these approaches clearly needs to consider a wider range of processes and time frames. As well as perturbations to the light field and distribution of productivity in the ocean, solar shading would also cool the surface ocean increasing its solubility to CO2 and could lead to changes in convection, turbulent mixing and stratification. Wider perturbations to ocean ecosystems, including deoxygenation, acidification and impacts on commercially important fish stocks, also need to be considered. Future research should assess the biophysical implications of these wider scale issues more fully using coupled three-dimensional ocean–atmosphere–ecosystem general circulation models together with localized field experiments prior to any large-scale test of these approaches.

In conclusion, this study suggests that reduction in solar insolation from geo-engineering approaches is unlikely to have a direct adverse effect on productivity in the oligotrophic, permanently stratified subtropical ocean gyres. It may be able to enhance surface primary production at the expense of production deeper in the water column, with a greater proportion of the CO2 fixed drawn from atmospheric sources (i.e. greater atmospheric uptake efficiency). Nonetheless, it is not able to alter the GPP : R balance, so cannot be expected to enhance the mass of carbon exported to intermediate water depths. Conversely, surface ocean fertilization, as well as increasing the total primary production in the water
column, was able to increase GPP over community respiration (i.e., induce net autotrophy) by altering the plankton community in favour of larger groups of phyto- and zooplankton and enhancing carbon export to the ocean interior. Export rates were consistent with those from iron enrichment studies, however, consideration of heterotrophic processes gave the integrated net carbon export over the following months as 3% of GPP. Overall, our results highlight the requirement for a fuller evaluation of marine ecosystem interactions and feedbacks, that goes beyond simplistic consideration of the stimulation of surface blooms, in evaluating putative geo-engineering approaches. Uncertainties associated with the long-term fate of any carbon sequestered and the wider impacts of geo-engineering approaches on the oceanic environment also require further investigation.

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