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Ocean iron fertilization may amplify climate change pressures on marine animal biomass for limited climate benefit

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Abstract

Climate change scenarios suggest that large-scale carbon dioxide removal (CDR) will be required to maintain global warming below 2°C, leading to renewed attention on ocean iron fertilization (OIF). Previous OIF modelling has found that while carbon export increases, nutrient transport to lower latitude ecosystems declines, resulting in a modest impact on atmospheric CO_2. However, the interaction of these CDR responses with ongoing climate change is unknown. Here, we combine global ocean biogeochemistry and ecosystem models to show that, while stimulating carbon sequestration, OIF may amplify climate-induced declines in tropical ocean productivity and ecosystem biomass under a high-emission scenario, with very limited potential atmospheric CO_2 drawdown. The 'biogeochemical fingerprint' of climate change, that leads to depletion of upper ocean major nutrients due to upper ocean stratification, is reinforced by OIF due to greater major nutrient consumption. Our simulations show that reductions in upper trophic level animal biomass in tropical regions due to climate change would be exacerbated by OIF within ~20 years, especially in coastal exclusive economic zones (EEZs), with potential implications for fisheries that underpin the livelihoods and economies of coastal communities. Any fertilization-based CDR should therefore consider its interaction with ongoing climate-driven changes and the ensuing ecosystem impacts in national EEZs.

KEYWORDS

biogeochemical cycles, climate change, marine carbon dioxide removal, marine ecosystems, ocean iron fertilization, ocean net primary production

1 | INTRODUCTION

Human emissions of CO_2 and other greenhouse gases continue to rise, resulting in increasing atmospheric concentrations and greater global radiative forcing. In response, global average temperatures are rising and are on a trajectory to exceed 1.5°C likely by 2030 and 2°C by 2050 (IPCC, 2021). Due to ongoing warming, a host of climate change impacts are also becoming increasingly evident, including heat waves, droughts, wildfires, loss of ice mass and sea level rise (Bindoff et al., 2022; IPCC, 2021, 2022a, 2022b). The latest IPCC assessment states that the use of carbon dioxide removal (CDR) will be needed to remove hard to abate residual emissions in order to

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achieve net zero emissions (IPCC, 2022a). In response, planning, evaluation and research into both terrestrial and marine CDR strategies are growing rapidly (Boettcher et al., 2019; National Academies of Sciences, Engineering, and Medicine, 2022; Williamson et al., 2022).

Ocean iron fertilization (OIF) of the biological carbon pump, thought to have contributed to past variations in atmospheric CO_2 across glacial cycles (Martinez-Garcia et al., 2014), is receiving renewed interest as a possible method of stimulating the ocean anthropogenic carbon sink. The idea is that by alleviating Fe limitation of primary production in the Southern Ocean, equatorial Pacific, sub-Arctic Pacific and North Atlantic (de Baar et al., 2005), more of the upwelled major nutrients (nitrate and phosphate) can be used, with the associated CO_2 uptake and export to depth then strengthening the ocean atmospheric CO_2 sink (Martin, 1990; Martin et al., 1991). Numerous field experiments have confirmed the controlling role of Fe in these systems, but increased C removal has only been observed in a subset of experiments (Boyd et al., 2007; Yoon et al., 2018). While OIF may induce additional CO_2 uptake or reduce outgassing, it will also decrease stocks of major nutrients in the upper ocean that are subsequently transported to low latitudes and adjacent regions to support additional net primary production (NPP) therein (Fripiat et al., 2021; Hauck et al., 2016; Holzer & Primeau, 2013; Palter et al., 2010). This so-called 'nutrient robbing' side effect of OIF has been recognized since the earliest modelling studies of OIF (Aumont & Bopp, 2006; Oschlies et al., 2010; Sarmiento & Orr, 1991).

Climate change is already driving changes to ocean ecosystems due to reduced nutrient supplies to the surface mixed layer. Warming of the sea surface and alterations to stratification and mixing (Sallee et al., 2021) lead to reduced physical supply of major nutrients (Bindoff et al., 2022; Kwiatkowski et al., 2020). Along with shifting isotherms, these ongoing changes are modifying marine ecosystem dynamics (Bindoff et al., 2022; Polovina et al., 2008). Looking to the future, there is substantial uncertainty around the directional change in NPP (Tagliabue et al., 2021), but there is a greater consensus that stocks of major nutrients in the upper ocean will decline due to increased stratification (Bindoff et al., 2022; Kwiatkowski et al., 2020). These impacts affect phytoplankton biomass (Bopp et al., 2022) and are amplified for upper trophic levels that respond to both warming and changing NPP, with projected declines in marine biomass expected in the low latitudes alongside increases in the Southern Ocean and Arctic (Lotze et al., 2019; Tittensor et al., 2021).

Previous modelling efforts to estimate the impacts of OIF only accounted for atmospheric CO_2 changes due to anthropogenic activity in a present-day climate, finding that OIF contributed only modestly as a CDR effort (Aumont & Bopp, 2006; Hauck et al., 2016; Oschlies et al., 2010). While there have been efforts to look at simplified parameterizations of OIF and climate change in earth system models of intermediate complexity (Keller et al., 2014), we lack an assessment of how OIF interacts with changes in climate in a state-of-the-art ocean biogeochemical models used for climate change assessments, as well as the implications for marine ecosystems. Given that CDR is expected to be deployed in the context of a changing climate, this represents an important knowledge gap, made more critical as impacts on upper trophic levels and fisheries are presently unknown. Lastly, there is a need to update the state of knowledge regarding the impact of OIF on the C cycle using the latest generation of ocean biogeochemical models. In this work, we modelled OIF scenarios with and without concurrent climate change forcing using state-of-the-art global ocean physics, biogeochemistry and ecosystem modelling to investigate interactive impacts of OIF on global NPP, C export and major nutrients, as well as on global- and exclusive economic zone (EEZ)-specific animal biomass (see Section 2). In particular, we assessed the cumulative impact (termed 'additionality') of OIF in a changing climate by comparing simulations that combine OIF and climate change, with simulations that only account for climate change.

2 | METHODS

We used the PISCESv2 ocean biogeochemical model (Aumont et al., 2015) within the NEMO ocean modelling framework and conducted offline simulations using output from the IPSL CM5A coupled climate model, as in previous studies (Tagliabue et al., 2020). PISCESv2 is an excellent candidate for these experiments as it is used in climate change simulations and includes a complex representation of the ocean Fe cycle, while explicitly representing the cycling of carbon, nitrate, phosphate, silicic acid, ammonium, oxygen, alkalinity and dissolved organic carbon. PISCES represents two phytoplankton functional groups with different affinities for nutrients that contribute to the production of two size classes of particulate organic matter that sink and are remineralized according to a variable reactivity continuum (Aumont et al., 2017). As the link between Fe supply and C fixation is an emergent property of the independent calculation of Fe uptake and primary production rates (with the former dependant on Fe concentrations and phytoplankton cell quotas), and with the parallel effect played by Fe in driving the balance between diatom and non-diatom phytoplankton (e.g. as documented in prior mesoscale OIF experiments; Boyd et al., 2007), our model has the potential to decouple the responses of NPP and carbon export to OIF. Natural Fe sources to the ocean in PISCES include dust, rivers, continental shelf sediments and hydrothermal vents.

We forced PISCESv2 with output from the pre-industrial control IPSL–CM5A simulation from 1801, branching the simulation to historical emissions in 1852 and the RCP8.5 high-emission scenario in 2005. We then conducted a suite of OIF experiments from 2005 to 2100. The first set followed those of Aumont and Bopp (2006) and maintained dissolved Fe concentrations at 2 nM, well above biological thresholds for growth limitation. These 'concentration'-based experiments can be thought of as a high efficiency OIF strategy that is able to overcome technical challenges to maintain high-surface Fe concentrations. They were performed globally and south of 60° S or 70° S. We also conducted a set of experiments where we applied a defined surface flux of Fe (10, 50, 100, or $250 \times 10^{-6}\,\mathrm{mol\,Fe\,m^{-2}\,year^{-1}}$). These 'flux' simulations were applied globally with continual Fe addition under historical climate forcing. Climate change simulations used the concentration-based OIF scenario and low Fe uptake (Tagliabue et al., 2020), which has been calibrated by an emergent constraint exercise (Shaked et al., 2021). All simulations ran until 2100, and changes are reported relative to the 1986–2005 reference period. We define the additionality due to climate change as the difference relative to the reference period and the additionality due to OIF as the differences in the climate change additionality with OIF (for all scenarios). We did not have an interactive atmospheric CO_2 reservoir and so even when the impact of OIF on CO_2 is converted to ppm and a typical airborne fraction is accounted for, impacts will remain an upper limit. We conducted two sets of experiments, using model solutions associated with a high and low Fe biological uptake scenario (following Tagliabue et al., 2020).

For the global high-efficiency concentration-based fertilization strategy that had the largest potential to drawdown atmospheric CO_2, we conducted additional experiments where the results from PISCES were used to force the APECOSM upper trophic level model. APECOSM (Maury, 2010) is a global ecosystem model that represents mechanistically the 3D dynamics of size-structured generic pelagic communities (the configuration used here includes epipelagic, resident and migratory mesopelagic communities). It integrates individual, population and community levels and includes the effects of life-history diversity with a trait-based approach (Maury & Poggiale, 2013). In APECOSM, energy uptake and utilization for individual growth, development, reproduction, somatic and maturity maintenance are modelled according to the Dynamic Energy Budget (DEB) theory (Kooijman, 2000). The model considers important ecological processes such as opportunistic size-structured trophic interactions and competition for food, predatory, disease, ageing and starvation mortality, key physiological aspects such as vision and respiration, as well as essential processes such as 3D passive transport by marine currents and active habitat-based movements, schooling and swarming. A combination of physical (temperature and horizontal current, vertical mixing) and biogeochemical (primary and secondary production—small and large phytoplankton, small and large zooplankton—detritus, light and oxygen) from our PISCES simulations are used to force the APECOSM simulations. In these experiments, PISCES and APECOSM were not fully coupled, meaning that feedbacks between upper trophic levels on nutrient cycling and lower trophic levels were neglected as they likely only have a minor effect on NPP and the carbon cycle (Dupont et al., 2023).

EEZ boundaries are defined using the Sea Around Us data set (http://www.seaaroundus.org) that subdivides the EEZs of 198 coastal states into a total of 280 EEZ regions.

3 | RESULTS

3.1 | OIF impacts on marine carbon and nutrient cycles

We first examined the outcomes of OIF in the PISCES model assuming no changes in climate. Applying a global, high-efficiency OIF strategy in which the Fe concentration is raised above limiting levels everywhere for 100 years (see Section 2) without climate change initially leads to a short-term ~25% stimulation of NPP by around 10 PgC year^{-1} (Figure 1a). However, decreased nutrient supplies to adjacent nitrogen-limited regions offset this initial boost over time, resulting in a cumulative NPP increase of 140 PgC by the end of the 100-year simulation (Figure 1b, note the small drift in the control experiment). Carbon export across 100 m water depth also increases in our simulations, and globally OIF stimulates a short-term increase of 2 PgC year^{-1} and an additional 80 PgC exported across 100 m over the 100-year simulation (Figure 1b; Figure S2).

On a regional scale, OIF causes increased NPP in the Fe-limited regions of the Southern Ocean, Equatorial Pacific, sub-Arctic Pacific and North Atlantic, with corresponding downstream decreases (Figure 1c). A similar regional response is found for C export (Figure S1a), which displays a greater relative impact, as OIF leads to shifts towards more efficiently exported phytoplankton communities (Waite & Nodder, 2001). The patterns we find in NPP are very similar to previous work, with the greatest response per square metre found in the equatorial Pacific (Aumont & Bopp, 2006; Dutkiewicz et al., 2006). However, the stimulation of NPP and C export are only around half that found in previous modelling exercises (Aumont & Bopp, 2006; Oschlies et al., 2010), likely because of the feedbacks associated with the improved representation of multiple natural Fe sources in the newer generation models and those associated with plankton physiology and Fe recycling (Somes et al., 2021; Tagliabue et al., 2016; Twining et al., 2020). As expected, promoting nutrient use in Fe-limited regions leads to a reduction in upper ocean major nutrients (Figure 1d), alongside reduced interior oxygen, except for the south Atlantic Ocean (due to reduced organic matter export due to OIF in this region, Figure S1).

We compared our high-efficiency OIF strategy that mimics the removal of Fe limitation with additional scenarios that applied specific fluxes of Fe to the sea surface and found very similar results. NPP and C export respond similarly and scale with the extent of Fe supply applied in our simulations (Figure 1; Figure S2). Due to abiotic processes that remove Fe and adjustments in phytoplankton C/Fe stoichiometry, the response to greater Fe fluxes eventually saturates (Tagliabue et al., 2010) meaning that the greatest OIF efficiency is restricted to the smallest Fe fluxes that elicit the lowest responses for NPP and C export (Figure S2, Arrigo & Tagliabue, 2005).

3.2 | OIF in concert with a changing climate

We examined the impact of OIF in concert with climate change using the RCP8.5 high-emission scenario (as in the Fifth Climate Model Intercomparison Project, CMIP5). In the standard climate change experiment with no OIF, climate change causes an ~5% cumulative decline in NPP (~130 PgC) and an ~12% drop in cumulative carbon export (45 PgC) by 2100 (relative to the historical reference era), consistent with prior work with other models as part of CMIP5 and later efforts with different high-emission

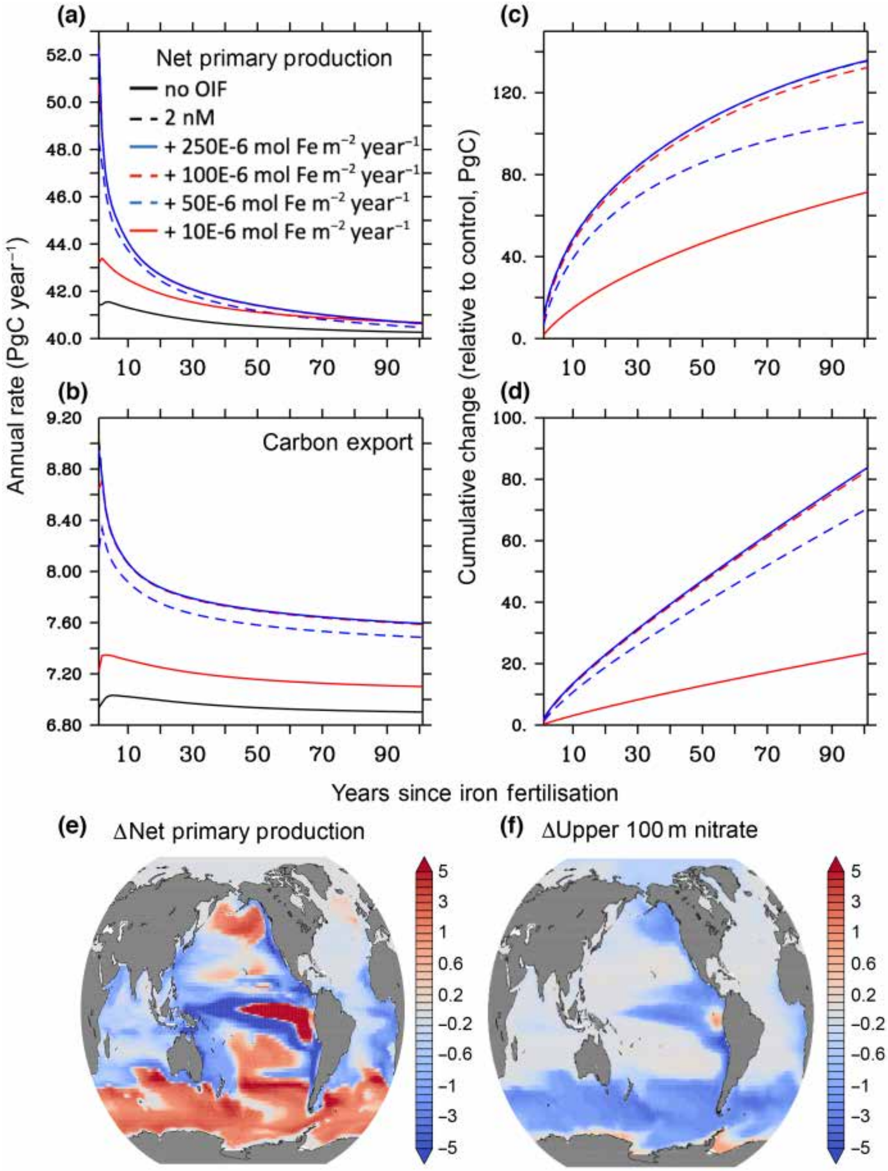
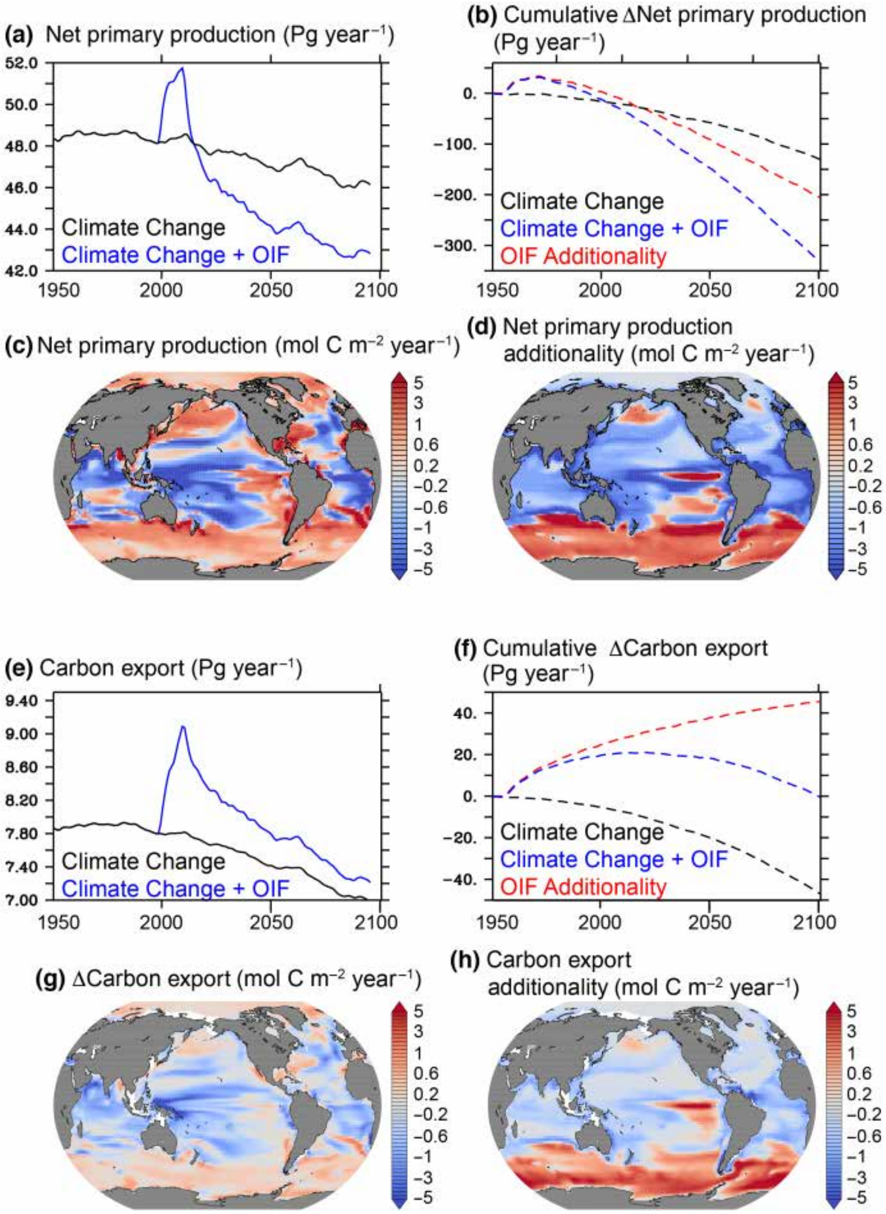


FIGURE 1 Evolution of (a) NPP and (b) carbon export across 100 m and the cumulative change in (c) NPP and (d) carbon export across 100 m under a range of concentration- and flux-based OIF strategies [see legend inset from (a)]. Maps of changes in (e) total NPP (mol C m^{-2} year^{-1}) and (f) averaged 0–100 m nitrate (mmol m^{-3}) after 100 years of 2 nM concentration-based OIF. The small change in NPP during the control simulation represents a small degree of model drift. Note some lines overlap with one another, with the dashed black 2 nM concentration-based estimate overlapping the solid blue 250E-6 mol Fe m^{-2} year^{-1} flux-based experiment in all panels and the dashed red 100E-6 mol Fe m^{-2} year^{-1} overlapping with the solid blue 250E-6 mol Fe m^{-2} year^{-1} in (a). NPP, net primary production; OIF, ocean iron fertilization.

scenarios as part of CMIP6 (Bopp et al., 2013; Kwiatkowski et al., 2020; Tagliabue et al., 2021). Initiation of global OIF at the end of the historical period again causes short-term boosts in both NPP (~4 PgC year^{-1}) and C export (~1 PgC year^{-1}) above the climate change-driven decline, with both reaching a peak after around 4–5 years (Figure 2a). However, global NPP then subsequently falls below that of the climate change-only simulation after around 10 years, indicating that despite OIF yielding enhanced NPP over the first decade, ultimately OIF leads to a cumulative NPP loss that exceeds 300 PgC by 2100 (Figure 2b). Thus, OIF amplifies the 130 PgC decline due to climate change alone more than twofold, with a net negative additionality due to OIF of ~200 PgC. The impact of OIF on C export remains positive by 2100, however, with a cumulative additionality of ~40 PgC by 2100 over the climate change scenario (Figure 2d). Overall, OIF leads to 45 PgC of additional cumulative ocean CO$_2$ uptake (relative to the rising CO$_2$ climate change simulation), translating to a roughly 10 ppm reduction in atmospheric CO$_2$ at the end of the 21st century (when applying a typical airborne fraction estimate; Friedlingstein et al., 2022).

In general, OIF amplifies the climate-driven NPP and C export increases in Fe-limited polar systems and exacerbates the climate-driven declines in the low latitude Atlantic, Indian and western Pacific oceans (Figure 2, consistent with prior CMIP5 and CMIP6 results; Bopp et al., 2013; Kwiatkowski et al., 2020; Tagliabue et al., 2021). OIF drives an increase in NPP in the Fe-limited Equatorial Pacific region, which is accompanied by large additional C export (Figure 2h). Overall, global OIF offsets part of the expected decrease in C export due to climate change, while climate change losses of NPP are amplified by global OIF after a decade. Due to greater consumption in the Southern Ocean in particular, upper ocean nitrate inventories decline due to OIF, again reinforcing the climate-driven trend noted in CMIP5 and CMIP6 (Figure 1f; Figure S3). The declines in NPP and C export that result from these downstream reductions in nutrient transport in the Atlantic and Indian oceans, in particular, lead to



(a) Net primary production (Pg year^{-1})

(b) Cumulative ΔNet primary production (Pg year^{-1})

(c) Net primary production (mol C m^{-2} year^{-1})

(d) Net primary production additionality (mol C m^{-2} year^{-1})

(e) Carbon export (Pg year^{-1})

(f) Cumulative ΔCarbon export (Pg year^{-1})

(g) ΔCarbon export (mol C m^{-2} year^{-1})

(h) Carbon export additionality (mol C m^{-2} year^{-1})

FIGURE 2 Time series of the evolution of (a) NPP (in PgC year^{-1}) due to climate change (black) and climate change + OIF (blue) and (b) cumulative change in NPP (in PgC) up to 2100 due to climate change (black dash) or climate change + OIF (blue dash), with OIF additionality is shown with red dash. Maps of (c) change (Δ) in 2091–2100, relative to 1986–2005 in NPP due to climate change and (d) OIF additionality in NPP (both in mol C m^{-2} year^{-1}). Time series of the evolution of (e) carbon export (in PgC year^{-1}) due to climate change (black) and climate change + OIF (blue) and (f) cumulative change in carbon export (in PgC) up to 2100 due to climate change (black dash) or climate change + OIF (blue dash), with OIF additionality is shown with red dash. Maps of (g) change (Δ) in 2091–2100, relative to 1986–2005 in carbon export due to climate change and (h) OIF additionality in carbon export (both in mol C m^{-2} year^{-1}). NPP, net primary production; OIF, ocean iron fertilization.

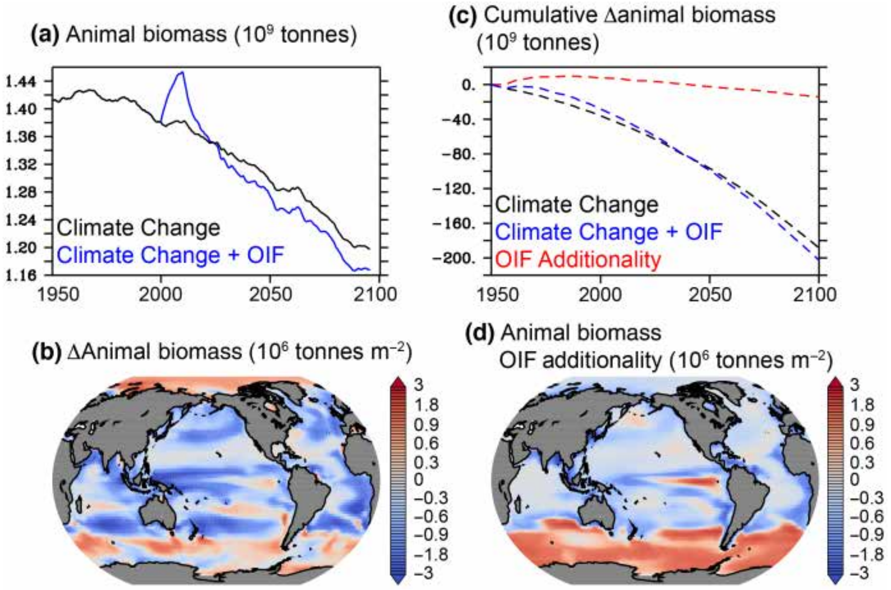
reduced sequestration of biological C and a small increase in interior oxygen in these regions (Figure S3).

The responses of NPP and C export to OIF are decoupled due to the parallel impact of climate change on stratification and nutrient supply, which then affects organic matter production and sinking. Without climate change, OIF increases both NPP and C export, despite removing major nutrients from the upper ocean, because any downstream reductions in NPP are less than those stimulated by OIF (Figure 1; Aumont & Bopp, 2006; Oschlies et al., 2010). Under climate change however, the benefit of OIF is now exceeded by the additional reduction in NPP due to the extra removal of upper ocean nutrients due to increased stratification. As additional Fe supply due to OIF also alters the relative production of large and small particles, there is a weaker feedback on C export in our model. A critical facet of the biogeochemical response we find is that the 'biogeochemical fingerprint' of climate change, which is to deplete upper ocean nutrients due to increased stratification, is identical to that of OIF and they thus reinforce one another.

3.3 | Response of marine ecosystems to OIF in a changing climate

Previous work predicts substantial declines in global marine animal biomass due to climate change (Bindoff et al., 2022; Lotze et al., 2019; Tittensor et al., 2021). We find similar results when we couple the APECOSM marine ecosystem model to PISCES output, with a cumulative loss of ~180×10^9 tonnes of biomass (15.5% loss) due to climate change by 2100 (Figure 3a). As for NPP and C export, applying global OIF leads to an initial boost in animal biomass by ~6×10^7 tonnes year^{-1} (or ~12%) that lasts for 19 years. From this point onwards, and similar to NPP, total animal biomass following OIF falls

FIGURE 3 As in Figure 2, but for total animal biomass.



steeply below that of the climate change-only run. However, unlike NPP, the periods of global animal biomass gains and losses nearly balance one another, with an ~5% cumulative global decline due to OIF above and beyond the 15.5% drop from climate change by 2100 (Figure 3c).

Biogeochemical and ecological effects of climate change and OIF will be experienced differently across regions. Climate change alone will cause strong declines in low latitude animal biomass, offsetting increases at high latitudes (Bindoff et al., 2022; Lotze et al., 2019; Tittensor et al., 2021). Our climate change-only simulations reproduce these findings, with strong declines in animal biomass throughout the tropics that exceed gains in polar seas and the equatorial Pacific (Figure 3b). As with NPP and C export, these patterns of change in animal biomass are amplified in response to OIF (Figure 3d). It is noteworthy that there are strong additional declines in animal biomass (above and beyond those arising from climate change) due to OIF projected for coastal regions in the Atlantic, Pacific and Indian oceans where the vast majority of the global fishing catch is made (Watson, 2017) (Figures 3d and 4).

The interactive effects of OIF and climate change will differ between EEZs, which will affect important socio-economic indicators like maximum catch potential and ecosystem health (Boyce et al., 2020). Overall, and consistent with prior work, we find that most EEZs (81%) experience reductions in animal biomass due to climate change, most notably in Asia and Africa (Figure 4). Combining these results with the impact of OIF reveals that only 8% of EEZs (or as little as 5% of the total EEZ area; Figure 4) would see an overall increase in animal biomass following OIF in the CC+OIF simulation. These are mostly small EEZs surrounding sub-Antarctic islands associated with high-GDP European nations. For the vast majority of EEZs (92% by number, or as much as 95% of total EEZ area; Figure S4), applying OIF as a CDR strategy in the context of climate change amplifies the biomass decrease due to climate change and results in pervasive reductions in animal biomass, with most nations across all continents, emerging as ‘losers’ (Figure 4). Thus, OIF emerges from our analysis as an additional burden, especially for those nations with limited adaptive capacity that are already dealing with (or preparing to deal with) the impacts of climate change on ecosystem services (Boyce et al., 2020). If OIF were undertaken at scale, our results suggest that OIF-mediated declines in animal biomass would start to occur within a decade or so, likely affecting fisheries and ecosystems. This raises questions about liability for negative impacts and how they are integrated into OIF planning and monitoring.

4 | DISCUSSION

Our results show that OIF likely has limited effectiveness as a marine CDR method and may cause adverse ecosystem impacts in our experiments. We found a small impact of OIF on strengthening the ocean uptake of atmospheric CO_2 at the expense of exacerbating climate-driven reductions in tropical and subtropical NPP and biomass of high trophic levels that are harvested by fisheries. In response to a global, high-efficiency OIF strategy that is assumed to overcome all technical challenges associated with sufficient delivery of bioavailable Fe, the ocean removed around 10 ppm CO_2, which is of similar order, but slightly lower than previous estimates that did not account for climate change (Aumont & Bopp, 2006; Hauck et al., 2016; Oschlies et al., 2010) due to the reduced efficiency with which Fe is predicted to fuel carbon sequestration in a changing climate. OIF leads to amplified reductions in low latitude NPP in our simulations, especially in the Atlantic and Indian Oceans, because it introduces an additional mechanism to deplete the upper ocean of the major nutrients that regulate NPP in these regions. Alleviating Fe-limitation also leads to greater consumption of nitrate and phosphate in the Southern Ocean that would otherwise be transported equatorward. The drop in NPP caused by the depletion of upper ocean nutrients counteracted much of the stimulation of NPP due to OIF, consistent with prior studies that only considered OIF in a fixed

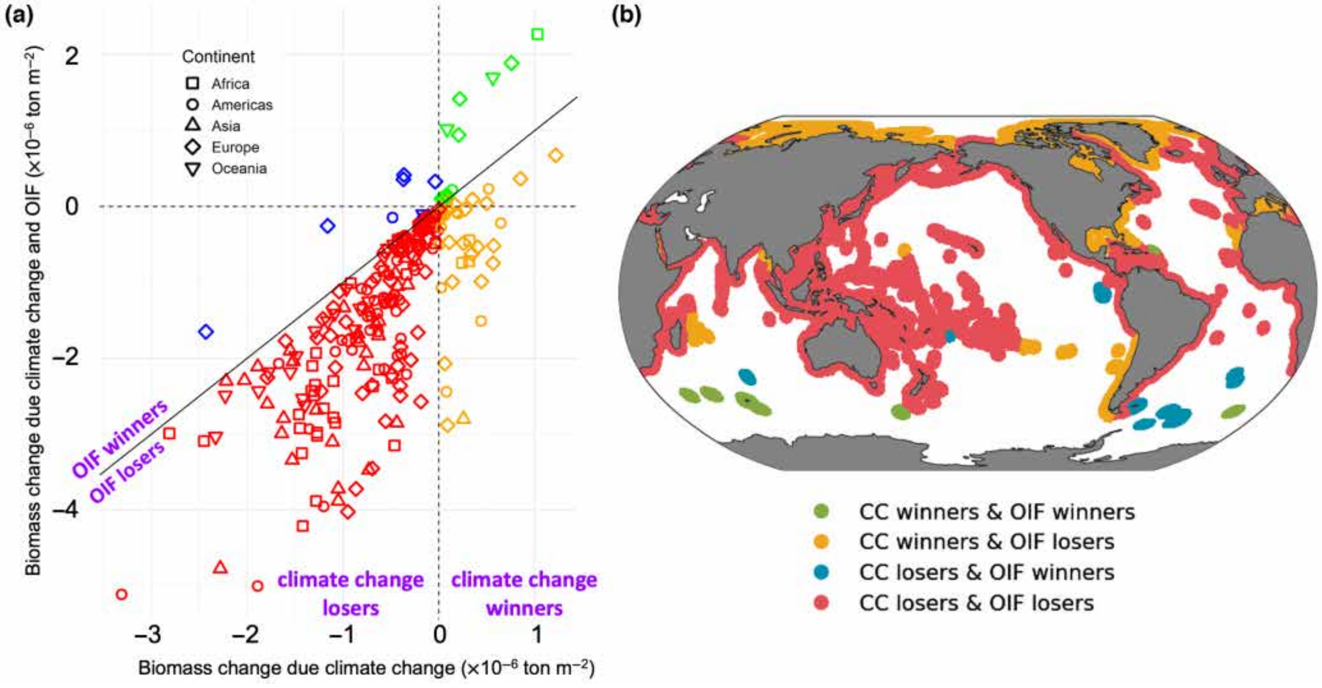


FIGURE 4 (a) Change in animal biomass in individual EEZs due to climate change versus climate change and ocean iron fertilization. Symbols indicate each individual EEZ. Only a few EEZs (blue and green) will benefit from ocean iron fertilization in a changing climate, while a majority of EEZs will experience declines under both scenarios (red). In some EEZs (orange), ocean iron fertilization will undo projected climate change increases in biomass. (b) Map of EEZs colour-coded by expected outcome [colours match (a)]. EEZ, exclusive economic zone; OIF, ocean iron fertilization.

climate. However, in a changing climate, greater stratification also reduces upper ocean major nutrients (Bindoff et al., 2022; Kwiatkowski et al., 2020), and augmenting this with additional nutrient loss due to OIF tips the balance such that NPP losses are greater than the gains after around a decade. It may be possible to mitigate against some of these nutrient losses, for example, by restricting OIF only to Antarctic waters south of the sub-Antarctic region from where intermediate and mode waters originate (Marinov et al., 2006), but this would also reduce the impact on atmospheric CO_2 and C export (e.g. Oschlies et al., 2010; Figure S5). Moreover, while the amplification of upper ocean major nutrient loss can be slightly mitigated by restricting OIF to the higher latitudes of the Southern Ocean, they are not eliminated, especially in the tropical Atlantic in our simulations (Figure S5). As removing atmospheric CO_2 is the central goal of all potential CDR strategies, our results suggest OIF would play only a minor role in this regard, with additional negative consequences under a changing climate.

Although our model includes many processes associated with the ocean Fe cycle and marine biogeochemistry, there are caveats that may mean these estimates are optimistic. The most important is that it is assumed that relief of Fe limitation allows drawdown of the larger major nutrient pool until it is exhausted or light limitation intervenes (Aumont & Bopp, 2006). However, other factors may become limiting before this maximal response is reached. For instance, in the Southern Ocean, Mn is present at very low levels and can limit phytoplankton in some places (Browning et al., 2021). Even if not directly limiting, the Mn deficiency typical of the Southern Ocean means that the response of the C cycle to the addition of Fe is more muted (Hawco et al., 2022), likely reducing the responses to OIF reported here. Additionally, the relatively coarse spatial resolution of our model (typical of contemporary ocean models) simplifies nutrient transport processes, within which mesoscale eddies are known to be important (McGillicuddy, 2016; Xiu & Chai, 2011). However, eddy-driven transport is only likely to affect the timing and scale of meridional nutrient transport rather than alter the direction of the OIF effects we report. Model representation of Fe cycling also introduces uncertainties. Particulate Fe is known to be important in the transport and removal of Fe (Bowie et al., 2009), but its cycling does not receive much attention in most ocean biogeochemical models (often not included as an explicit tracer; Tagliabue et al., 2016). Assessing the impact of uncertain aspects of biological Fe cycling, such as uptake and storage (Tagliabue et al., 2020), may lead to twofold variations in the calculated impact of OIF on atmospheric CO_2, but with little effect on the change in marine animal biomass (Figure S6). Lastly, most biogeochemical models neglect possible chemical feedbacks between climate change and the Fe cycle that may be driven by anthropogenic changes to pH, temperature, or stratification/irradiance. This highlights key remaining uncertainties about the Fe cycle that must be better understood to constrain future predictions (with or without OIF).

Understanding of controls on carbon export and the range of processes that drive carbon flux from the ocean surface and through the mesopelagic are also incomplete and limit full representation of these in ocean biogeochemical models. Model assessment and the development of more detailed parameterizations is hindered by a paucity of measurements, as well as significant spatial and temporal variability (Henson et al., 2019; Siegel et al., 2023). Our model includes a relatively complex formulation for organic matter export and cycling, accounting for differential organic matter lability and aggregation/disaggregation processes (see Section 2). Comparisons of PISCES vertical organic matter fluxes with available observations indicate reasonable agreement, but modelled fluxes in the surface and deep Southern Ocean are both higher and lower than available points of comparison (Aumont et al., 2017). Similar evaluations are not available for other models, but there is documented uncertainty across climate change scenarios (Wilson et al., 2022). Processes controlling the vertical export of carbon following blooms, particularly those containing Southern Ocean diatoms, are known to be poorly constrained (Assmy et al., 2013; Giering et al., 2023; Rembauville et al., 2015) and the role(s) of biomineralized phytoplankton also remains unresolved (Henson et al., 2012). At the same time, attention is growing on the processes that drive the 'transfer efficiency' of particulate organic matter through the mesopelagic, including particle fragmentation (Briggs et al., 2020) and the role of zooplankton (Mayor et al., 2020). More mechanistic insight into the processes governing carbon and nutrient export and cycling will help refine models further.

Monitoring, reporting and verification (MRV) is an important part of ocean-based CDR (UNFCCC, 2014). Our modelling results suggest that MRV will need to be applied globally and over a period of decades following any large-scale OIF effort. This is because it will be necessary to document the way in which anomalies in major nutrients are redistributed by ocean circulation, in addition to the need to quantify any direct stimulation of the biological C pump that operates more locally. Of major importance is the need for appropriate MRV regarding the consequences of OIF for ecosystems across most EEZs. In our experiments, negative impacts of OIF on NPP and animal biomass begin to emerge 10–20 years after the OIF scenario was initiated, implying a long-term investment in MRV is obligated. Further work, potentially with higher resolution models, may be necessary to refine these estimates and the specific timescale appropriate for MRV efforts to pick up impacts in different EEZs with different degrees and rates of connectivity to the OIF zone. Moreover, further work to explore how the magnitude and timescales of feedbacks operate under alternative climate scenarios is recommended. A particular challenge moving forward will be the ability to detect any signal associated with OIF from the noise of natural and climate change-induced variability, which will end up requiring even longer periods of MRV, raising challenges for the practical management of OIF.

Ocean iron fertilization is not the only perturbation to ocean Fe supply likely to occur over the coming decades. Atmospheric deposition of Fe is also changing, in response to both anthropogenic aerosols and Fe inputs associated with fires that can stimulate phytoplankton productivity in Fe-limited regions (Hamilton et al., 2021; Tang et al., 2021). Efforts to quantify these changing atmospheric Fe fluxes emphasize the importance of the underlying biogeochemical regime and downstream feedbacks associated with changing major nutrient availability (Hamilton et al., 2020; König et al., 2022). Our results indicate that it will be imperative to also account for the parallel modifications to ocean circulation and biogeochemistry due to climate change, both in the future and during the historical era. Exercises to assess the response of the marine C cycle to changing 'natural' Fe delivery are undermined by the same set of uncertainties as those associated with OIF.

5 | CONCLUSIONS

Overall, inadequate progress to date on the mitigation of CO_2 fluxes from fossil fuels and land use change has stimulated interest in fertilization-based CDR. Our results suggest that OIF can only contribute very modestly to such efforts, especially in a climate change context. Moreover, our work has identified a previously underappreciated amplification of the negative effect of climate change on marine ecosystems by OIF that has broad ramifications for fisheries and dependent communities that are already under growing pressures (Blanchard et al., 2017). Ultimately, the efficacy and impacts of any large-scale ocean fertilization CDR effort will depend on how effectively the export of C can be decoupled from the export of nutrients, which occurs over large spatial and temporal scales. While the ocean presents opportunities for CDR, it is critical to fully characterize the responses of the ocean, its ecosystems and how their contributions to humans might change with such a large-scale manipulation. Moreover, the reversibility in case of harm should also be raised as an important point to be considered. Regulators and the scientific community must therefore engage in transparent, rigorous evaluation of all proposed approaches to ensure efficacy and a full appreciation of the consequences across natural and human systems worldwide.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

Final model datafiles are archived on zenodo at https://doi.org/10.5281/zenodo.8060053. PISCES code is freely available.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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