Iron availability imposes an upper bound on long-term oceanic primary production.

Supplementary Analysis

Brief methods

We define the ULN as the nutrient for which increased inputs enhance total ocean productivity over timescales longer than whole ocean nutrient residence times. To investigate the ULN, we ran simulations with nutrient input fluxes increased by 10-200% or reduced by 10-50%.

The NutGEnIE model features a 36 × 36 equal-area horizontal grid with 16 vertical layers, representing both ocean physics and biogeochemistry[1]. Nutrient cycles within the model are 'open', each possessing at least one defined input and output flux. The PO_4^{3-} cycle incorporates a river input and a burial output flux; the NO_3^- cycle includes a surface input, nitrogen fixation, burial output, and also denitrification as a loss process; the Fe cycle is characterised by both surface and seafloor input fluxes, with water column scavenging and burial serving as output fluxes. The model distinguishes between two phytoplankton groups: other phytoplankton (OP), which require PO_4^{3-}, dissolved inorganic nitrogen (DIN, defined here as the sum of NO_3^- and NH_4^+), and Fe for growth, and diazotrophs (Diaz), which require PO_4^{3-} and Fe for growth, as they possess the ability to fix dissolved dinitrogen.

In the results section we distil the findings from simulations in which nutrient input fluxes, individually and in combination, were increased by 125%. As depicted in Figure 1, these fertilisation simulations reveal the dynamics of phosphate uptake (as a measure of the rate of primary production) by both OP and Diaz across the duration of each scenario, benchmarked against the control simulation. The results show the impacts of single and multiple whole ocean scale nutrient additions on OPP. We focus on the consequences for OPP over long time scales and therefore the simulation end-states (after 200 kyr, substantially beyond the residence times of all three nutrients). The principal rates and concentrations are detailed in Sup table 1. Our analysis proceeds from the effects of single nutrient additions to simulations involving simultaneous enrichment by two and finally all three nutrients.

Methodology

The NutGEnIE model is based on cGEnIE with modifications that are designed to facilitate investigations into the Ultimate Limiting Nutrient (ULN) for oceanic primary production[1]. The desiderata that guided the model design are the needs for: (1) cycling and biological uptake of (and potential limitation by) three nutrients (N, P, Fe), (2) nitrogen-fixing as well as non-fixing phytoplankton, (3) spatial resolution, as opposed, for instance, to representing the whole surface ocean with one box, (4) the ability to carry out model runs exceeding the residence times of all three nutrients, and (5) external inputs (e.g. delivery of nutrients down rivers) and external outputs (e.g. delivery of nutrients to seafloor sediments via burial) in an 'open' model allowing total ocean inventories of nutrients to change over time. The design and validation of NutGEnIE are described in the model description paper of Stappard, et al.[1]. A pertinent feature of NutGEnIE to consider is the nutrient input fluxes as it is these fluxes that are adjusted in the fertilisation simulations.

S_{PO4} and S_{NO3} represent surface input flux, such as riverine inputs, of PO_4^{3-} and NO_3^- respectively. S_{PO4} and S_{NO3} fluxes are distributed evenly to cells adjacent to land (excluding Antarctica); all other cells do not receive the input fluxes. B_{Fe} represents a seafloor input flux of Fe, such as hydrothermal or sedimentary inputs. All cells immediately above the seafloor receive the input flux which is distributed evenly among those cells. DD_{Fe} represents a dust deposition surface input flux of Fe. All cells at the surface receive the input flux, but in greatly varying degrees according to a distribution based on a re-gridding of Mahowald, et al.[2]. See Sup figure 32 for the spatial distributions of S_{PO4} and S_{NO3}, Sup figure 33 for the spatial distribution of B_{Fe} and Sup figure 34 for the spatial distribution of DD_{Fe}.

The magnitudes of these fluxes are configurable via parameters that define the annual rate of supply of each nutrient added. Sup table 5 provides the annual magnitude of the input fluxes in the control simulation. In the fertilisation simulations an additional 10%, 25%, 75%, 125% or 200% is added to each input flux. In the reduction simulations each input flux is reduced by 10%, 25%, or 50%. Combined PO_4^{3-} uptake by the other phytoplankton and diazotroph classes of phytoplankton is used as a proxy for OPP. In particular, changes in PO_4^{3-} uptake in the nutrient fertilization and reduction simulations relative to the control simulation provide a proxy of percentage change in OPP.

Figure 1 and Sup Table 1 present the results of the 125% fertilisation simulations, while Figure 2 and Sup Table 2 detail the outcomes of the 25% nutrient reduction scenarios. Each fertilisation and nutrient removal simulation, including the control, was systematically evaluated for end-state (200 kyr) nutrient dynamics and distributions. The end-state primary production rates, surface and global nutrient concentrations, and patterns of surface ocean limitation are summarised in Sup Table 1 and Sup Table 2. Supplementary figures corresponding to each scenario are referenced, with key findings described.

To characterise surface nutrient limitation for other phytoplankton and diazotrophs, we present figures indicating the proximate limiting nutrient (PLN). At each model timestep, limitation is assessed by evaluating the Michaelis-Menten uptake terms to identify the nutrient most restricting growth. These PLNs are visualised using an RGB colour scheme: iron limitation appears as green, PO_4^{3-} as red, and DIN as blue, with mixed limitations shown as intermediate hues within a Maxwell triangle representation[1].

Utilising the nutrient deficiency diagnostic framework of Moore[3], deficiencies within the ocean interior were assessed by comparing nutrient concentrations along transects to phytoplankton elemental requirements. The nutrient present at the lowest concentration relative to cellular demand was identified as the first-degree deficient nutrient as described by Moore[3]. This approach was applied to analyse ocean interior transects for both other phytoplankton and diazotrophs. Stoichiometric requirements for each phytoplankton functional type were determined using the parameterisation of the NutGEnIE model detailed in Table 2 of Stappard, et al.[1]. The nutrient deficiency transects were determined using the final nutrient concentrations from each simulation.

The spatial patterns and magnitudes of nutrient uptake by both other phytoplankton and diazotrophs are also presented. For the control simulation, spatial maps illustrate nutrient uptake rates (mol P kg^{-1} yr^{-1}) for each group (Sup figure 2). Equivalent analyses are provided for all fertilisation and reduction scenarios (Sup figure 4 to 30), including maps displaying the change relative to the control (Δ, scenario - control). To facilitate direct comparison, colour scales are the same across all simulations.

Detailed simulation results

Control simulation

Surface nutrient uptake by other phytoplankton (Sup figure 1a), is predominantly limited by DIN at lower latitudes and by Fe at higher latitudes; selected equatorial Pacific regions also exhibit Fe limitation. PO_4^{3-} limitation is largely restricted to the Mediterranean and Caribbean Seas. Quantitatively, surface limitation for other phytoplankton is attributed to PO_4^{3-} in 2% of surface waters, DIN in 67%, and Fe in 31%. For diazotrophs (Sup figure 1b), iron is the dominant limiting factor, across 92% of the ocean surface, whereas PO_4^{3-} limitation is mainly detected in the low-latitude North Atlantic, Mediterranean, and northern Indian Ocean. In the ocean interior (Sup figure 1c and 1d), iron is almost everywhere the most deficient nutrient for both classes.

Globally, mean phosphate uptake by other phytoplankton (Sup figure 2a) is 0.50 μmol P kg^{-1} yr^{-1}, with peak rates observed in the North Atlantic and Southern Ocean. In contrast, diazotroph phosphate uptake (Sup figure 2b) is largely restricted to low-latitude regions of the Northern Hemisphere, with a mean rate of 0.30 nmol P kg^{-1} yr^{-1}.

Phosphate +125% fertilisation simulation

Surface nutrient uptake by other phytoplankton (Sup figure 3a) is largely limited by DIN in low-latitude regions, with Fe limitation prevailing at higher latitudes and in areas of upwelling, such as the equatorial Pacific. PO_4^{3-} limitation has been eradicated. Quantitative analysis indicates that DIN and iron respectively limit uptake in 62% and 38% of surface waters. For diazotrophs (Sup figure 3b), Fe is the sole limiting factor, restricting uptake across the entire ocean surface. Within the ocean interior (Sup figure 3c and 3d) iron deficiency is the dominant limitation.

Globally, mean phosphate uptake by other phytoplankton (Sup figure 4a) is 0.55 μmol P kg^{-1} yr^{-1}, with peak rates in the North Atlantic and Southern Ocean. Relative to control simulations, surface ocean uptake by other phytoplankton (Sup figure 4c) shows only minor enhancements, notably in the North Atlantic and northern Indian Ocean. In contrast, diazotroph PO_4^{3-} uptake (Sup figure 4b and 4d), increases markedly compared to control, particularly in regions previously limited by phosphate. The mean uptake rate for diazotrophs reaches 0.64 nmol P kg^{-1} yr^{-1} reflecting moderate increases of 7% for other phytoplankton, 100% for diazotrophs and 7% for total PP compared to the control simulation.

With the substantial increase in PO_4^{3-} input, the global mean [PO_4^{3-}] rises from 2.09 to 14.9 μmol kg^{-1}. Concurrently, a higher rate of uptake by diazotrophs drives an increase in global mean [NO_3^-], from 28.8 to 31.4 μmol kg^{-1}.

Nitrate +125% fertilisation simulation

With increased NO_3^- input, the limitation on other phytoplankton uptake shifts: Fe dominates in high latitudes, while PO_4^{3-} prevails in low latitudes (Sup figure 5a). DIN limitation is eliminated. Surface uptake by other phytoplankton is limited by Fe in 59% and PO_4^{3-} in 41% of surface waters. For diazotrophs (Sup figure 5b), Fe remains the principal limiting factor, constraining 77% of the ocean surface, while PO_4^{3-} limits the remaining 23%. In the ocean interior, Fe continues to be the most deficient for both phytoplankton groups (Sup figure 5c and 5d).

Globally, mean uptake by other phytoplankton (Sup figure 6a) remains at 0.49 μmol P kg^{-1} yr^{-1}, largely unchanged from the control simulation. Diazotroph uptake (Sup figure 6b and 6d), is negligible, as regions previously favouring diazotrophs under low DIN conditions no longer exist.

With the elevation of NO_3^- input, global mean [NO_3^-] increases from 28.8 to 37.2 μmol kg^{-1}, while global mean [PO_4^{3-}] declines from 2.09 to 1.92 μmol kg^{-1}. As shown in Figure 1, the increased NO_3^- flux initially stimulates uptake by other phytoplankton, a response that persists over several thousand years. This transient enhancement in uptake is gradually counteracted by a negative PO_4^{3-} budget (output fluxes greater than input fluxes), driven by elevated burial rates, induces a steady decrease in global mean [PO_4^{3-}]. The consequent depletion is sustained throughout the simulation, ultimately returning other phytoplankton uptake rates to pre-fertilisation values.

Iron +125% fertilisation simulation

Following Fe enrichment, the limiting factors for other phytoplankton uptake (Sup figure 7a) are redistributed: Fe limitation becomes largely confined to the Southern Ocean, while DIN limits uptake across most low- and mid-latitude regions. In contrast, PO_4^{3-} limitation predominates in certain sectors of the Atlantic north of the equator and the northern Indian Ocean. Overall, surface nutrient limitation for other phytoplankton is attributable to DIN in 73% of surface waters, Fe in 15%, and PO_4^{3-} in 11%. For diazotrophs (Sup figure 7b), Fe limitation persists mainly at high latitudes and in upwelling zones such as the equatorial Pacific, whereas phosphate limitation expands to 56% of the ocean surface, with Fe constraining the remaining 44%. Despite elevated Fe inputs, deficiency of Fe remains the primary factor for both phytoplankton groups in the ocean interior (Sup figure 7c and 7d),

Globally, mean uptake by other phytoplankton (Sup figure 8a) remains at 0.48 μmol P kg^{-1} yr^{-1}, largely unchanged from the control simulation. Notable regional shifts include reduced uptake in the

North Atlantic and enhanced uptake in the Southern Ocean (Sup figure 8c). Diazotroph uptake (Sup figure 8b and 8d), decreases to from 0.20 nmol kg^{-1} yr^{-1} with a shift towards the subtropical gyre margins and declining in the central Atlantic Ocean.

Global mean [Fe] rises modestly from 0.73 to 0.89 nmol kg^{-1} while both [PO_4^{3-}] and [NO_3^-] reduce. Notably, increased Fe supply is accompanied by higher rates of iron scavenging, explaining the small degree of increase in [Fe]. The increased Fe flux initially stimulates enhanced uptake by both other phytoplankton and diazotrophs, a response that persists for approximately two millennia. Thereafter, increased denitrification drives a negative NO_3^- budget, and gradual depletion of global NO_3^- and PO_4^{3-} concentrations leads to sustained declines in uptake rates among diazotrophs and other phytoplankton over the course of the simulation.

Phosphate and iron +125% fertilisation simulation

Surface nutrient uptake by other phytoplankton (Sup figure 9a), is predominantly limited by DIN with Fe limitation in the North Atlantic and Southern Ocean. PO_4^{3-} limitation has been eradicated. Quantitatively, surface limitation for other phytoplankton is attributed to DIN in 78%, and Fe in 22% of surface waters. For diazotrophs (Sup figure 9b), iron is the dominant limiting factor, constraining 100% of the ocean surface. In the ocean interior (Sup figure 9c and 9d), iron deficiency is dominant.

Globally, mean phosphate uptake by other phytoplankton (Sup figure 10a) reaches 0.71 µmol P kg^{-1} yr^{-1}, with elevated rates observed in the North Atlantic, North Indian Ocean, and Southern Ocean. Relative to control simulations, surface ocean uptake by other phytoplankton (Sup figure 10c) increases most markedly in the Northern Atlantic, Mediterranean, Northern Indian Ocean, and Southern Ocean, with more modest enhancements in the Pacific. Diazotroph phosphate uptake (Sup figure 10b and 10d) is more widespread than in the control simulation, expanding across the Pacific subtropical gyres, a larger portion of the Atlantic, and the Northern Indian Ocean. The mean uptake rate by diazotrophs is 2.4 nmol P kg^{-1} yr^{-1} reflecting substantial increases of 40% for other phytoplankton, 680% for diazotrophs and 41% for overall PP compared to the control simulation.

The pronounced increase in diazotroph uptake leads to an elevation of global mean [NO_3^-] to 37.6 µmol kg^{-1}, compared to 28.8 µmol kg^{-1} observed in the control simulation. This increase results in the simultaneous enhancement of all potentially limiting nutrient concentrations with the most modest increase being in Fe.

Phosphate and nitrate +125% fertilisation simulation

Surface nutrient uptake by other phytoplankton (Sup figure 11a) is largely limited by DIN in low-latitude regions, with Fe limitation prevailing at mid to high latitudes. PO_4^{3-} limitation has been eradicated. Quantitative analysis indicates that DIN and iron respectively limit uptake in 33% and 67% of surface waters. For diazotrophs (Sup figure 11b), Fe is the sole limiting factor, restricting uptake across the entire ocean surface. Within the ocean interior (Sup figure 11c and 11d), iron deficiency is dominant.

Globally, mean phosphate uptake by other phytoplankton (Sup figure 12a) is 0.59 µmol P kg^{-1} yr^{-1}, with peak rates in the North Atlantic and Southern Ocean. Relative to control simulations, surface ocean uptake by other phytoplankton (Sup figure 12c) shows only minor enhancements, notably in the North Atlantic and northern Indian Ocean. Diazotroph PO_4^{3-} uptake (Sup figure 12b and 12d) increases marginally compared to control; the mean uptake rate for diazotrophs reaches 0.34 nmol P kg^{-1} yr^{-1} reflecting moderate increases of 14% for other phytoplankton, 6% for diazotrophs and 14% for total PP compared to the control simulation.

With the substantial increase in PO_4^{3-} input, the global mean [PO_4^{3-}] rises from 2.09 to 14.2 µmol kg^{-1}. Concurrently, global mean [NO_3^-] increases, from 28.8 to 34.6 µmol kg^{-1}, relative to the control simulation.

Nitrate and iron +125% fertilisation simulation

Following NO_3^- and Fe enrichment, the limiting factors change for other phytoplankton uptake (Sup figure 13a). PO_4^{3-} limitation predominates across most surface waters, while Fe is the limiting factor in the Southern Ocean and the northern Pacific Ocean. Overall, surface nutrient limitation for other phytoplankton is attributable to PO_4^{3-} in 79% of surface waters, Fe in 21%. For diazotrophs (Sup figure 13b) Fe limitation persists mainly at high latitudes and in upwelling zones such as the equatorial Pacific, whereas phosphate limitation expands to 66% of the ocean surface, with Fe constraining the remaining 34%. Despite elevated Fe inputs, deficiency of Fe remains the primary factor for both phytoplankton groups in the ocean interior, however, for other phytoplankton in the North Atlantic (approx. 50° N) PO_4^{3-} deficiency extends to depths greater than 1 000 m (Sup figure 13c and 13d).

Globally, mean uptake by other phytoplankton (Sup figure 14a) remains at 0.48 μmol P kg^{-1} yr^{-1}, largely unchanged from the control simulation. Notable regional shifts include reduced uptake in the North Atlantic and enhanced uptake in the Southern Ocean (Sup figure 14c). Diazotroph uptake, (Sup figure 14b and 14d) is eradicated as regions previously favouring diazotrophs under low DIN conditions no longer exist.

Global mean [Fe] rise modestly from 0.73 to 0.90 nmol kg^{-1} and [NO_3^-] increases from 28.8 to 38.2 μmol kg^{-1} while [PO_4^{3-}] reduces. The increased fluxes initially stimulate enhanced uptake by both other phytoplankton and diazotrophs, a response that persists for several millennia. Thereafter gradual depletion of global [PO_4^{3-}] leads to a sustained decline in uptake rates among diazotrophs and other phytoplankton over the course of the simulation.

Phosphate, nitrate and iron +125% fertilisation simulation

Surface nutrient uptake by other phytoplankton (Sup figure 15a) is predominantly limited by DIN with Fe limitation in the North Atlantic, Arctic Ocean and Southern Ocean. PO_4^{3-} limitation has been eradicated. Quantitatively, surface limitation for other phytoplankton is attributed to DIN in 73%, and Fe in 27% of surface waters. For diazotrophs, Sup figure 15b), iron is the dominant limiting factor, constraining 100% of the ocean surface. In the ocean interior (Sup figure 15c and 15d) iron deficiency is dominant.

Globally, mean phosphate uptake by other phytoplankton (Sup figure 16a) reaches 0.74 μmol P kg^{-1} yr^{-1}, with elevated rates observed in the North Atlantic, North Indian Ocean, and Southern Ocean. Relative to the control simulation, surface ocean uptake by other phytoplankton (Sup figure 16c) increases most markedly in the Northern Atlantic, Mediterranean, Northern Indian Ocean, and Southern Ocean, with more modest enhancements in the Pacific. Diazotroph phosphate uptake (Sup figure 16b and 16d) is more widespread than in the control simulation, expanding across the Pacific subtropical gyres, a larger portion of the Atlantic, and the Northern Indian Ocean. The mean uptake rate by diazotrophs is 2.0 nmol P kg^{-1} yr^{-1} reflecting substantial increases of 45% for other phytoplankton, a five-fold increase (550%) for diazotrophs and 46% for overall PP compared to the control simulation.

Phosphate input flux 25% reduction simulation

Reducing PO_4^{3-} input flux fundamentally increases surface nutrient limitation by PO_4^{3-} across the global ocean. For other phytoplankton, PO_4^{3-} emerges as the primary limiting nutrient over much of the surface, except in the northern Pacific and Southern Ocean, where Fe dominates as the key limiting factor (Sup figure 17a). Quantitative analysis reveals that PO_4^{3-} constrains nutrient uptake in approximately 78% of the surface ocean, with Fe accounting for limitation in the remaining 22%; DIN limitation is eliminated in this scenario. For diazotrophs, surface nutrient limitation (Sup figure 17b) is predominantly governed by PO_4^{3-}, 61% of the surface ocean and notably between 30°N and 30°S, while Fe imposes limitation in the Arctic, northern Pacific, equatorial Pacific upwelling regions and the Southern Ocean equating to 39% of the surface ocean. Within the ocean interior, Fe deficiency prevails, as indicated in Sup figure 17c and 17d. Notably, for other phytoplankton, a region between 50°N and 60°N in the Atlantic exhibit PO_4^{3-} deficiency at depths down to 3,000 m.

Globally, mean PO_4^{3-} uptake by other phytoplankton (Sup figure 18a) is 0.36 μmol P kg^{-1} yr^{-1}, with peak rates in the North Atlantic and Southern Ocean. Compared to control simulations, surface ocean uptake by other phytoplankton (Sup figure 18c) declines, especially in the North Atlantic and northern Indian Ocean. Diazotroph PO_4^{3-} uptake (Sup figure 18b and 18d) is eliminated across the surface ocean with mean uptake rate of 0.00 nmol P kg^{-1} yr^{-1}. The reduced input flux of PO_4^{3-} results in a 25% decrease in uptake for other phytoplankton, an elimination (100% decrease) of diazotrophs, and a 25% reduction in total primary production relative to the control simulation.

With the substantial reduction in PO_4^{3-} input, the global mean [PO_4^{3-}] reduces from 2.09 to 1.33 μmol kg^{-1}. Concurrently, an elimination of uptake by diazotrophs results in decreases in global mean [NO_3^-] relative to the control simulation from 28.8 to 24.0 μmol kg^{-1}.

Nitrate input flux 25% reduction simulation

The reduction in NO_3^- supply did not substantially alter the spatial patterns of surface nutrient limitation for either other phytoplankton or diazotrophs by the end of the simulation (Sup figure 19a and 19b). Quantitatively for other phytoplankton, 70% of the surface ocean was limited by DIN, 29% by Fe, and 1% by PO_4^{3-}. For diazotrophs, surface nutrient uptake was primarily limited by Fe, 93%, with PO_4^{3-} accounting for limitation in the remaining 7%, closely mirroring the spatial distribution observed in the control simulation. In the ocean interior, Fe deficiency is the dominant limitation for both phytoplankton groups (Sup figure 19c and 19d).

Globally, mean PO_4^{3-} uptake by other phytoplankton (Sup figure 20a) is 0.50 μmol P kg^{-1} yr^{-1}, the same as the control simulation with consistent spatial distribution. The reduction in NO_3^- input flux stimulates a moderate increase in diazotroph nutrient uptake to 0.41 nmol P kg^{-1} yr^{-1} (Sup figure 20b and 20d). Relative to the control, there is no discernible change in uptake by other phytoplankton or total primary production, while diazotrophs exhibit a 39% increase in nutrient uptake. In summary, N_2 fixation increases to compensate the lower riverine NO_3^- supply, resulting in a system more or less identical to the control except for the elevated N_2 fixation.

Iron input flux 25% reduction simulation

A reduction in Fe supply leads to increased limitation of nutrient uptake by Fe (Sup figure 21a and 21b). Consequently, in 57% of the surface ocean, other phytoplankton exhibit Fe-limited uptake, while 43% are limited by DIN, and less than 1% by PO_4^{3-}. For diazotrophs, nutrient uptake at the surface is primarily Fe-limited (99%), with PO_4^{3-} contributing to limitation in the remaining 1%. In the ocean interior, Fe deficiency predominates for both phytoplankton groups (Sup figure 21c and 21d).

Globally, mean phosphate uptake by other phytoplankton (Sup figure 22a) is 0.49 μmol P kg^{-1} yr^{-1}, representing a minor decrease compared to the control simulation and maintaining a similar spatial distribution. Diazotroph nutrient uptake rates also remain comparable to control conditions, although diazotroph activity exhibits a modest northward shift in the Atlantic Ocean (Sup figure 22d). Relative to the control simulation, mean uptake by other phytoplankton and total primary production both decrease by 4%, and nutrient uptake by diazotrophs declines by 3%.

A 25% reduction in iron input fluxes results in an 8% decrease in [Fe], from 0.73 nmol kg^{-1} in the control simulation to 0.67 nmol kg^{-1}. Notably, reduced iron supply is accompanied by lower rates of iron scavenging.

Phosphate and iron input flux 25% reduction simulation

Reducing PO_4^{3-} and Fe input flux increases surface nutrient limitation by PO_4^{3-} across the global ocean. For other phytoplankton, PO_4^{3-} emerges as the primary limiting nutrient over much of the surface, except in the northern Pacific, equatorial Pacific upwelling region and Southern Ocean, where Fe dominates as the key limiting factor (Sup figure 23a). Quantitatively PO_4^{3-} constrains nutrient uptake in approximately 70% of the surface ocean, with Fe accounting for limitation in the remaining 30%; DIN limitation is eliminated under these conditions. For diazotrophs, surface nutrient limitation (Sup figure 23b) is split between PO_4^{3-}, 51% of the surface ocean and notably between 30°N and 30°S apart from the equatorial Pacific upwelling region, while Fe imposes limitation in the higher latitudes and equatorial Pacific upwelling region equating to 49% of the surface ocean. Within the ocean interior, Fe deficiency prevails (Sup figure 23c and 23d).

Globally, mean PO_4^{3-} uptake by other phytoplankton (Sup figure 24a) is 0.36 μmol P kg^{-1} yr^{-1}, with peak rates in the Southern Ocean. Compared to control simulations, surface ocean uptake by other phytoplankton (Sup figure 24c) declines, especially in the North Atlantic. Diazotroph PO_4^{3-} uptake (Sup figure 24b and 24d) is eliminated across the surface ocean. The reduced input flux of PO_4^{3-} results in a 25% decrease in uptake for other phytoplankton, an elimination (100% decrease) for diazotrophs, and a 25% reduction in total primary production relative to the control simulation.

With the substantial reduction in PO_4^{3-} input, the global mean [PO_4^{3-}] reduces to 1.35 μmol kg^{-1}. Concurrently, an elimination of uptake by diazotrophs results in decreases in global mean [NO_3^-], from 28.8 to 24.0 μmol kg^{-1}, while [Fe] only reduces from 0.73 to 0.72 nmol kg^{-1} relative to the control simulation.

Phosphate and nitrate input flux 25% reduction simulation

Reducing PO_4^{3-} and NO_3^- input fluxes increases surface nutrient limitation by PO_4^{3-} across the global ocean. For other phytoplankton, PO_4^{3-} expands to limit much of the Arctic, lower latitude northern Atlantic and northern Indian Ocean; Fe limits the Southern Ocean with DIN limiting remaining areas (Sup figure 25a). Quantitatively DIN constrains nutrient uptake in approximately 68% of the surface ocean, with Fe and PO_4^{3-} both limiting 16%. For diazotrophs, surface nutrient limitation (Sup figure 25b) is split between PO_4^{3-}, 54% of the surface ocean and notably between 30°N and 30°S apart from the equatorial Pacific upwelling region, while Fe imposes limitation in the higher latitudes and equatorial Pacific upwelling region equating to 46% of the surface ocean. Within the ocean interior, Fe deficiency prevails (Sup figure 25c and 25d). Notably, for other phytoplankton, a region between 50°N and 60°N in the Atlantic exhibits PO_4^{3-} deficiency to depths below 2,000 m.

Globally, mean PO_4^{3-} uptake by other phytoplankton (Sup figure 26a) is 0.36 μmol P kg^{-1} yr^{-1}, with peak rates in the Southern Ocean. Compared to the control simulations, surface ocean uptake by other phytoplankton (Sup figure 26c) declines, especially in the North Atlantic. Diazotroph PO_4^{3-} uptake (Sup figure 26b and 26d), is almost eliminated across the surface ocean with mean uptake rate of 0.03 nmol P kg^{-1} yr^{-1}. The reduced input fluxes result in a 25% decrease in uptake for other phytoplankton, an 89% decrease for diazotrophs, and a 25% reduction in total primary production relative to the control simulation.

With the substantial reduction in PO_4^{3-} input, the global mean [PO_4^{3-}] reduces from 2.09 to 1.35 μmol kg^{-1}. Concurrently, global mean [NO_3^-] decreases, from 28.8 to 21.2 μmol kg^{-1} relative to the control simulation.

Nitrate and iron input flux 25% reduction simulation

A reduction in both NO_3^- and Fe supply leads to increased limitation of nutrient uptake by Fe (Sup figure 27a and 27b). Consequently, in 57% of the surface ocean other phytoplankton exhibit Fe-limited uptake, while 43% are limited by DIN, and less than 1% by PO_4^{3-}. For diazotrophs, nutrient uptake at the surface is primarily Fe-limited (99%), with PO_4^{3-} imitating in the remaining 1%. In the ocean interior, Fe deficiency predominates for both phytoplankton groups (Sup figure 27c and 27d).

Globally, mean phosphate uptake by other phytoplankton (Sup figure 28a) is 0.48 μmol P kg^{-1} yr^{-1}, representing a minor decrease compared to the control simulation and maintaining a similar spatial distribution. Diazotroph nutrient uptake rates increase relative to control conditions at 0.40 nmol P kg^{-1} yr^{-1}, and diazotroph activity exhibits a modest northward shift in the Atlantic Ocean (Sup figure 28d). Relative to the control simulation, mean uptake by other phytoplankton and total primary production both decrease by 5%, and nutrient uptake by diazotrophs increases by 25%.

A 25% reduction in iron input fluxes results in an 7% decrease in [Fe], from 0.73 nmol kg^{-1} in the control simulation to 0.68 nmol kg^{-1}.

Phosphate, nitrate and iron input flux 25% reduction simulation

Reducing the input flux of all nutrients tends to increase surface nutrient limitation by PO_4^{3-} (Sup figure 29a). For other phytoplankton, PO_4^{3-} limitation expands to a wider area of the northern Atlantic Ocean, northern Indian Ocean and some coastal southwestern areas. Fe limitation prevails in the Southern and Arctic Oceans and is co-limiting in the northern Pacific. DIN remains the primary limiting factor throughout most of the global surface ocean, accounting for approximately 68% of the area, while Fe and PO_4^{3-} constrain uptake in 21% and 11%, respectively. For diazotrophs, which circumvent nitrogen limitation via fixation, surface nutrient limitation is distributed between Fe (63%) and PO_4^{3-} (37%), with iron predominating in high latitudes and the equatorial Pacific upwelling zone, and phosphate elsewhere (Sup figure 29b). Within the ocean interior, iron deficiency is widespread (Sup figure 29c and 29d).

Globally, mean PO_4^{3-} uptake by other phytoplankton (Sup figure 30a) is 0.36 µmol P kg^{-1} yr^{-1}, with maximal rates observed in the Southern Ocean. Compared to control simulations, surface ocean uptake by other phytoplankton (Sup figure 30c) declines, especially in the North Atlantic. Diazotroph PO_4^{3-} uptake (Sup figure 30b and 30d) is nearly eliminated across the surface ocean with mean uptake rate of 0.04 nmol P kg^{-1} yr^{-1}. Relative to control, these reduced nutrient inputs drive a 25% reduction in other phytoplankton uptake, an 86% decline in diazotroph uptake, and an overall 25% decrease in total primary production.

Globally, mean [PO_4^{3-}] falls to 1.37 µmol kg^{-1}, while mean [NO_3^-] decreases, from 28.8 to 21.5 µmol kg^{-1} relative to the control simulation. [Fe] remains comparatively unchanged at 0.72 nmol kg^{-1}.

Summary of 125% nutrient fertilisation simulations

To summarise the 125% nutrient fertilisation simulations, we focus on the consequences for ocean PP at the simulation end-state (200 kyr). The principal rates and concentrations are detailed in Sup Table 1.

Firstly, single nutrient fertilisation simulations reveal that only PO_4^{3-} addition results in a sustained enhancement of ocean PP, yielding a 7% increase, including a twofold rise in diazotroph uptake. This intensified diazotroph activity drives a positive NO_3^- budget (input fluxes greater than output fluxes) and a 9% increase in the global ocean NO_3^- inventory, from 28.8 to 31.4 µmol kg^{-1}, with global Fe inventory remaining largely stable. In the surface ocean, nutrient uptake by other phytoplankton is limited by both Fe and DIN, while diazotrophs are Fe-limited. Whereas NO_3^- levels increase in response to elevated PO_4^{3-} inputs (because of N_2 fixation), Fe levels do not, constraining further increases in overall PP. Addition of NO_3^- produces an initial 5% rise in ocean PP; however, this transient boost is counteracted by the development of a negative PO_4^{3-} budget. Persistent PO_4^{3-} depletion ultimately restores other phytoplankton uptake rates to pre-fertilisation levels, and diazotrophs are eliminated due to the absence of low-DIN regions that previously favoured them. Similarly, Fe addition leads to a short-lived increase in ocean PP by as much as 13%, stimulating greater uptake by both other phytoplankton and diazotrophs for approximately two millennia. Subsequently, intensified denitrification drives a negative NO_3^- budget, and the gradual depletion of global NO_3^- and PO_4^{3-} concentrations result in sustained decreases in uptake rates for both phytoplankton groups, returning to baseline rates over the course of the simulation. In summary, among the single nutrient fertilisation experiments, only PO_4^{3-} enrichment yields a long-term increase in ocean PP.

Secondly, dual nutrient fertilisation simulations are considered. The combined addition of PO_4^{3-} and Fe produces a sustained increase in overall PP, with total rates rising by 41% (from 15.1 to 21.3 Tmol P yr^{-1}) and a striking 680% enhancement in diazotroph nutrient uptake (from 9.06 to 70.7 Gmol P yr^{-1}). This pronounced stimulation of diazotroph activity elevates mean global [NO_3^-] from 28.8 to 37.6 µmol kg^{-1}. This increase in NO_3^- alongside the fertilisation of PO_4^{3-} and Fe results in the simultaneous enhancement of all potentially limiting nutrients and supports the increased overall PP. Simultaneous enrichment with PO_4^{3-} and NO_3^- yields a moderate 14% increase in global primary production, rising from 15.1 to 17.3 Tmol P yr^{-1}. Diazotroph nutrient uptake remains largely unchanged under this regime. Enhanced Fe limitation emerges across the surface ocean, constraining further gains in primary productivity despite the dual nutrient additions. Simultaneous enrichment with NO_3^- and Fe results in a transient increase in ocean PP by as much as 15%, stimulating greater uptake by both other phytoplankton and diazotrophs for approximately two millennia. However, the gradual depletion of global PO_4^{3-} concentrations subsequently leads to persistent declines in uptake rates for both phytoplankton groups. Eventually, other phytoplankton uptake returns to baseline rates over the course of the simulation, while diazotrophs are eliminated due to the loss of low-DIN regions that previously sustained their activity. Among dual nutrient fertilisation scenarios, only simulations involving PO_4^{3-} yield sustained increases in oceanic PP, with combined PO_4^{3-} and Fe fertilisation producing the most pronounced and sustained enhancement.

Finally, we consider the scenario where all nutrient fluxes are increase simultaneously. An increase of 125% in nutrient fluxes results in a 46% increase in oceanic PP. Notably, global mean [Fe] increases modestly, by only 15%, reaching 0.84 nmol kg^{-1}. this results in an even more pronounced Fe deficiency in the deep ocean. These results suggest that deep-water iron deficiency ultimately sets an upper limit to oceanic primary productivity.

Summary of nutrient reduction simulations

We present a summary of the simulation scenarios with a 25% reduction in nutrient input fluxes, focusing on implications for oceanic primary production (OPP) and the system state at 200 kyr, with principal rates and concentrations detailed in Sup table 2.

A decreased input of PO_4^{3-} establishes a negative global budget, driving a decline in global mean [PO_4^{3-}]. By the simulation's conclusion, diazotroph activity is eradicated, while both other phytoplankton and total OPP decrease by 25%. In contrast, reducing NO_3^- inputs stimulate a 40% increase in diazotroph nutrient uptake, which helps stabilise global mean [NO_3^-] concentrations at the same level as in the control simulation; notably, uptake rates for other phytoplankton and total OPP are unaffected (the same as in the control simulation). Reducing Fe input fluxes lowers mean global [Fe] from 0.73 to 0.67 nmol kg^{-1} relative to the control, but only minimally impacts nutrient uptake: diazotroph uptake falls by 3%, while other phytoplankton and OPP decline by just 4%.

For dual nutrient input reductions that include PO_4^{3-}, the changes in OPP are dominated by the impacts on the PO_4^{3-} budget. For both the PO_4^{3-} and NO_3^- reduction and PO_4^{3-} and Fe reduction a negative PO_4^{3-} budget drives a decline in global mean [PO_4^{3-}]. By the simulation's conclusion, diazotroph uptake is eradicated in the case of PO_4^{3-} and Fe and reduced by 89% for PO_4^{3-} and NO_3^-, while both other phytoplankton and total OPP decrease by 25%. Reducing NO_3^- and Fe simultaneously reduces mean global [Fe] from 0.73 to 0.67 nmol kg^{-1} relative to the control, but only minimally impacts nutrient uptake: diazotroph uptake increases by 25%, while other phytoplankton and OPP decline by just 5%. Reducing the input fluxes of the three nutrients simultaneously once again results in a decline in global mean [PO_4^{3-}] due to a negative PO_4^{3-} budget. Diazotroph uptake is reduced by 86%, while both other phytoplankton and total OPP decrease by 25%.

Spatial analysis

There are some notable variations in the impacts of fertilisation between the ocean basins. To focus on these Sup table 3 provides nutrient uptake rates for OPP, other phytoplankton and diazotroph globally and then specifically for the Atlantic Ocean, Pacific Ocean and Southern Ocean. Noteworthy examples of basin of variations are: (a) for PO_4^{3-} addition, other phytoplankton and diazotroph uptake increase by 21% and 95% respectively in the Atlantic Ocean with smaller magnitude changes in the other basins; (b) for Fe addition, Atlantic Ocean changes in uptake rates for other phytoplankton and diazotroph are -23% and -81%, Pacific Ocean changes are 0% and 69%, Southern Ocean changes are 22% and 0%; (c) for PO_4^{3-} and Fe addition, the magnitude of other phytoplankton uptake increases is greatest in the Atlantic Ocean (72%), then the Southern

Ocean (28%) and Pacific Ocean (23%); (d) PO_4^{3-} and NO_3^- addition show a similar pattern to PO_4^{3-} addition but with greater magnitudes and (e) NO_3^- and Fe addition are similar to Fe addition but with greater magnitudes.

Statistical analysis of nutrient transects

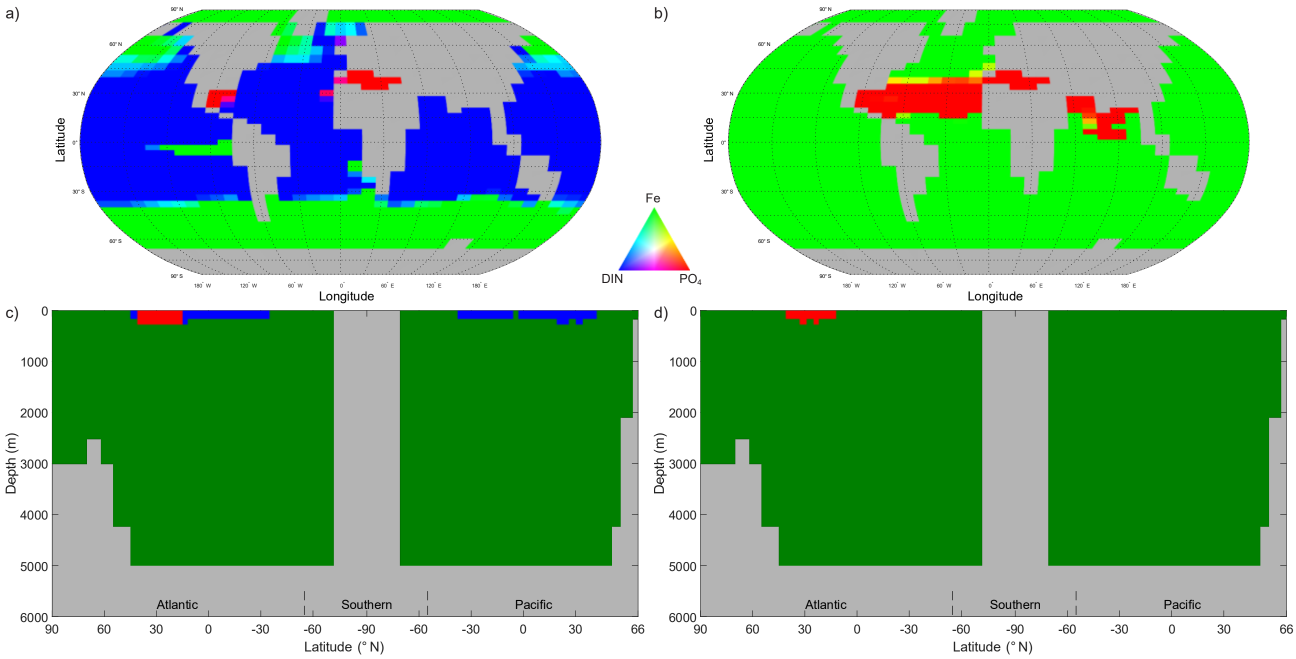
Figure 3 provides deep water (≈2 750 m) nutrient and O_2 concentrations along a transect southward from the North Atlantic to the Southern Ocean and then northward to the North Pacific. It appears obviously from Figure 3 that concentration of PO_4^{3-} and NO_3^- increase along the transect, they have higher concentrations in the Pacific Ocean than the Atlantic Ocean. The opposite is true for O_2 concentrations higher values are seen in the Atlantic Ocean with reduced concentrations in the Pacific Ocean. However, Fe concentrations appear constant along the transect with no noticeable difference between the Atlantic and Pacific Oceans. These observations from Figure 3 are tested statistically by the establishment of three hypotheses.

$^1H_0$ null hypothesis is that the Atlantic Ocean and Pacific Ocean are samples from continuous distributions with equal medians. The statistical test appropriate to test this $^1H_0$ is a Mann-Whitney U test as the test does not assume a normal distribution. $^2H_0$ null hypothesis is that the Atlantic Ocean and Pacific Ocean comes from independent random samples from normal distributions with equal means and equal variances. The statistical test appropriate to test this $^2H_0$ is a t-test as a normal distribution is assumed. $^3H_0$ null hypothesis is that the population mean for the Pacific Ocean data points is less than the population mean Atlantic Ocean data points. The hypothesis is again tested using a t-test but with a sided test. Fe, PO_4^{3-}, NO_3^- and O_2 mean concentrations and standard deviations for Atlantic and Pacific Ocean data points are provided in Sup table 4; results of hypothesis test are also provided and support the observations from Figure 3.

Supplementary figures

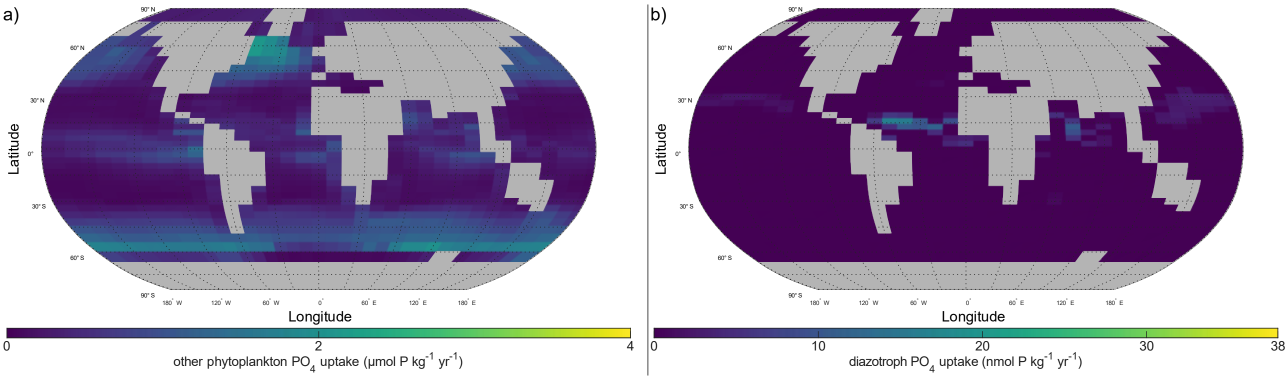
Control

Sup figure 1 – Control surface limitation and nutrient deficiency



Sup figure 1: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for control simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

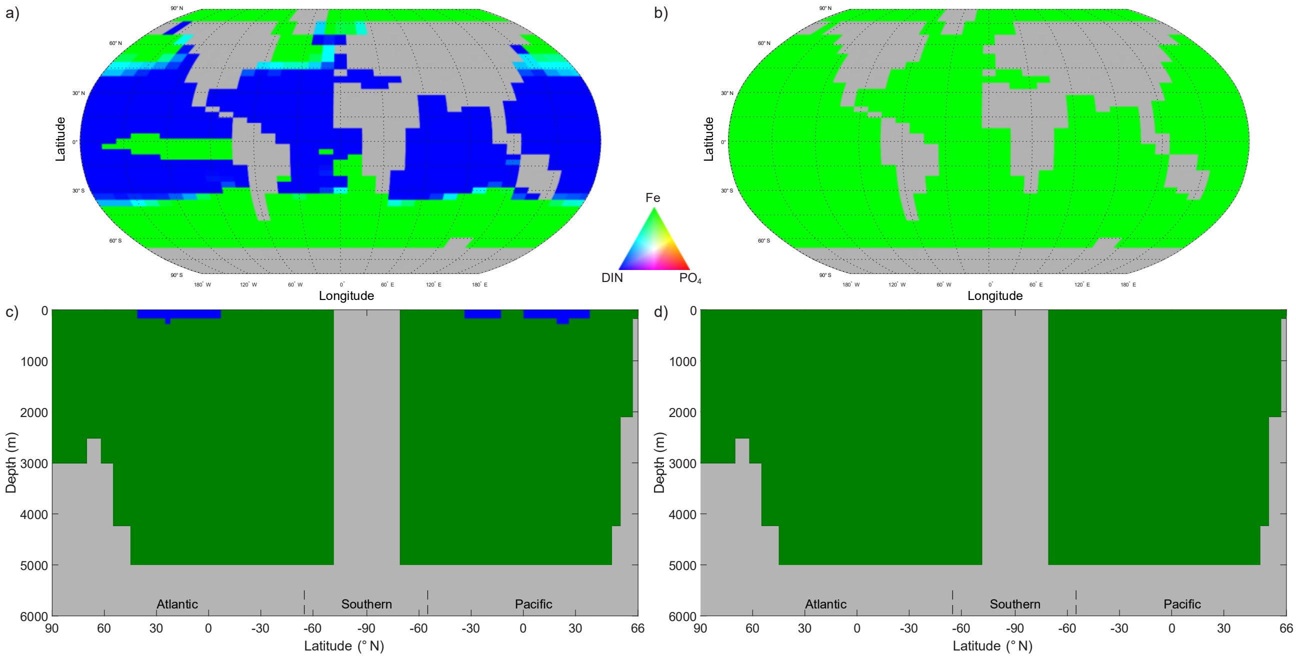
Sup figure 2 – Control uptake



***Sup figure 2: Nutrient uptake for other phytoplankton and diazotrophs for the control simulation.** a) other phytoplankton PO_4^{3-} uptake in μmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}.*

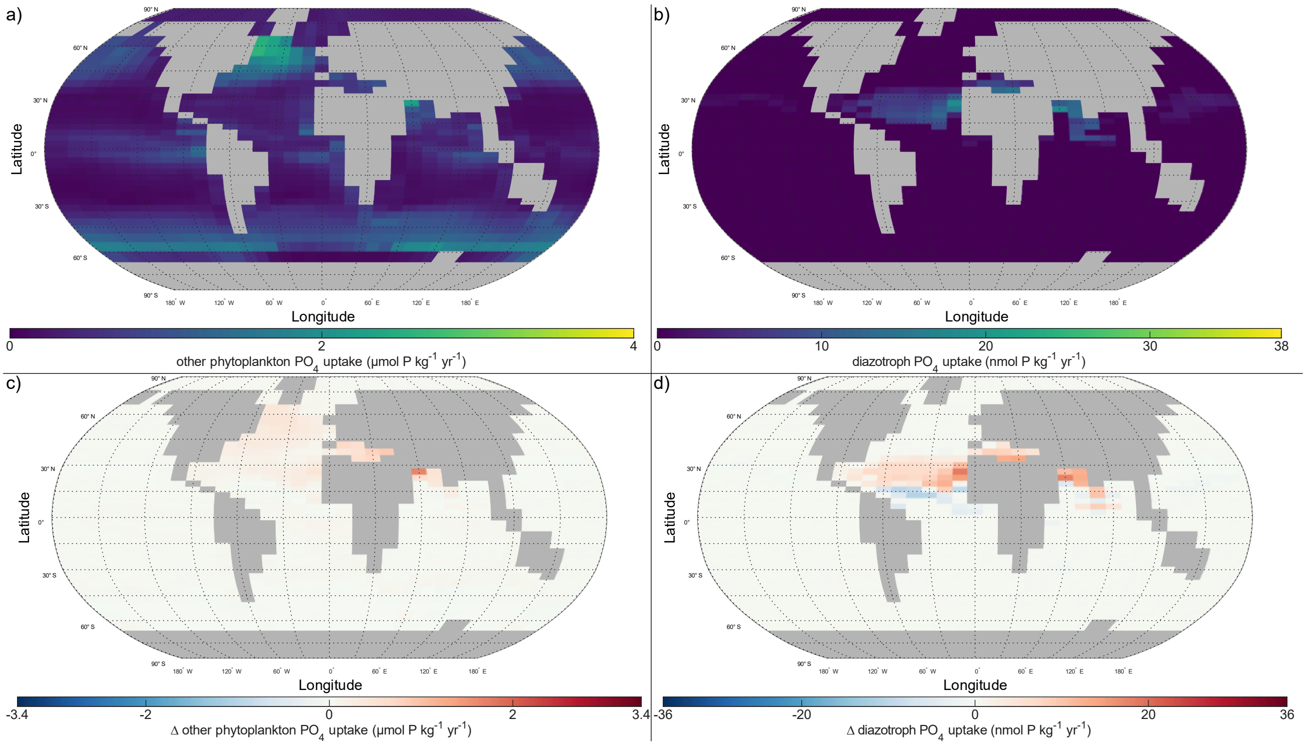
Addition fertilisation simulations

Sup figure 3 – Phosphate fertilisation, surface limitation and nutrient deficiency



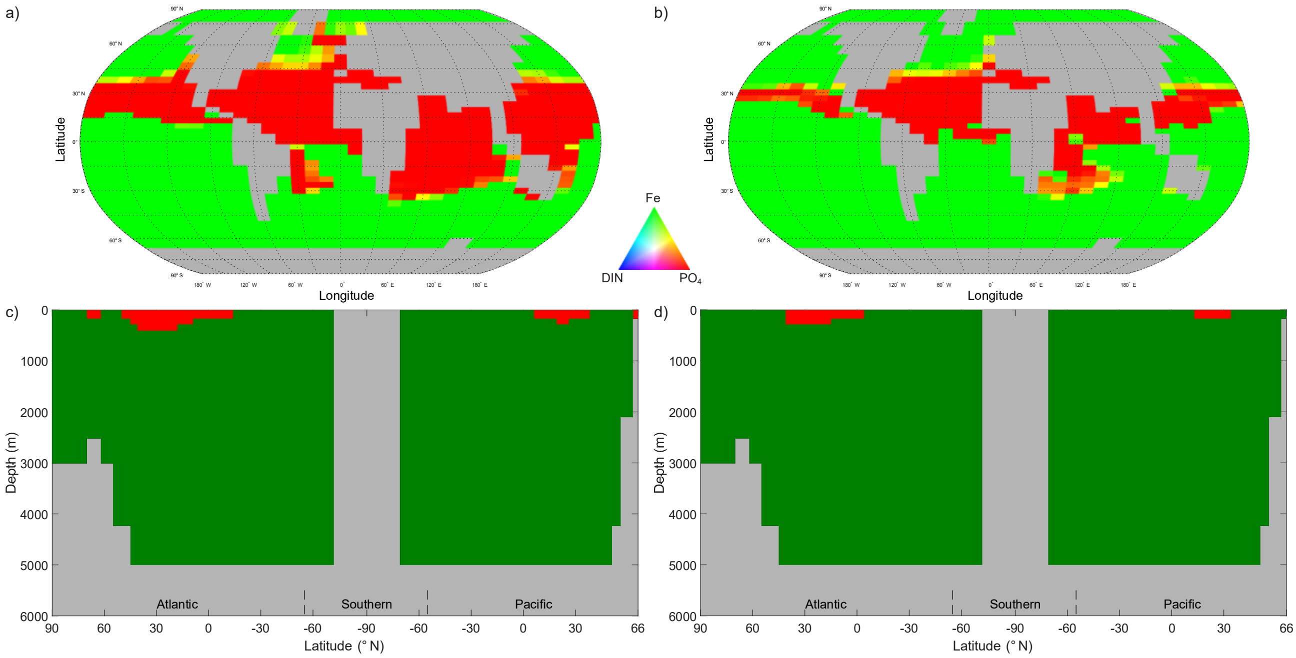
Sup figure 3: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 125% phosphate fertilisation simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 4 – Phosphate fertilisation, Uptake and delta uptake



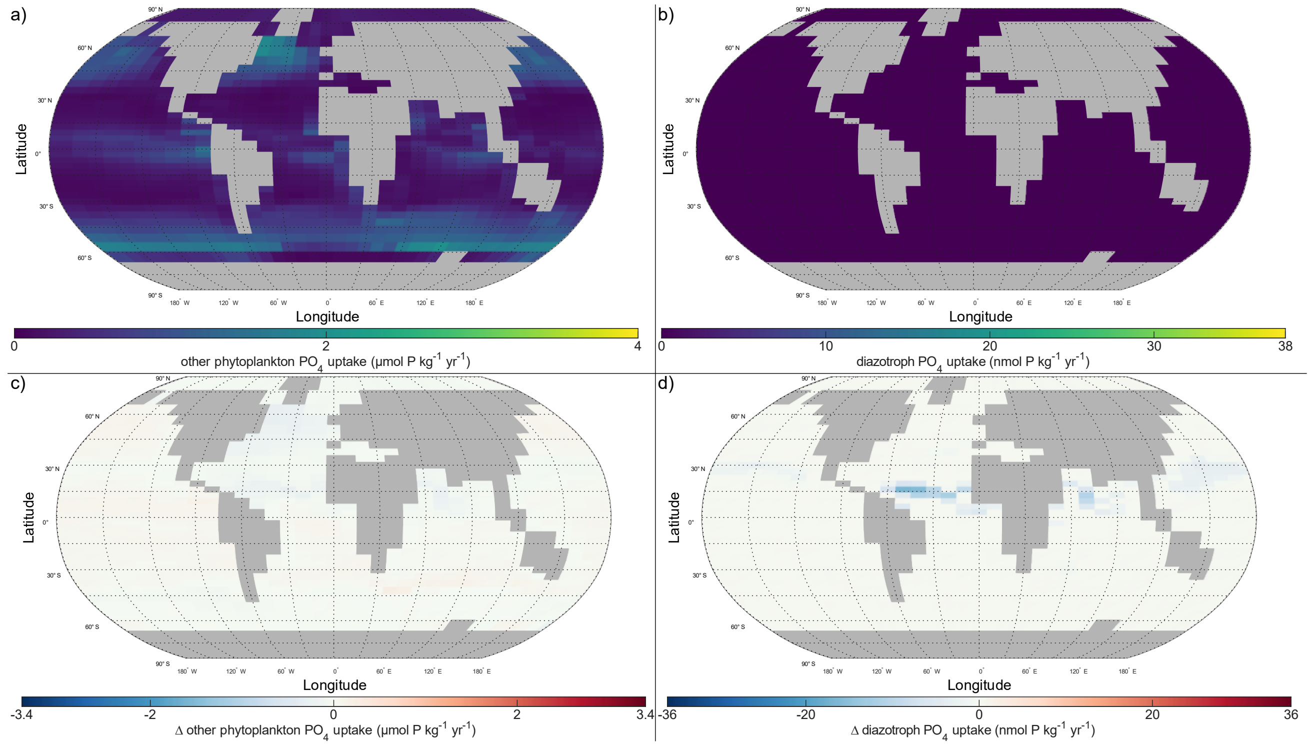
Sup figure 4: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for +125% phosphate fertilisation simulation. *a) other phytoplankton PO_4^{3-} uptake in µmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (fertilisation simulation - control) in µmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (fertilisation simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 5 – Nitrate fertilisation, surface limitation and nutrient deficiency



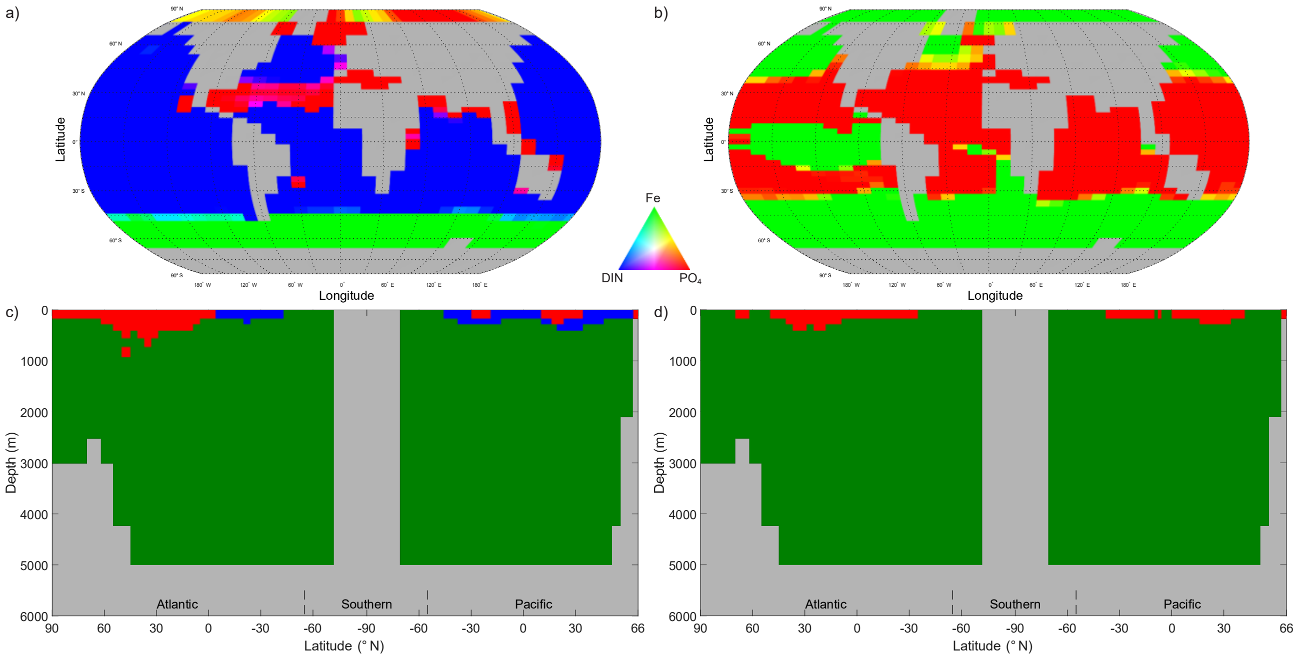
Sup figure 5: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 125% nitrate fertilisation simulation. *a) other phytoplankton surface limitation: red =* PO_4^{3-} *limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red =* PO_4^{3-} *limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red =* PO_4^{3-} *deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 6 – Nitrate fertilisation, Uptake and delta uptake



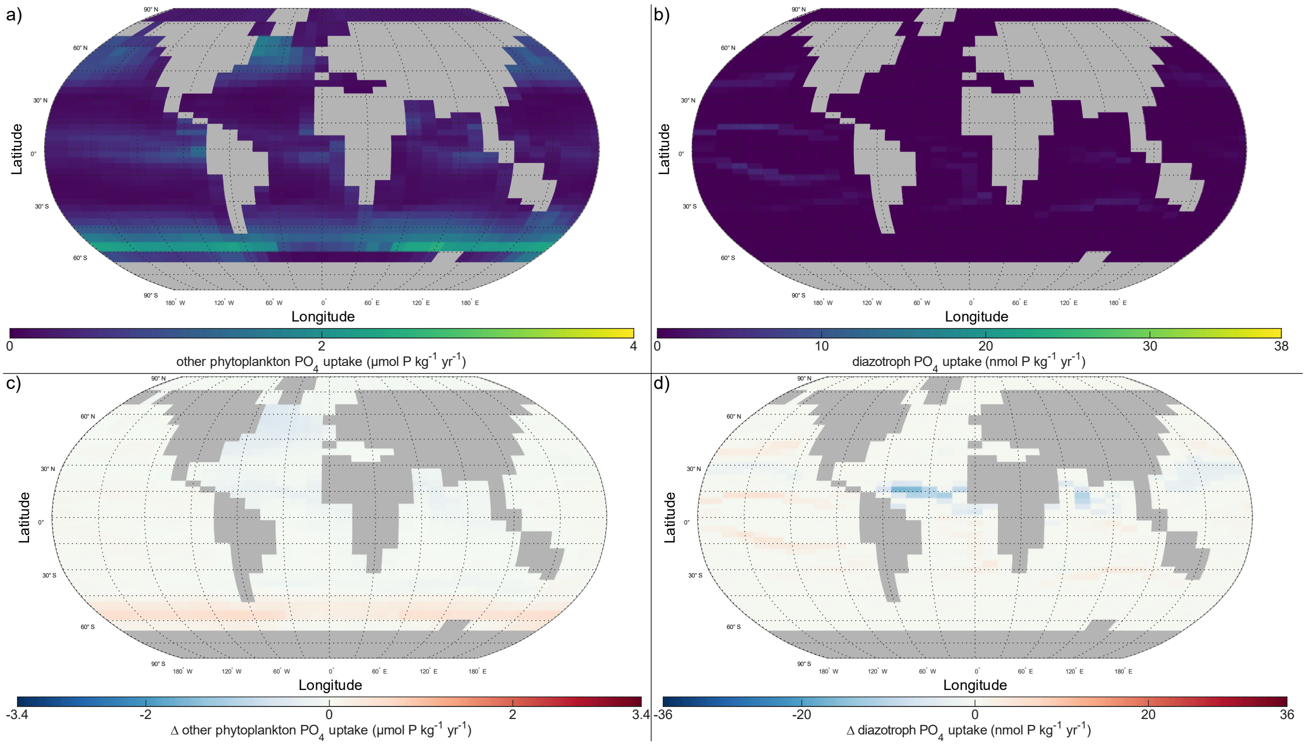
Sup figure 6: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for +125% nitrate fertilisation simulation. *a) other phytoplankton PO_4^{3-} uptake in μmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (fertilisation simulation - control) in μmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (fertilisation simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 7 – Iron fertilisation, surface limitation and nutrient deficiency



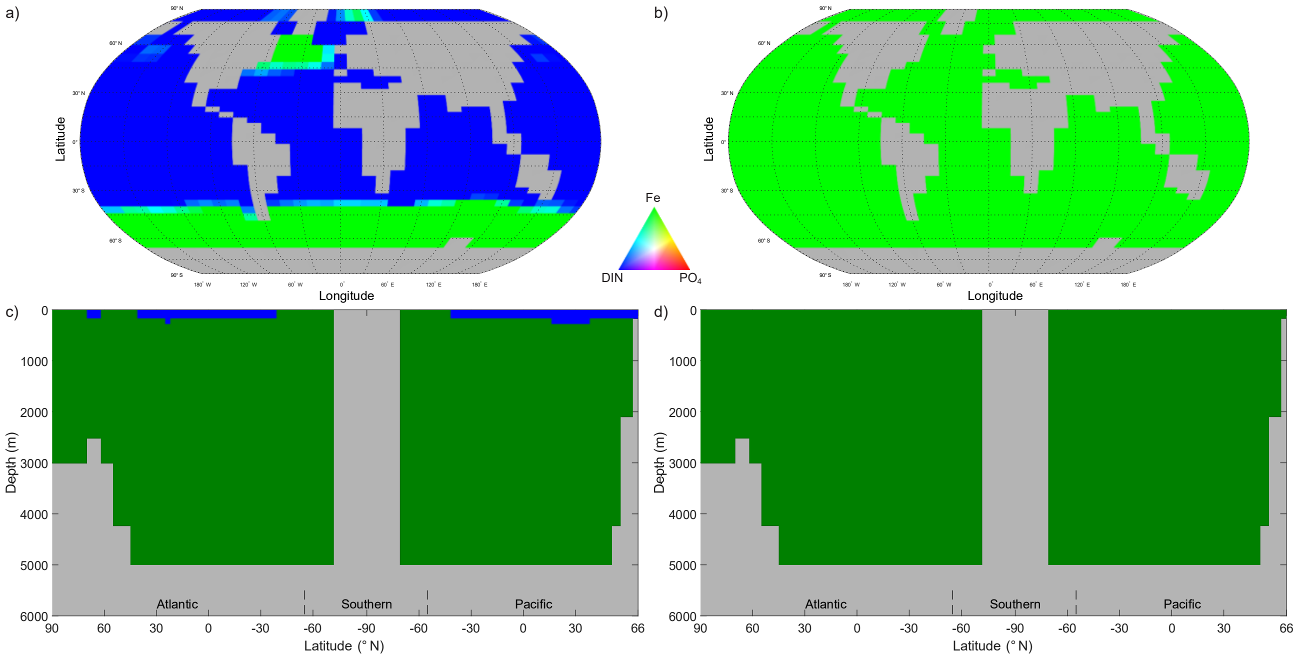
Sup figure 7: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 125% iron fertilisation simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 8 – Iron fertilisation, Uptake and delta uptake



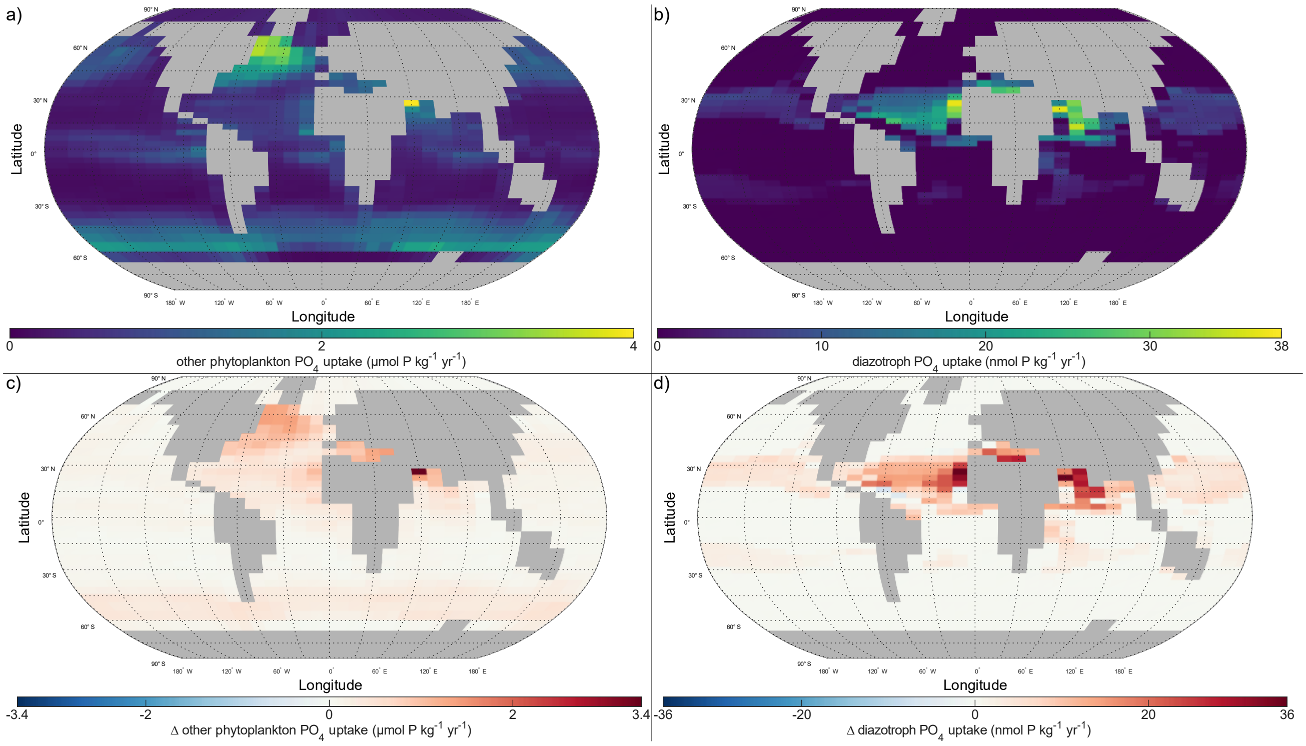
Sup figure 8: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for +125% iron fertilisation simulation. *a) other phytoplankton PO_4^{3-} uptake in µmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (fertilisation simulation - control) in µmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (fertilisation simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 9 – Phosphate and iron fertilisation, surface limitation and nutrient deficiency



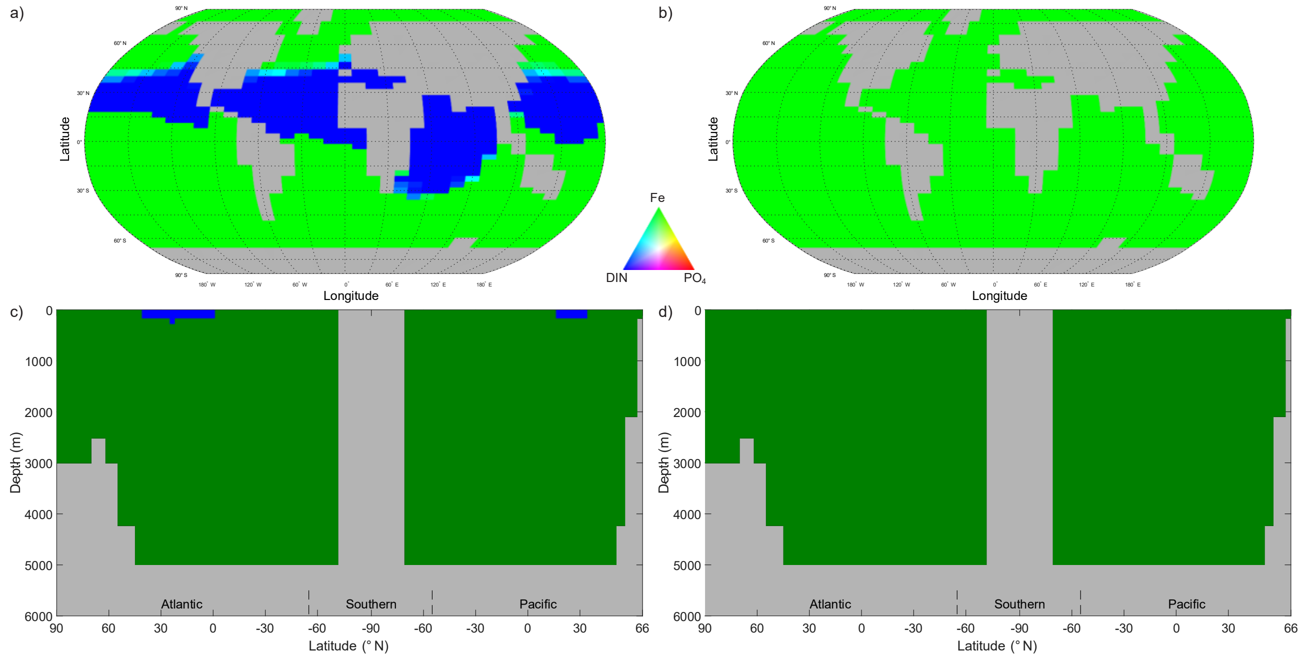
Sup figure 9: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 125% phosphate and iron fertilisation simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 10 – Phosphate and iron fertilisation, Uptake and delta uptake



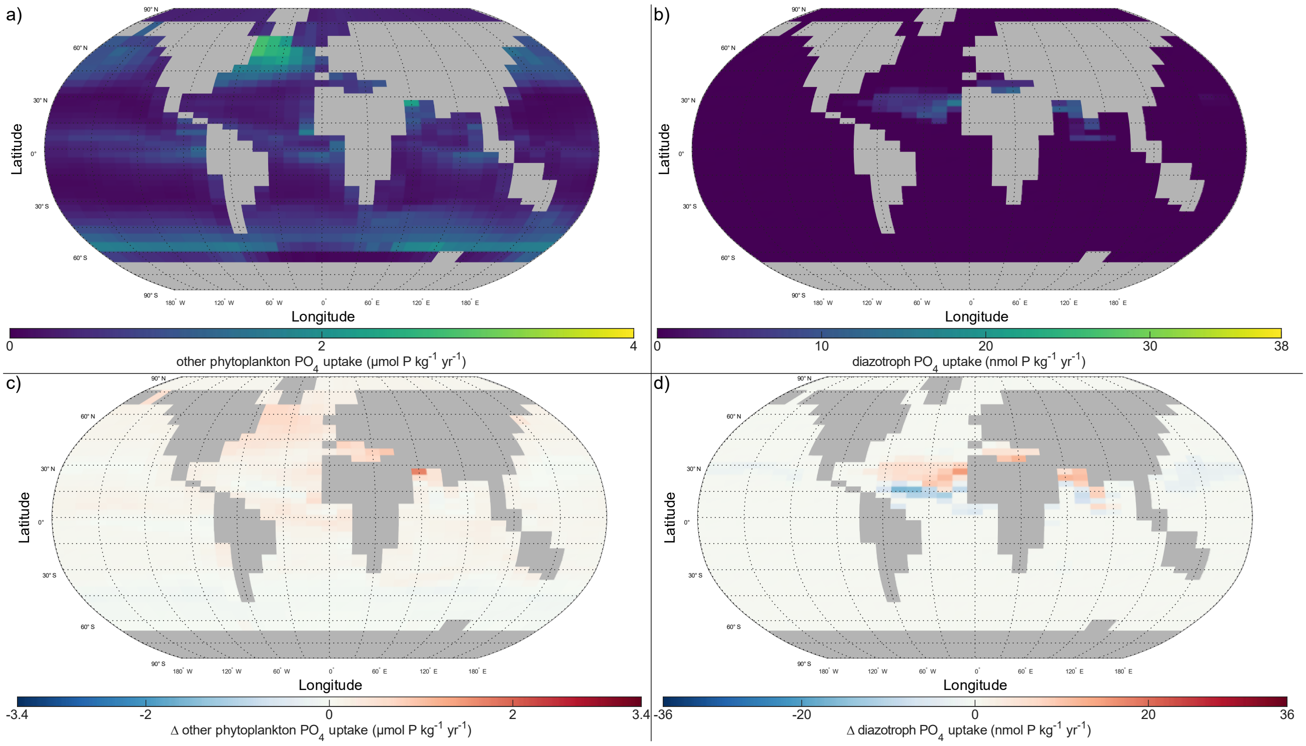
Sup figure 10: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for +125% phosphate and iron fertilisation simulation. *a) other phytoplankton PO_4^{3-} uptake in μmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (fertilisation simulation - control) in μmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (fertilisation simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 11 – Phosphate and nitrate fertilisation, surface limitation and nutrient deficiency



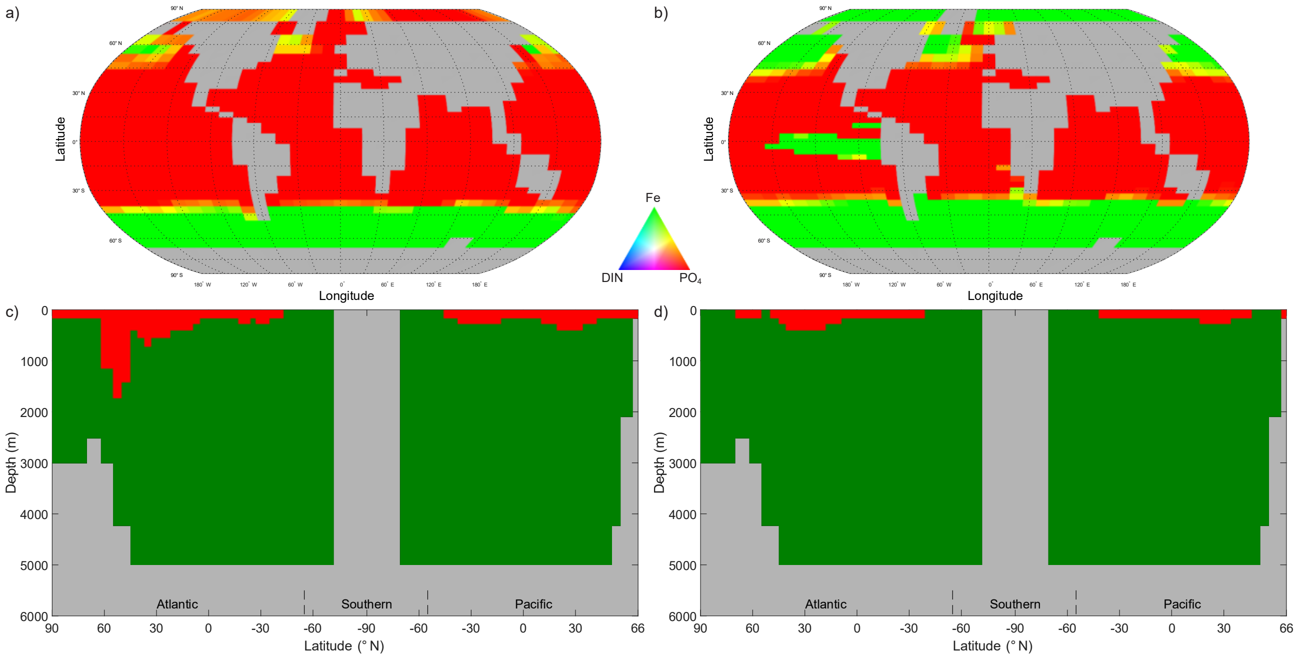
Sup figure 11: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 125% phosphate and nitrate fertilisation simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 12 – Phosphate and nitrate fertilisation, Uptake and delta uptake



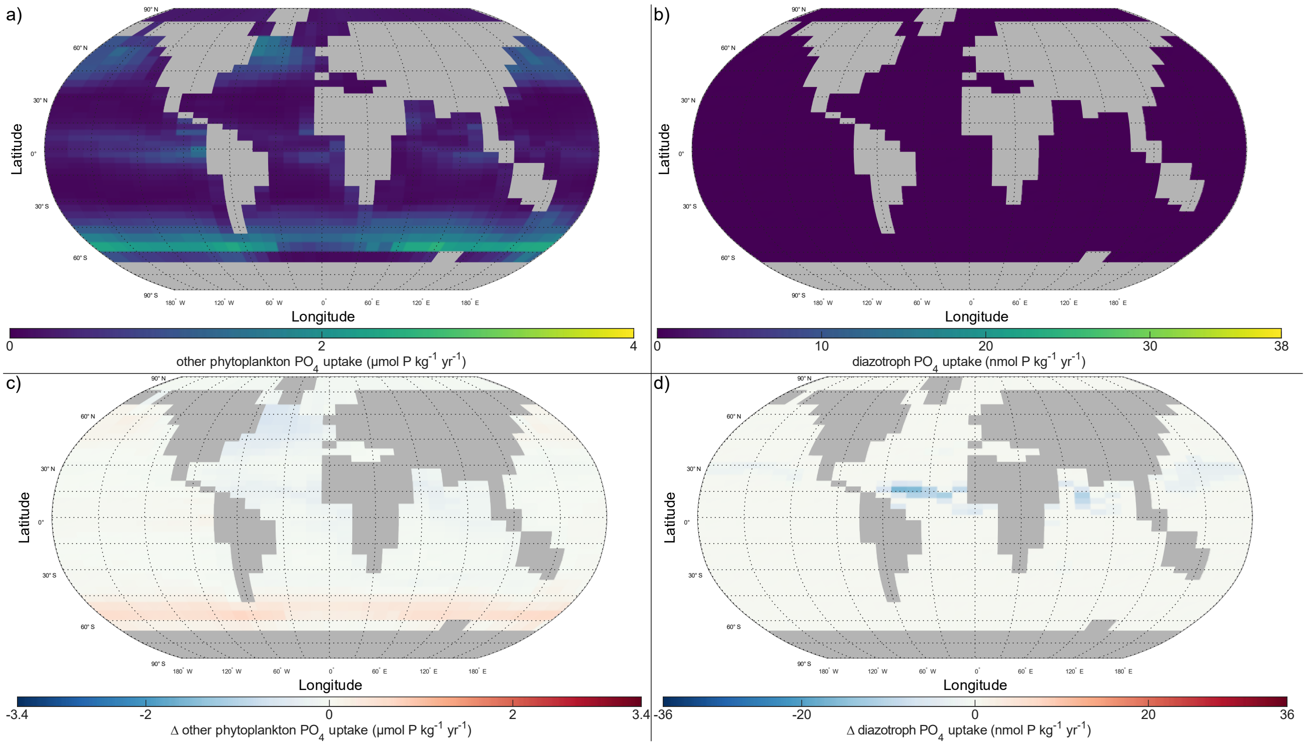
Sup figure 12: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for +125% phosphate and nitrate fertilisation simulation. *a) other phytoplankton PO_4^{3-} uptake in μmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (fertilisation simulation - control) in μmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (fertilisation simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 13 – Nitrate and iron fertilisation, surface limitation and nutrient deficiency



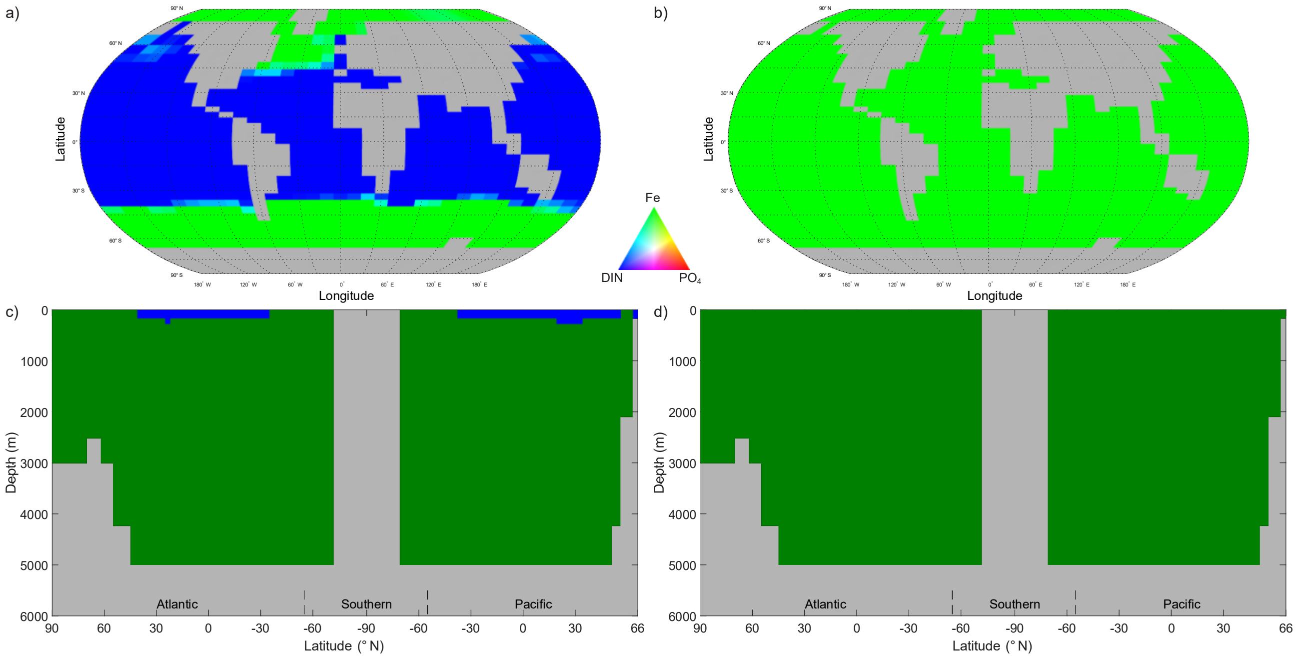
Sup figure 13: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 125% nitrate and iron fertilisation simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 14 – Nitrate and iron fertilisation, Uptake and delta uptake



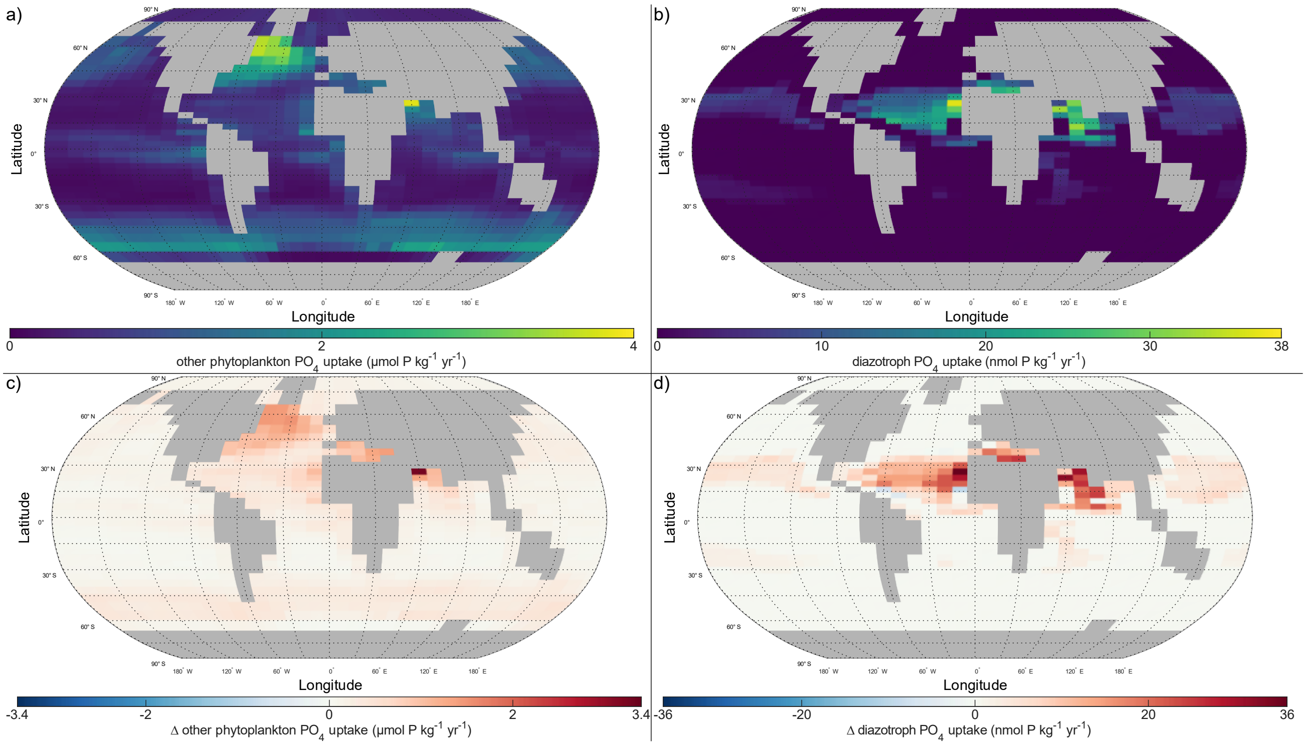
Sup figure 14: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for +125% nitrate and iron fertilisation simulation. *a) other phytoplankton PO_4^{3-} uptake in μmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (fertilisation simulation - control) in μmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (fertilisation simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 15 – Phosphate, nitrate and iron fertilisation, surface limitation and nutrient deficiency



Sup figure 15: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 125% phosphate, nitrate and iron fertilisation simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

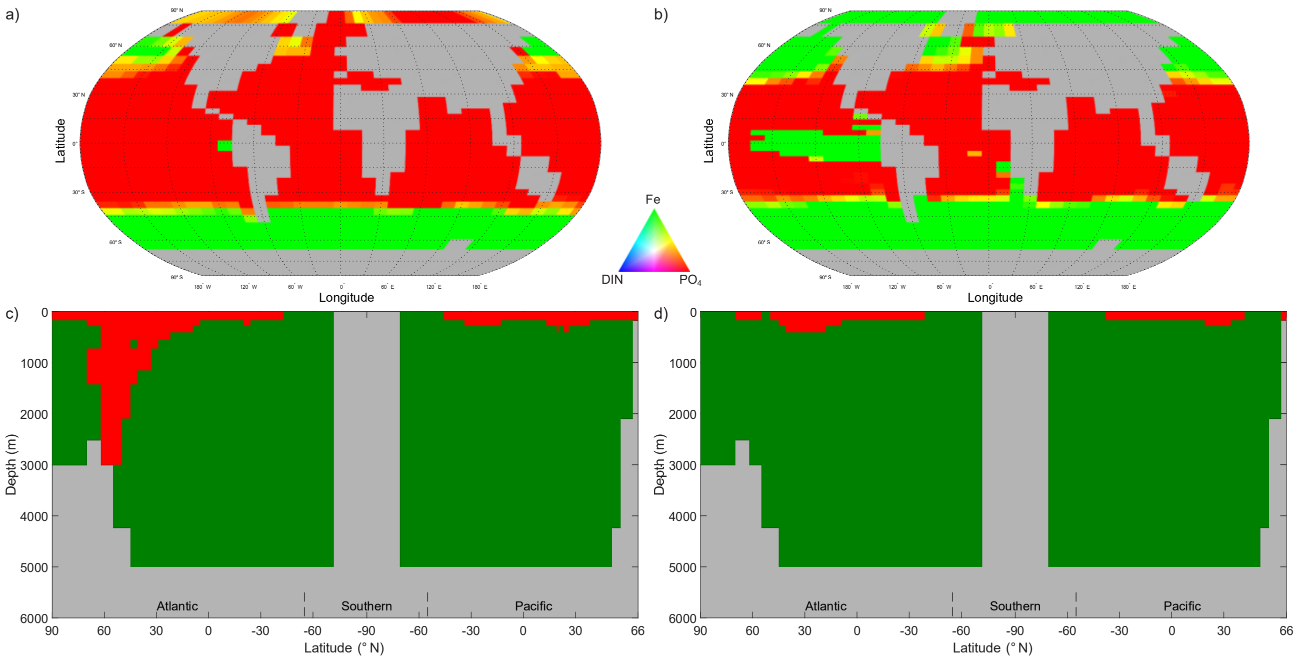
Sup figure 16 – Phosphate, nitrate and iron fertilisation, Uptake and delta uptake



Sup figure 16: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for +125% phosphate, nitrate and iron fertilisation simulation. *a) other phytoplankton PO_4^{3-} uptake in μmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (fertilisation simulation - control) in μmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (fertilisation simulation - control) in nmol kg^{-1} yr^{-1}.*

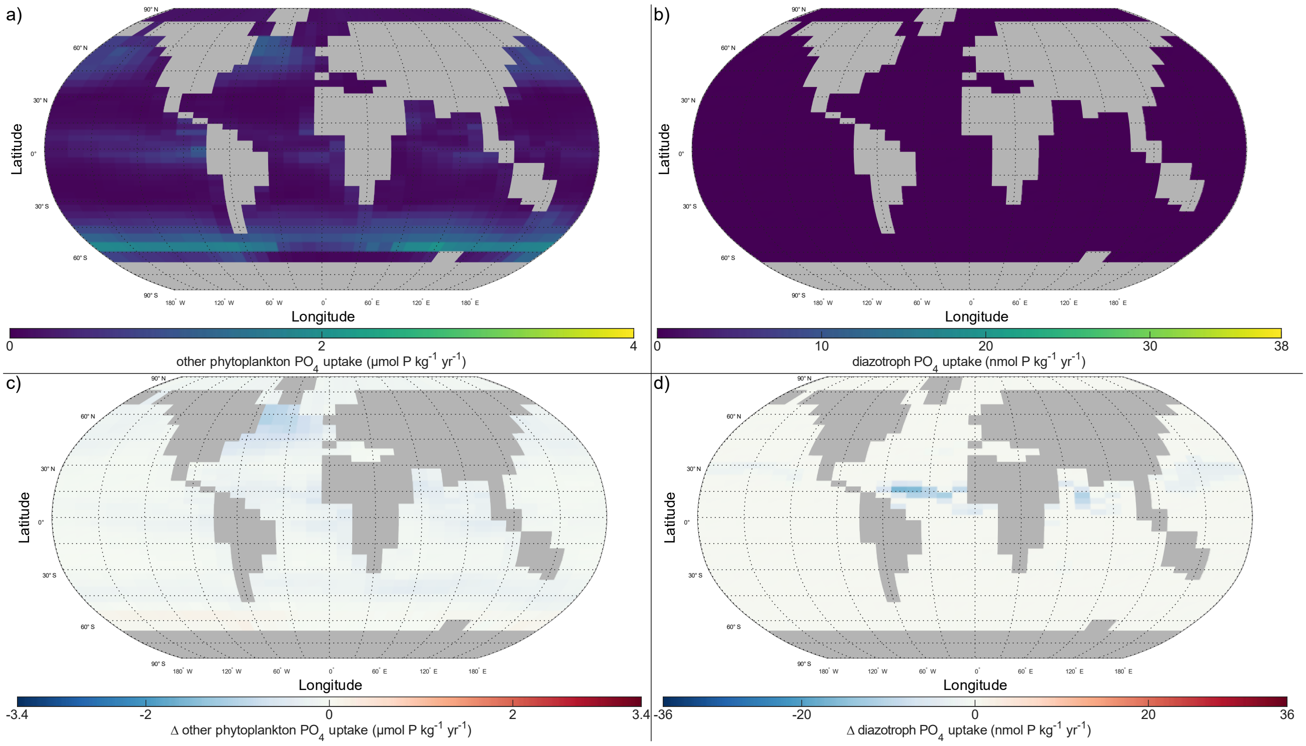
Nutrient reduction simulations

Sup figure 17 – Phosphate nutrient reduction, surface limitation and nutrient deficiency



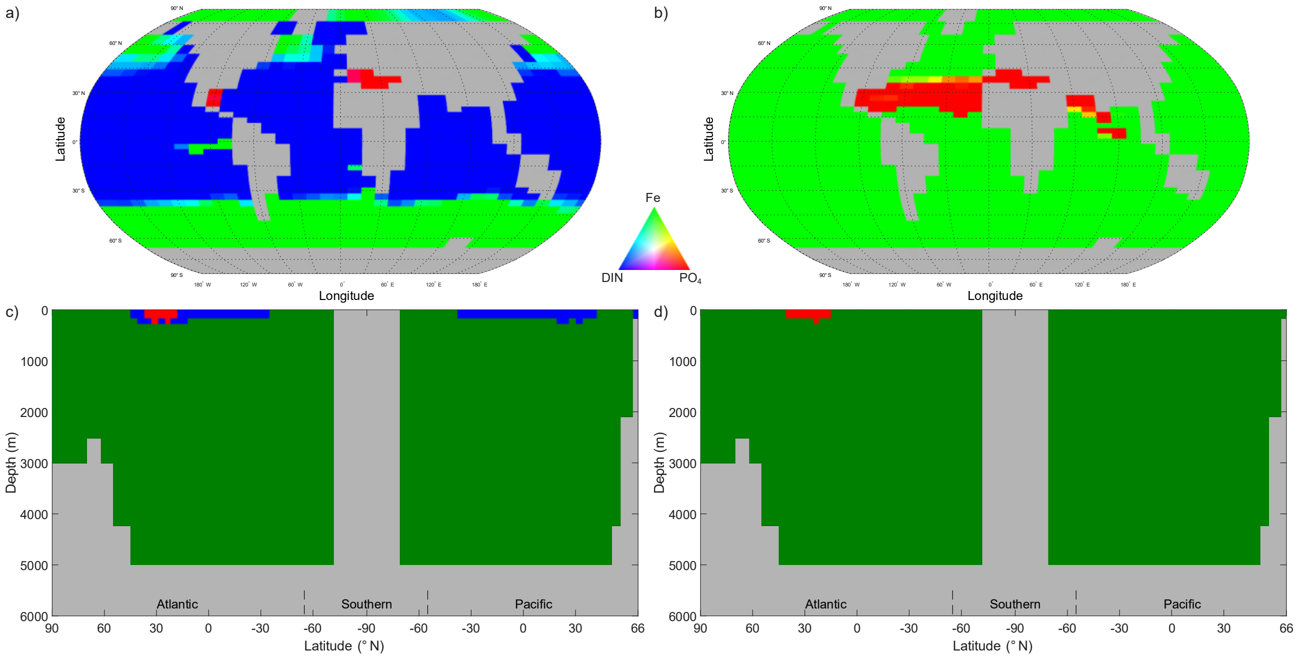
Sup figure 17: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 25% phosphate nutrient reduction simulation. *a) other phytoplankton surface limitation: red =* PO_4^{3-} *limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red =* PO_4^{3-} *limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red =* PO_4^{3-} *deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 18 – Phosphate nutrient reduction, Uptake and delta uptake



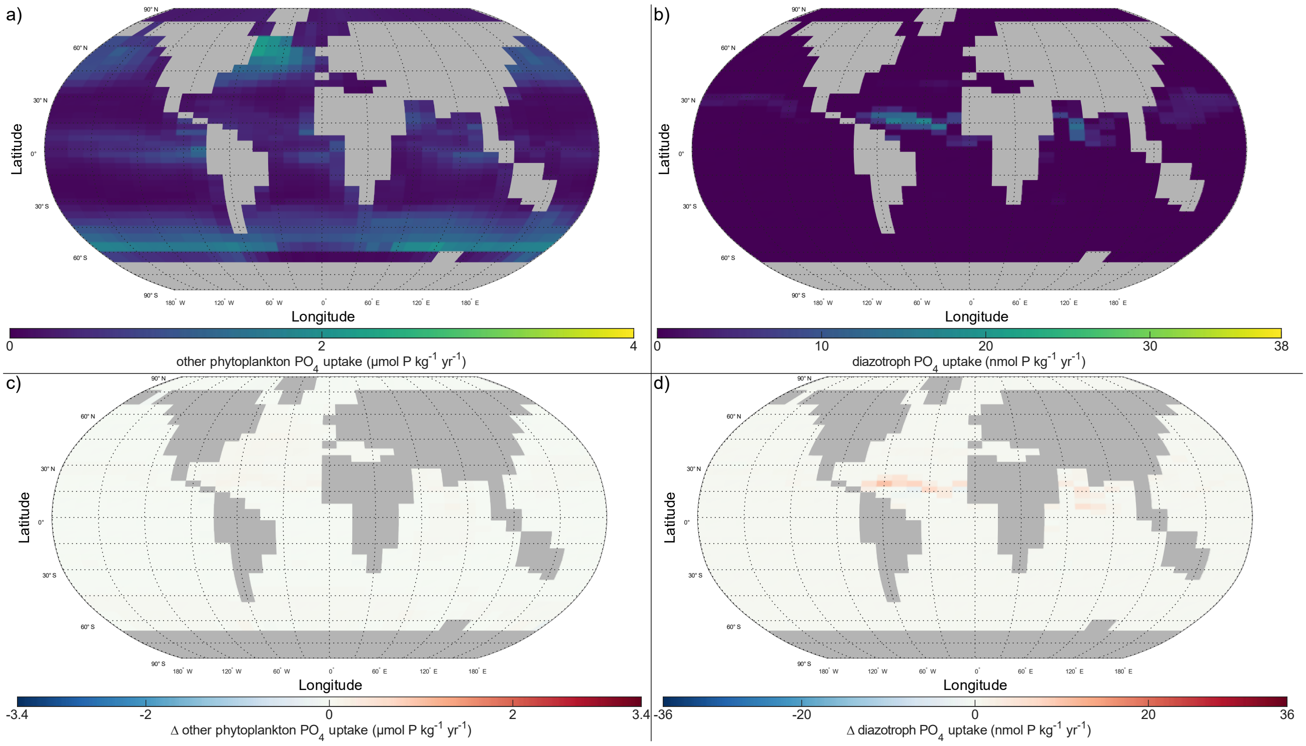
Sup figure 18: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for 25% phosphate nutrient reduction simulation. *a) other phytoplankton PO_4^{3-} uptake in µmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (reduction simulation - control) in µmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (reduction simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 19 – Nitrate nutrient reduction, surface limitation and nutrient deficiency



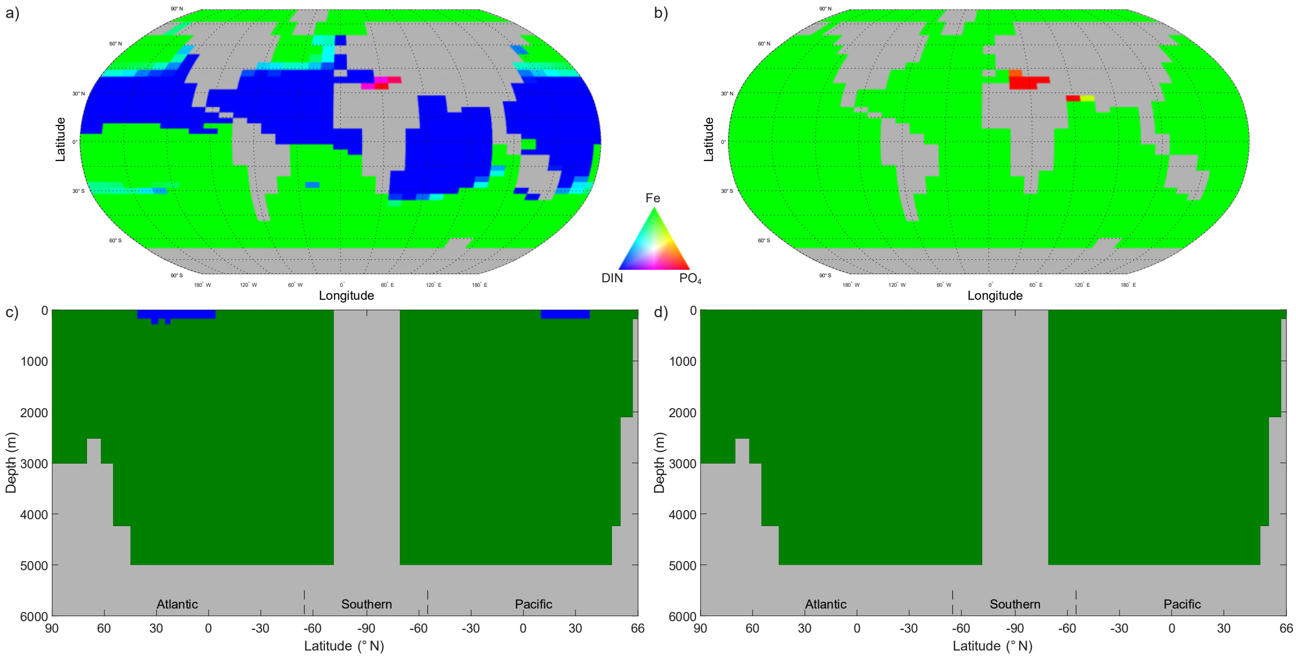
Sup figure 19: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 25% nitrate nutrient reduction simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 20 – Nitrate nutrient reduction, Uptake and delta uptake



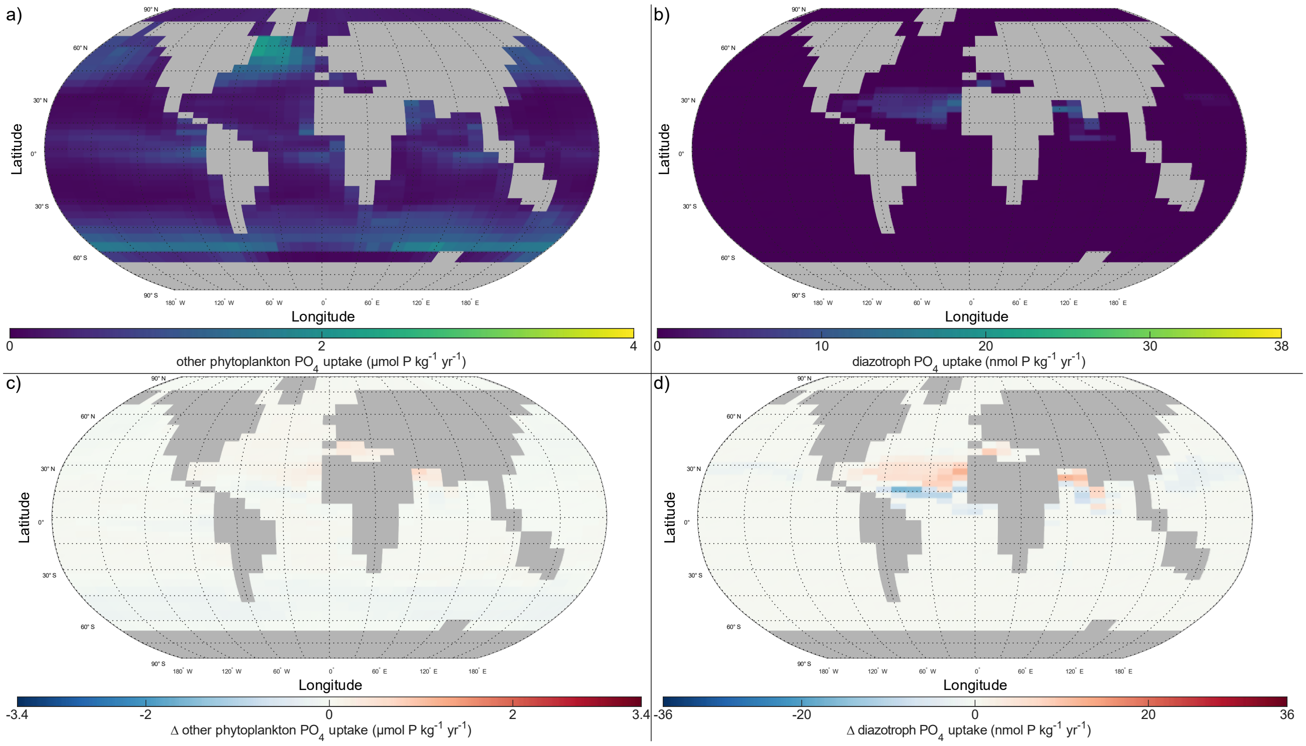
Sup figure 20: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for 25% nitrate nutrient reduction simulation. *a) other phytoplankton PO_4^{3-} uptake in µmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (reduction simulation - control) in µmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (reduction simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 21 – Iron nutrient reduction, surface limitation and nutrient deficiency



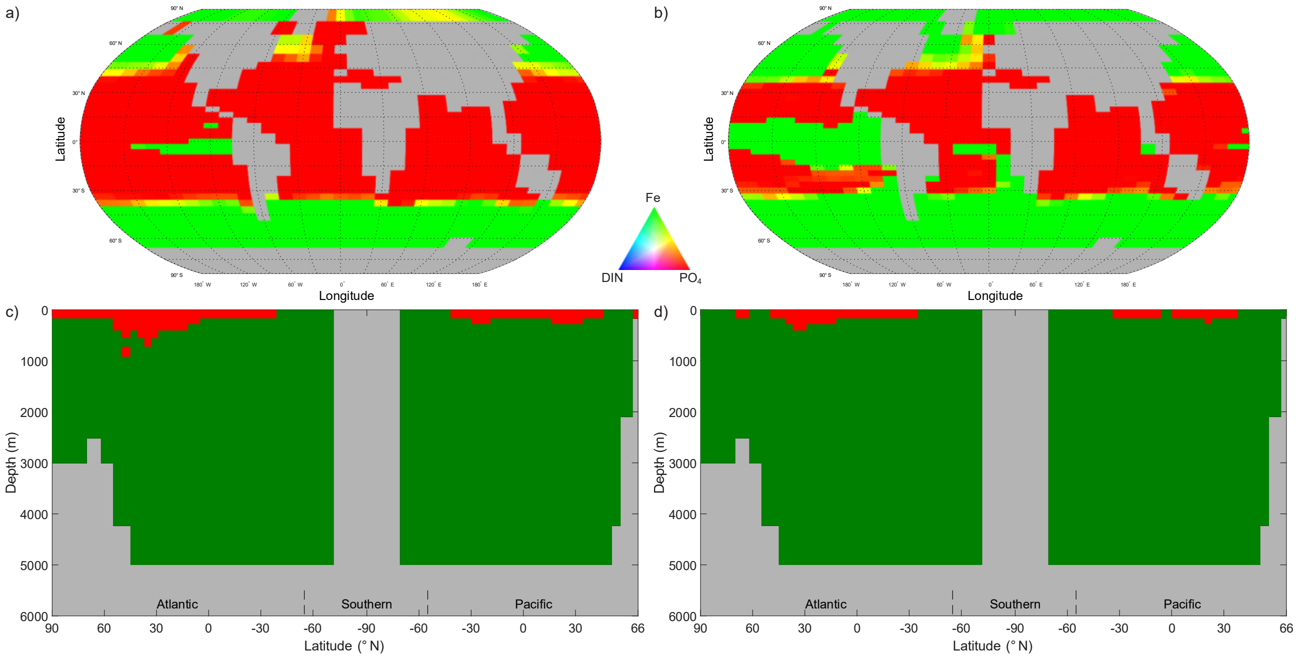
Sup figure 21: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 25% iron nutrient reduction simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 22 – Iron nutrient reduction, Uptake and delta uptake



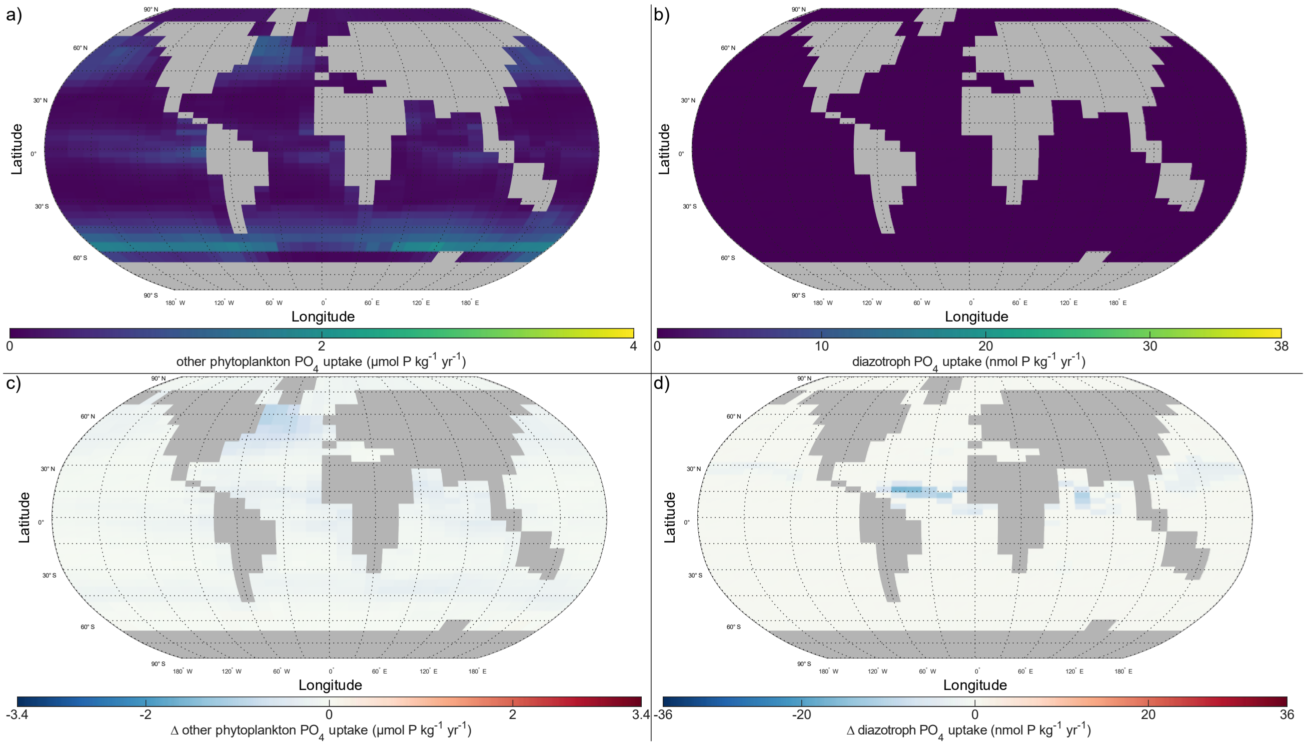
Sup figure 22: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for 25% iron nutrient reduction simulation. *a) other phytoplankton PO_4^{3-} uptake in μmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (reduction simulation - control) in μmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (reduction simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 23 – Phosphate and iron nutrient reduction, surface limitation and nutrient deficiency



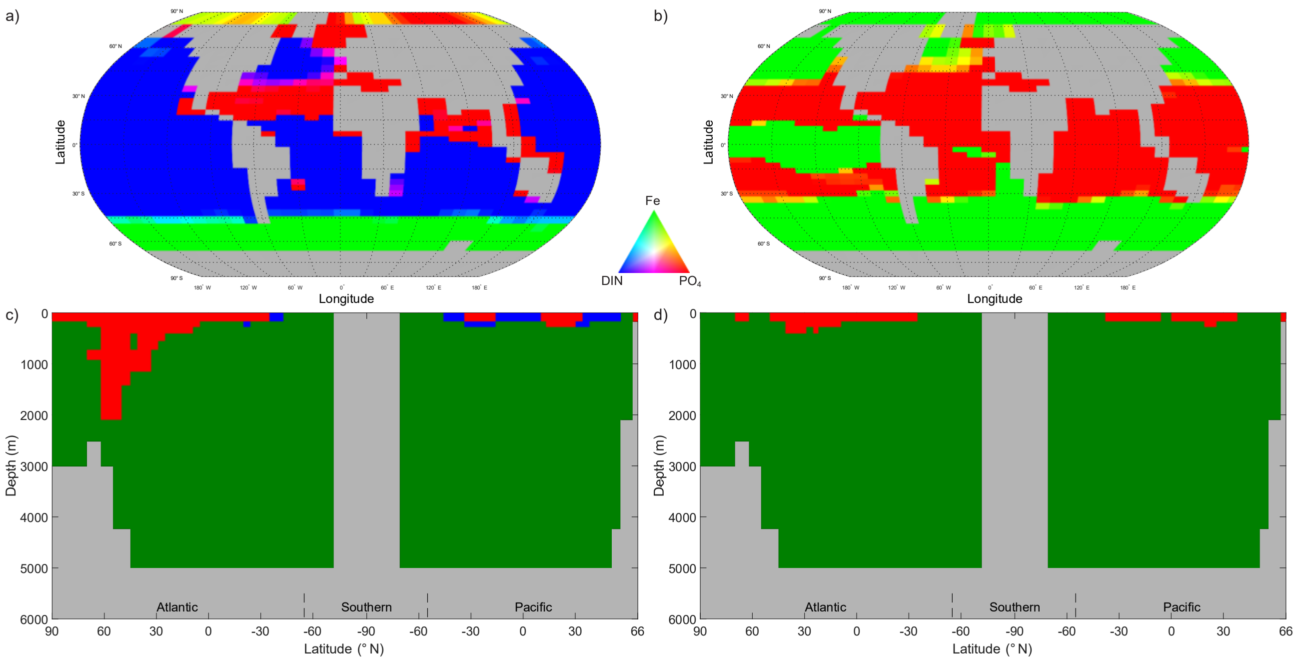
Sup figure 23: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 25% phosphate and iron nutrient reduction simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 24 – Phosphate and iron nutrient reduction, Uptake and delta uptake



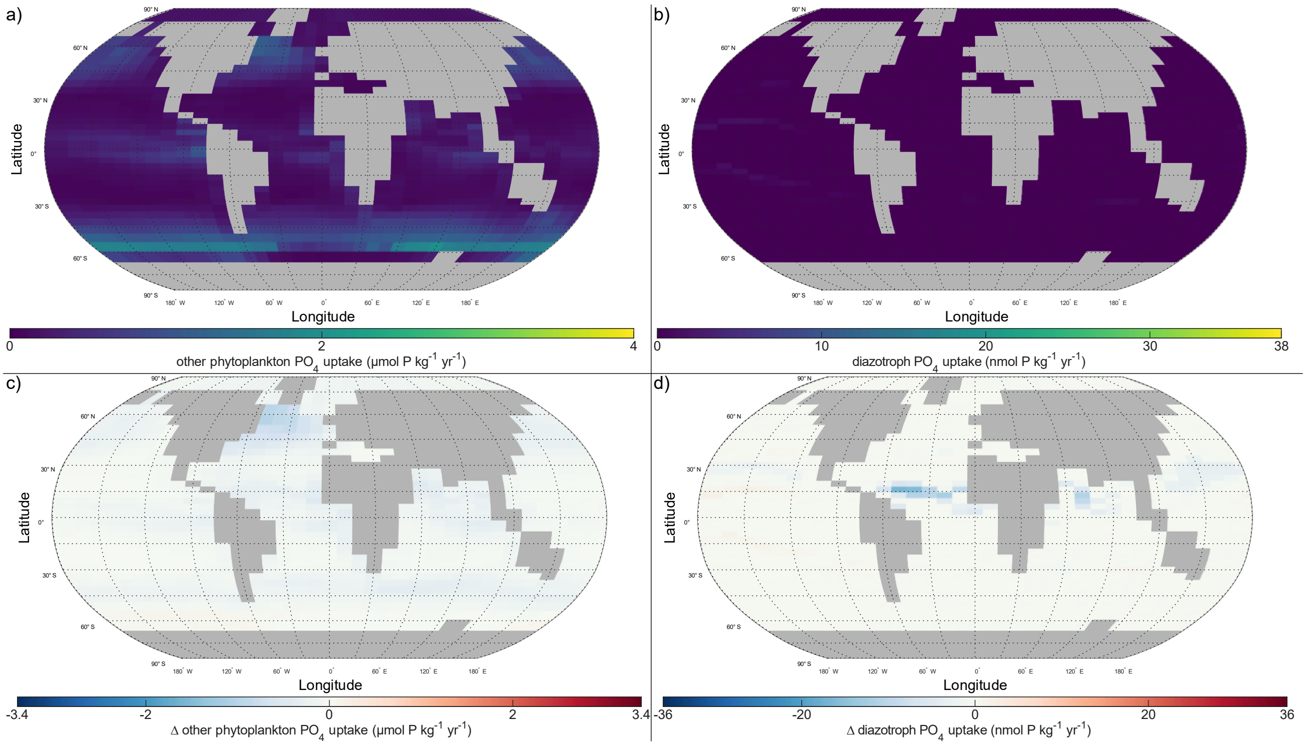
Sup figure 24: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for 25% phosphate and iron nutrient reduction simulation. *a) other phytoplankton PO_4^{3-} uptake in μmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (reduction simulation - control) in μmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (reduction simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 25 – Phosphate and nitrate nutrient reduction, surface limitation and nutrient deficiency



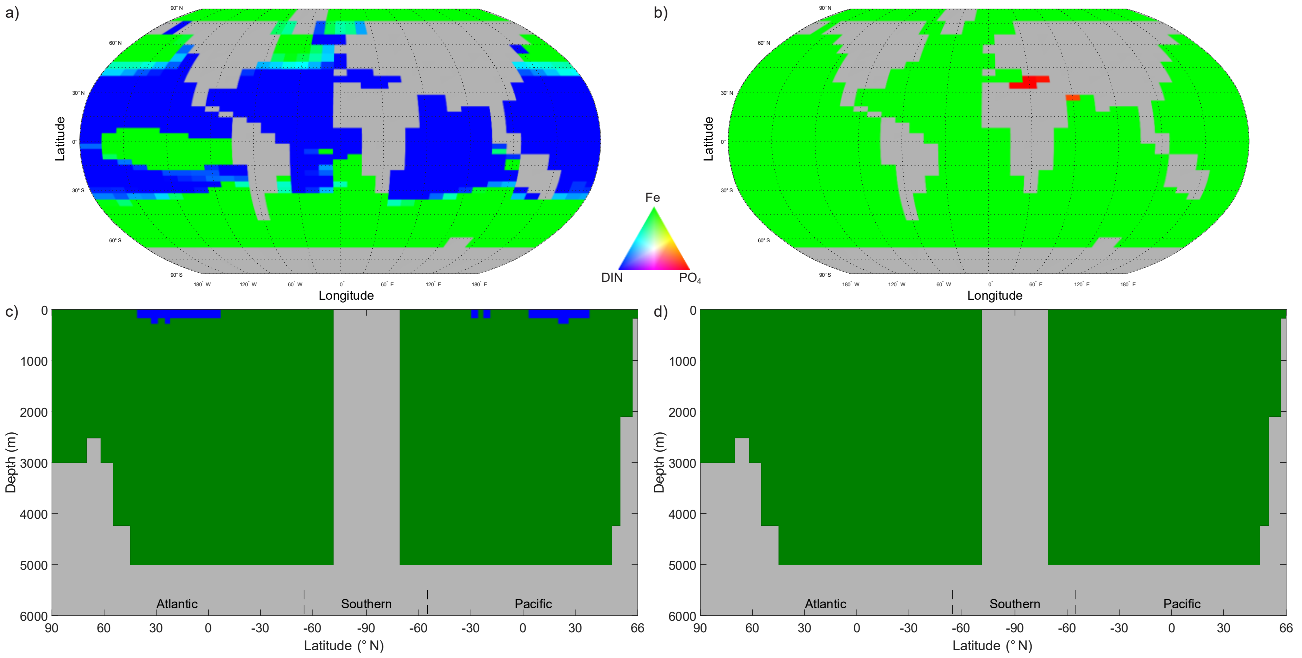
Sup figure 25: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 25% phosphate and nitrate nutrient reduction simulation *a) other phytoplankton surface limitation: red =* PO_4^{3-} *limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red =* PO_4^{3-} *limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red =* PO_4^{3-} *deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 26 – Phosphate and nitrate nutrient reduction, Uptake and delta uptake



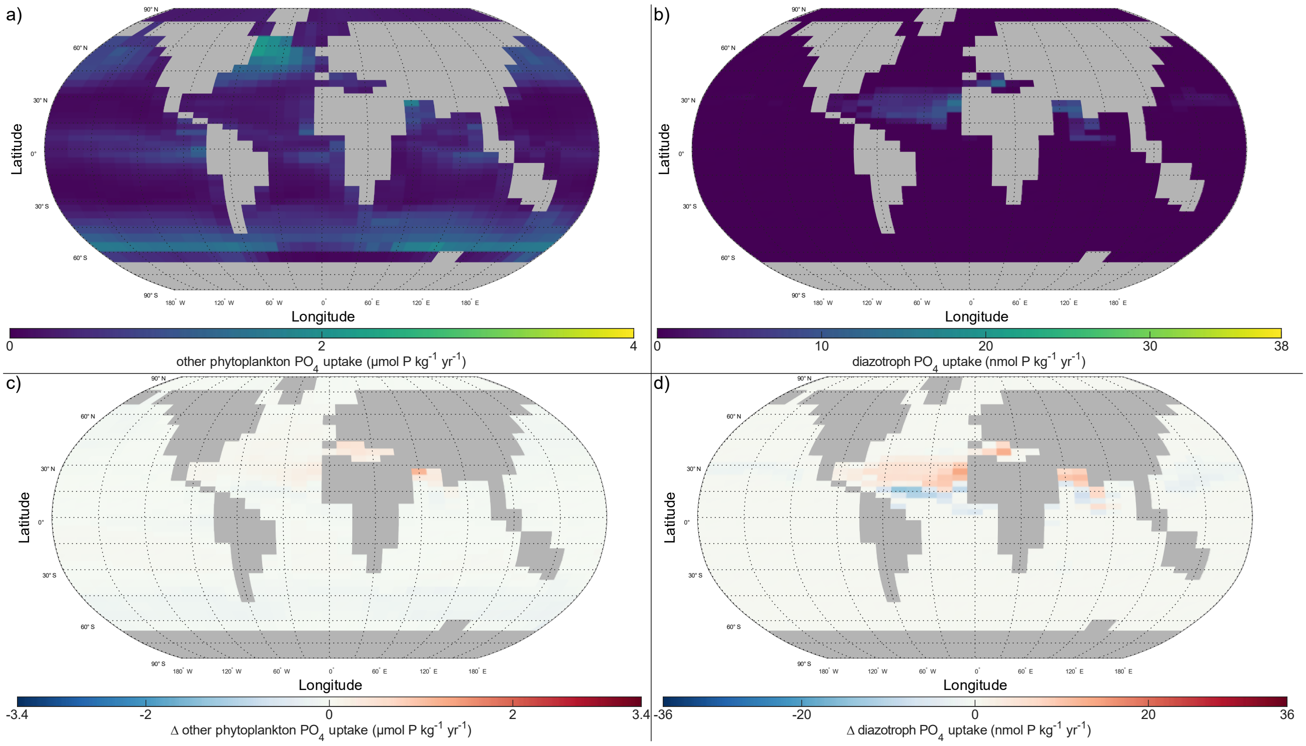
Sup figure 26: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for 25% phosphate and nitrate nutrient reduction simulation. *a) other phytoplankton PO_4^{3-} uptake in µmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (reduction simulation - control) in µmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (reduction simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 27 – Nitrate and iron nutrient reduction, surface limitation and nutrient deficiency



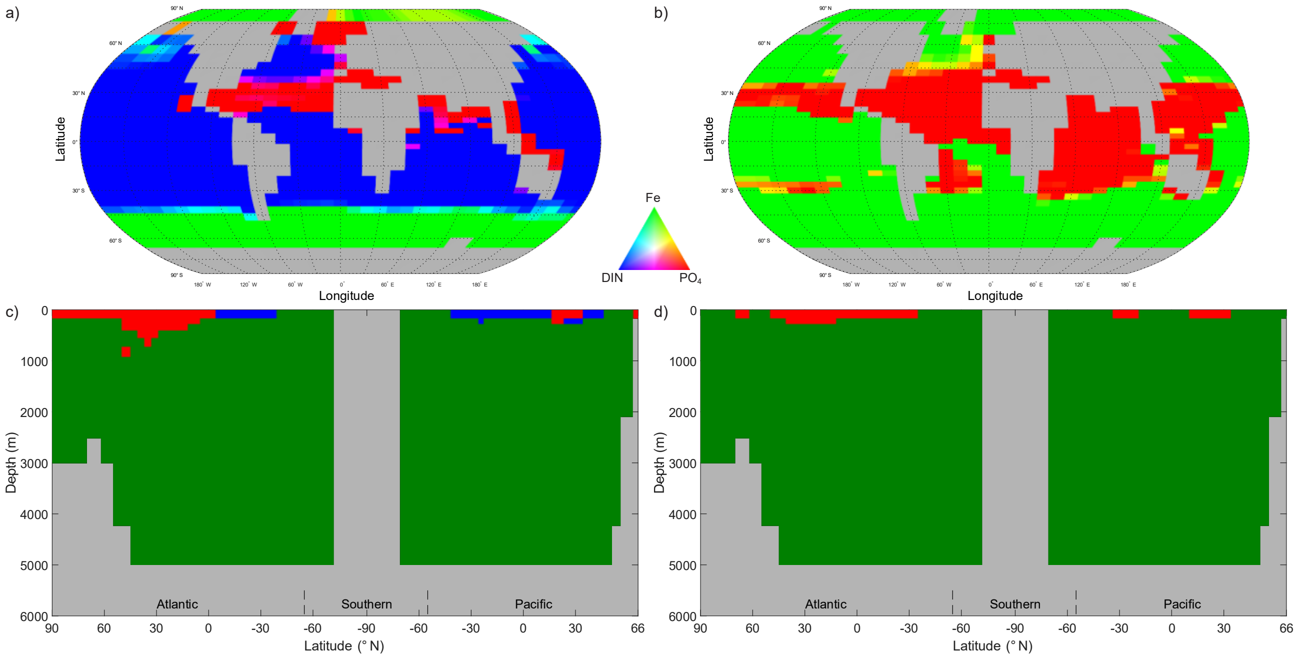
Sup figure 27: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 25% nitrate and iron nutrient reduction simulation. *a) other phytoplankton surface limitation: red = $PO_4{}^{3-}$ limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = $PO_4{}^{3-}$ limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = $PO_4{}^{3-}$ deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 28 – Nitrate and iron nutrient reduction, Uptake and delta uptake



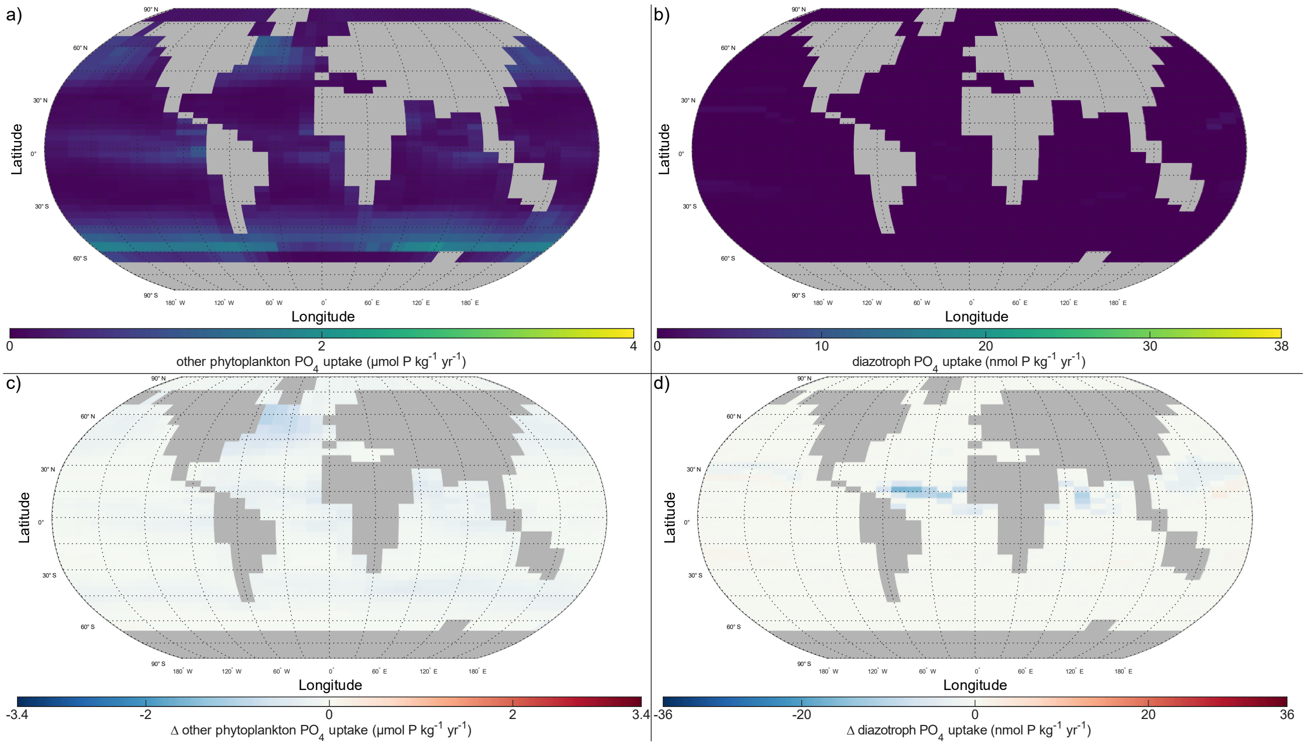
Sup figure 28: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for 25% nitrate and iron nutrient reduction simulation. *a) other phytoplankton PO_4^{3-} uptake in μmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (reduction simulation - control) in μmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (reduction simulation - control) in nmol kg^{-1} yr^{-1}.*

Sup figure 29 – Phosphate, nitrate and iron nutrient reduction, surface limitation and nutrient deficiency



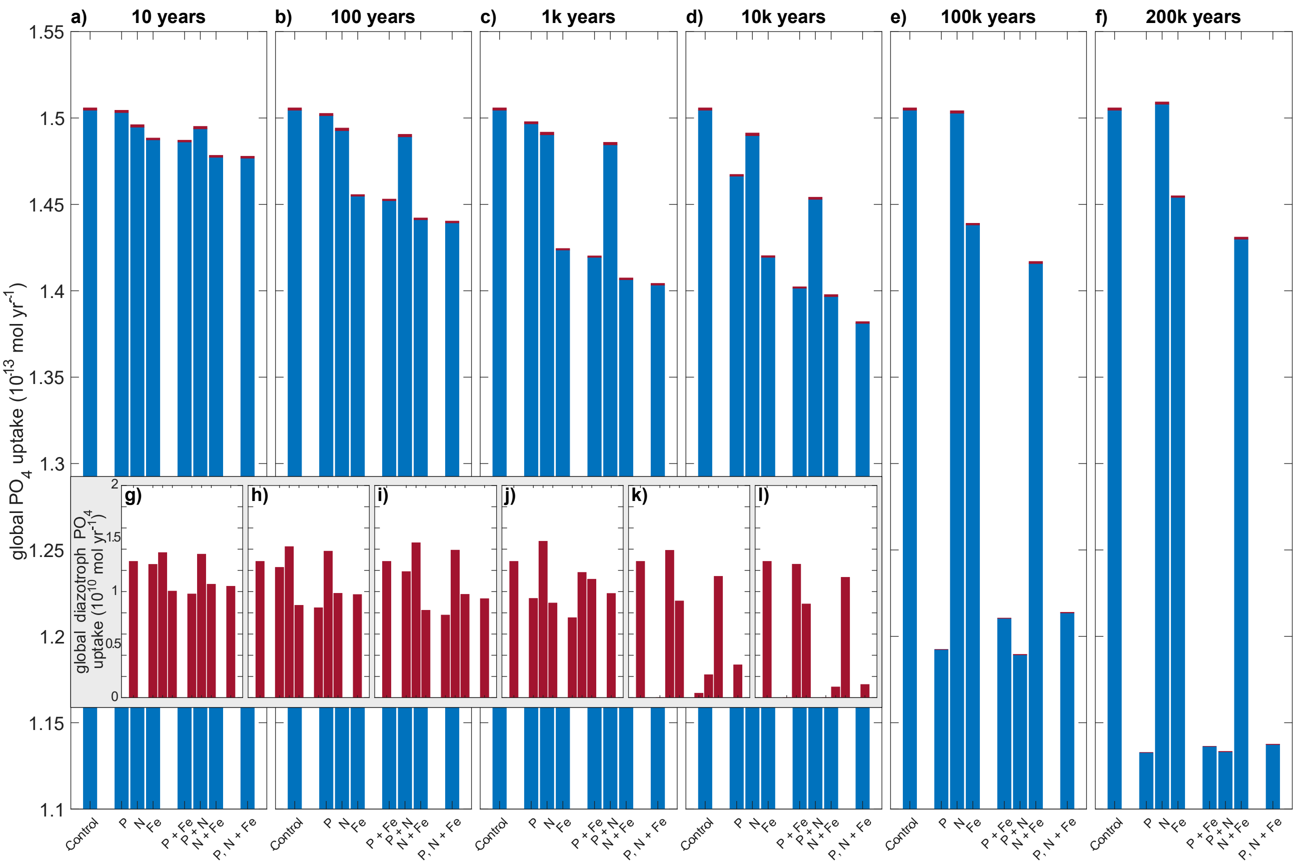
Sup figure 29: Surface nutrient limitation of nutrient uptake and interior nutrient deficiency for other phytoplankton and diazotrophs for 25% phosphate, nitrate and iron nutrient reduction simulation. *a) other phytoplankton surface limitation: red = PO_4^{3-} limitation, green = Fe limitation, blue = DIN limitation. b) diazotrophs surface limitation (they are not limited by DIN as nitrogen is considered freely available via nitrogen fixation): red = PO_4^{3-} limitation, green = Fe limitation. c and d) First-degree deficient nutrient based on phytoplankton stoichiometric requirements of nutrients: green = Fe deficiency, red = PO_4^{3-} deficiency and blue = DIN deficiency. c) other phytoplankton, d) diazotrophs - DIN deficiency is not calculated as nitrogen is considered freely available via nitrogen fixation.*

Sup figure 30 – Phosphate, nitrate and iron nutrient reduction, Uptake and delta uptake



Sup figure 30: Nutrient uptake and delta nutrient uptake for other phytoplankton and diazotrophs for 25% phosphate, nitrate and iron nutrient reduction simulation. *a) other phytoplankton PO_4^{3-} uptake in µmol kg^{-1} yr^{-1}. b) diazotrophs PO_4^{3-} uptake in nmol kg^{-1} yr^{-1}. c) other phytoplankton PO_4^{3-} uptake delta (reduction simulation - control) in µmol kg^{-1} yr^{-1}. d) diazotrophs PO_4^{3-} uptake delta (reduction simulation - control) in nmol kg^{-1} yr^{-1}.*

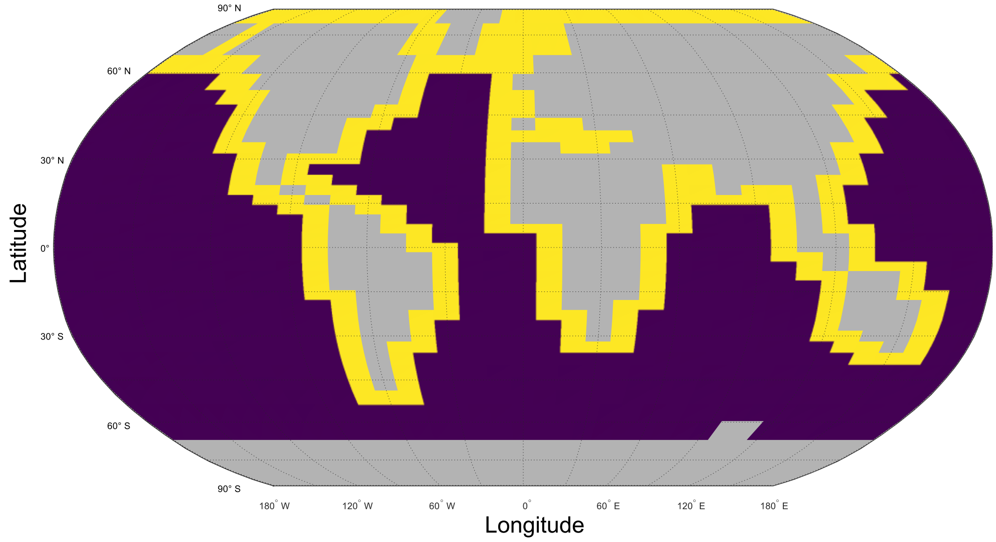
Sup figure 31 – Primary production (PP) response to reduced input flux



Sup figure 31 **Primary production (PP) response to reduced input flux of single, dual and all nutrients over time.** PP is measured by global uptake of phosphate in mol yr^{-1}. Main panels (a-f) show total PP response (10^{13} mol yr^{-1}) with other phytoplankton in blue and diazotrophs in red. Insert panels (g-l) show diazotrophs' response (10^{10} mol yr^{-1}) in red. Fertilisation simulations include: control (inputs maintained at standard levels); single nutrient (inputs of phosphate, nitrate, and iron reduced by 25%); dual nutrient (combinations of phosphate, iron, and nitrate inputs reduced by 25%); and all nutrients (inputs of phosphate, nitrate, and iron simultaneously reduced by 25%).

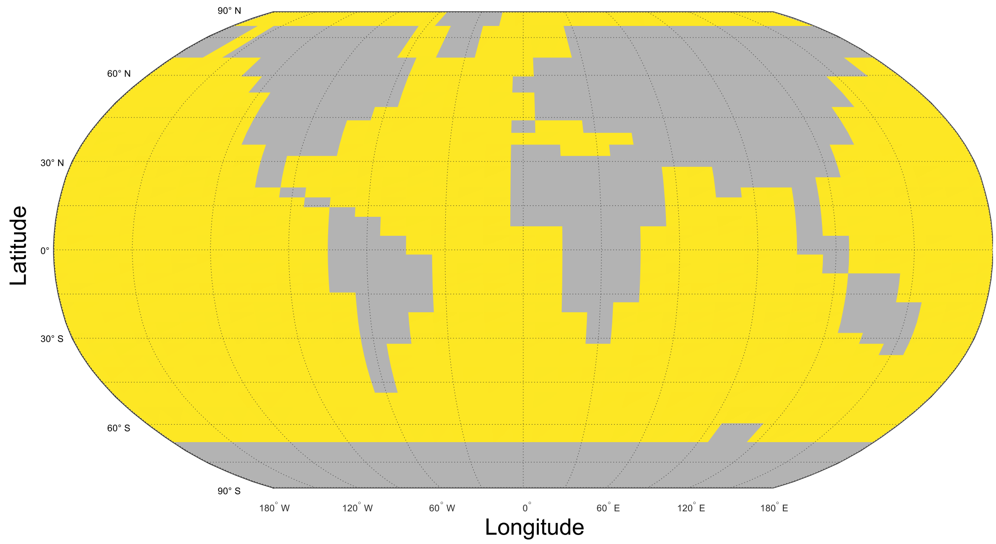
Nutrient input spatial distributions.

Sup figure 32 – Spatial distribution of surface nutrient input fluxes



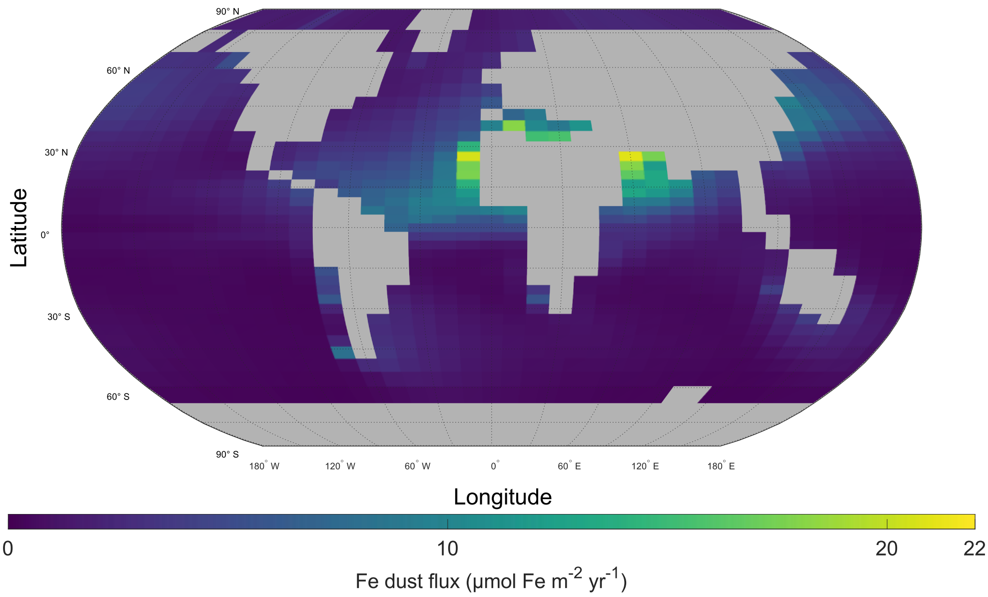
***Sup figure 32*: *Spatial distribution of surface nutrient input fluxes*.** *This spatial distribution is applied to riverine phosphate (S_{PO4}) and riverine nitrate (S_{NO3}). Those cells adjacent to land (excluding Antarctica) and coloured yellow receive the input flux; all other cells, coloured dark blue, do not receive the input flux. The total input flux is distributed evenly among those cells (coloured yellow) that receive it.*

Sup figure 33 – Spatial distribution of seafloor nutrient input fluxes



***Sup figure 33: Spatial distribution of seafloor nutrient input flux*.** *This spatial distribution is applied to benthic (seafloor) iron (B_{Fe}). All cells immediately above the seafloor receive the input flux. The total input flux is distributed evenly among those cells (coloured yellow) that receive it.*

Sup figure 34 – Spatial distribution of surface dust input flux of iron.



Sup figure 34: Spatial distribution of surface dust input flux of iron. *This spatial distribution is applied to dust iron (DDFe). All cells at the surface receive the input flux, but in greatly varying degrees according to the colour shown (distribution based on a re-gridding of Mahowald, et al.[2] to match the NutGEnIE grid cells). The implementation in NutGEnIE is as described in Matsumoto, et al.[4]. The total input flux is distributed unevenly across the ocean surface, with little or none going to those cells coloured dark blue and large amounts to those coloured yellow.*

Supplementary Tables

Sup table 1 - fertilisation simulation end states.

***Sup table 1: +125% fertilisation simulation end state primary production rates**, **nutrient concentrations and nutrient limitations**. For each fertilisation simulation the end state values are at 200 kyr. Nutrient limitation is percentage of the surface ocean limited by each nutrient. Table cell background colour coded on a green to red graduated scale where full red is less than or equal to 50% of the control value and full green is greater than or equal to 150% of the control value. Nutrient limitation table cells are coloured full green if value is 100% and full red if value is 0%. Phosphate uptake is used as a proxy for all primary production (PP), other phytoplankton (OP) and diazotroph (Diaz).*

		Fertilisation simulation							
	Units	**Control**	**P**	**N**	**Fe**	**P + Fe**	**P + N**	**N + Fe**	**P+N+Fe**
Primary production									
PO_4^{3-} uptake all PP	Tmol P yr^{-1}	15.1	16.3	15.1	15.1	21.3	17.3	15.1	22.0
PO_4^{3-} uptake OP	Tmol P yr^{-1}	15.1	16.2	15.1	15.1	21.2	17.3	15.1	21.9
PO_4^{3-} uptake Diaz	Gmol P yr^{-1}	9.06	18.1	0.00	6.28	70.7	9.57	0.00	58.8
Nutrient [ ]									
Global mean [PO_4^{3-}]	µmol kg^{-1}	2.09	14.9	1.92	1.81	11.6	14.2	1.76	11.2
Global mean [NO_3^-]	µmol kg^{-1}	28.8	31.4	37.2	27.3	37.6	34.6	38.2	39.0
Global mean [TDFe]	nmol kg^{-1}	0.73	0.72	0.73	0.89	0.84	0.71	0.90	0.84
Surface mean [PO_4^{3-}]	µmol kg^{-1}	0.45	13.2	0.23	0.18	9.4	12.4	0.16	8.89
Surface mean [NO_3^-]	µmol kg^{-1}	3.07	3.43	11.2	2.78	3.6	5.19	13.6	3.92
Surface mean [TDFe]	nmol kg^{-1}	0.22	0.18	0.22	0.53	0.3	0.14	0.55	0.28
Nutrient limitation									
OP P	%	2	0	41	11	0	0	79	0
OP N	%	67	62	0	73	78	33	0	73
OP Fe	%	31	38	59	15	22	67	21	27
Diaz P	%	8	0	23	56	0	0	66	0
Diaz Fe	%	92	100	77	44	100	100	34	100

Sup table 2 – Nutrient reduction simulation end state.

***Sup table 2: nutrient reduction (25%) simulation end state primary production rates, nutrient concentrations and nutrient limitations**. For each fertilisation simulation the end state values are at 200 kyr. Nutrient limitation is percentage of the surface ocean limited by each nutrient. Table cell background colour coded on a green to red graduated scale where full red is less than or equal to 50% of the control value and full green is greater than or equal to 150% of the control value. Nutrient limitation table cells are coloured full green if value is 100% and full red if value is 0%. Phosphate uptake is used as a proxy for all primary production (PP), other phytoplankton (OP) and diazotroph (Diaz).*

		Nutrient reduction simulation							
	Units	**Control**	**P**	**N**	**Fe**	**P + Fe**	**P + N**	**N + Fe**	**P+N+Fe**
Primary production									
PO_4^{3-} uptake all PP	Tmol P yr^{-1}	15.1	11.3	15.1	14.6	11.4	11.3	14.3	11.4
PO_4^{3-} uptake OP	Tmol P yr^{-1}	15.1	11.3	15.1	14.5	11.4	11.3	14.3	11.4
PO_4^{3-} uptake Diaz	Gmol P yr^{-1}	9.06	0.00	12.6	8.83	0.00	1.01	11.3	1.24
Nutrient [ ]									
Global mean [PO_4^{3-}]	μmol kg^{-1}	2.09	1.33	2.14	2.61	1.35	1.35	2.77	1.37
Global mean [NO_3^-]	μmol kg^{-1}	28.8	24.0	28.8	28.8	24.0	21.2	28.0	21.5
Global mean [TDFe]	nmol kg^{-1}	0.73	0.78	0.73	0.67	0.72	0.78	0.68	0.72
Surface mean [PO_4^{3-}]	μmol kg^{-1}	0.45	0.12	0.51	1.03	0.13	0.1	1.23	0.14
Surface mean [NO_3^-]	μmol kg^{-1}	3.07	5.20	2.99	3.43	5.01	2.40	3.1	2.44
Surface mean [TDFe]	nmol kg^{-1}	0.22	0.38	0.22	0.15	0.29	0.37	0.16	0.28
Nutrient limitation									
OP P	%	2	78	1	0	70	16	0	11
OP N	%	67	0	70	43	0	68	57	68
OP Fe	%	31	22	29	57	30	16	43	21
Diaz P	%	8	61	7	1	51	54	1	37
Diaz Fe	%	92	39	93	99	49	46	99	63

Sup table 3 – Basin analysis of 125% addition fertilisation simulation.

***Sup table 3: Basin analysis of 125% addition fertilisation simulation end state primary production rates**. For each fertilisation simulation the end state values are at 200 kyr. Table cell background colour coded on a green to red graduated scale where full red is less than or equal to 50% of the control value and full green is greater than or equal to 150% of the control value. Nutrient limitation table cells are coloured full green if value is 100% and full red if value is 0%. Phosphate uptake is used as a proxy for all primary production (PP), other phytoplankton (OP) and diazotroph (Diaz).*

		Fertilisation simulation							
	Units	**Control**	**P**	**N**	**Fe**	**P + Fe**	**P + N**	**N + Fe**	**P+N+Fe**
PP rates - Global									
PO_4^{3-} uptake all PP	μmol P kg^{-1} yr^{-1}	0.50	0.54	0.50	0.50	0.70	0.57	0.50	0.73
PO_4^{3-} uptake OP	μmol P kg^{-1} yr^{-1}	0.50	0.54	0.50	0.50	0.70	0.57	0.50	0.72
PO_4^{3-} uptake Diaz	nmol P kg^{-1} yr^{-1}	0.30	0.59	0.00	0.21	2.31	0.31	0.00	1.92
PP rates - Atlantic									
PO_4^{3-} uptake all PP	μmol P kg^{-1} yr^{-1}	0.51	0.61	0.46	0.39	0.88	0.69	0.37	0.92
PO_4^{3-} uptake OP	μmol P kg^{-1} yr^{-1}	0.50	0.61	0.46	0.39	0.87	0.69	0.37	0.92
PO_4^{3-} uptake Diaz	nmol P kg^{-1} yr^{-1}	0.70	1.37	0.00	0.14	4.23	0.75	0.00	3.60
PP rates - Pacific									
PO_4^{3-} uptake all PP	μmol P kg^{-1} yr^{-1}	0.39	0.40	0.42	0.39	0.48	0.46	0.39	0.52
PO_4^{3-} uptake OP	μmol P kg^{-1} yr^{-1}	0.39	0.40	0.42	0.39	0.48	0.46	0.39	0.52
PO_4^{3-} uptake Diaz	nmol P kg^{-1} yr^{-1}	0.19	0.14	0.00	0.32	1.32	0.01	0.00	1.05
PP rates - Southern									
PO_4^{3-} uptake all PP	μmol P kg^{-1} yr^{-1}	1.01	0.99	0.99	1.23	1.29	0.96	1.28	1.28
PO_4^{3-} uptake OP	μmol P kg^{-1} yr^{-1}	1.01	0.99	0.99	1.23	1.29	0.96	1.28	1.28
PO_4^{3-} uptake Diaz	nmol P kg^{-1} yr^{-1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Sup table 4 – Ocean transects statistics

Sup table 4: GEOTRACES deep water transect statistical analysis. *Data for Fe transects come from for GEOTRACES cruises GA02, GIPY05, GP19 and GPc06; NO_3 and PO_4 data come from cruises GEOTRACES GA02, GIPY05, GP19 and GP15; O2 data come from cruises GEOTRACES GA02 and GP15. Point* on depth profile *closest to 2 764 m is used and must be within the range 2 264 to 3 264 m. Atlantic and Pacific Ocean points are within latitude range 65° N to 30° S and 55° N to 30° S respectively.*

Compound	**TDFe (nmol kg^{-1})**	**PO_4 (µmol kg^{-1})**	**NO_3 (µmol kg^{-1})**	**O_2 (µmol kg^{-1})**
Atlantic Ocean mean	0.67	1.24	19	250
Atlantic Ocean s.d.	0.09	0.12	1.7	13
Pacific Ocean mean	0.63	2.61	38	121
Pacific Ocean s.d.	0.16	0.12	1.4	18
$^1H_0$ Mann–Whitney U test	Accepted, $p = 0.17$	Rejected, $p = 2.1 \times 10^{-11}$	Rejected, $p = 9.4 \times 10^{-11}$	Rejected, $p = 8.9 \times 10^{-9}$
$^2H_0$ t–test	Accepted, $p = 0.22$	Rejected, $p = 7.6 \times 10^{-53}$	Rejected, $p = 2.0 \times 10^{-51}$	Rejected, $p = 6.1 \times 10^{-31}$
$^3H_0$ t–test		Rejected, $p = 3.8 \times 10^{-53}$	Rejected, $p = 1.0 \times 10^{-51}$	Accepted, $p = 1.0$

$^1H_0$ null hypothesis is that the Atlantic Ocean and Pacific Ocean are samples from continuous distributions with equal medians. $^2H_0$ null hypothesis is that the Atlantic Ocean and Pacific Ocean comes from independent random samples from normal distributions with equal means and equal variances. $^3H_0$ null hypothesis is that the population mean for the Pacific Ocean data points is less than the population mean Atlantic Ocean data points.

Sup table 5 – Nutrient cycle fluxes

Sup table 5: Nutrient cycle fluxes applied in NutGEnIE. *Fluxes as applied to control experiment. Fertilisation and reduction simulations are a percentage of these fluxes.*

Name	Control value	Unit	Description and literature reference
S_{PO4}	7.3×10^{10}	mol P yr^{-1}	Surface input flux of phosphate.
S_{NO3}	3.2×10^{12}	mol N yr^{-1}	Surface input flux of nitrate.
DD_{Fe}	8.4×10^{8}	mol Fe yr^{-1}	Surface dust deposition flux of iron.
B_{Fe}	8.0×10^{8}	mol Fe yr^{-1}	Seafloor input flux of iron.

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3 Moore, C. M. Diagnosing oceanic nutrient deficiency. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **374**, 20150290 (2016). https://doi.org/doi:10.1098/rsta.2015.0290

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