Phosphorus limitation reduces hypoxia in the northern Gulf of Mexico: results from a physical-biogeochemical model


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Summary

In the northern Gulf of Mexico, excess dissolved inorganic nitrogen (N) and phosphorus (P) loads from the Mississippi-Atchafalaya River system promote high primary production and contribute to the seasonal development of hypoxic bottom waters on the Louisiana Shelf. While phytoplankton growth is considered to be typically N-limited in marine waters, P limitation has been observed in this region during peak river discharge in spring and early summer. River-induced P limitation is a common phenomenon in coastal hypoxic systems. Although a key aspect of nutrient load reduction strategies for hypoxia mitigation, there is still limited direct evidence for the effect of P limitation on hypoxia. Here we present a synthesis of recent investigations that quantitatively assessed, using a realistic physical-biogeochemical model, the effect of P limitation on primary production and hypoxia development on the Louisiana Shelf.

Simulations show that P limitation delays and displaces westward a portion of river-stimulated primary production and depositional fluxes, resulting in a redistribution of respiration processes toward the western Louisiana Shelf. This redistribution does not promote a westward expansion or relocation of hypoxia. Rather, the onset of hypoxia is delayed and the size of the hypoxic zone reduced. In other words, P limitation dilutes the effects of eutrophication on the Louisiana shelf. Two additive effects explain this reduction, namely the westward shift of organic matter respiration against the backdrop of weakening vertical stratification and the net shift of respiration from the sediments to the water column.

Model description

Circulation model

The Regional Ocean Modelling System (ROMS) is configured to simulate the circulation over the Louisia continental shelf.

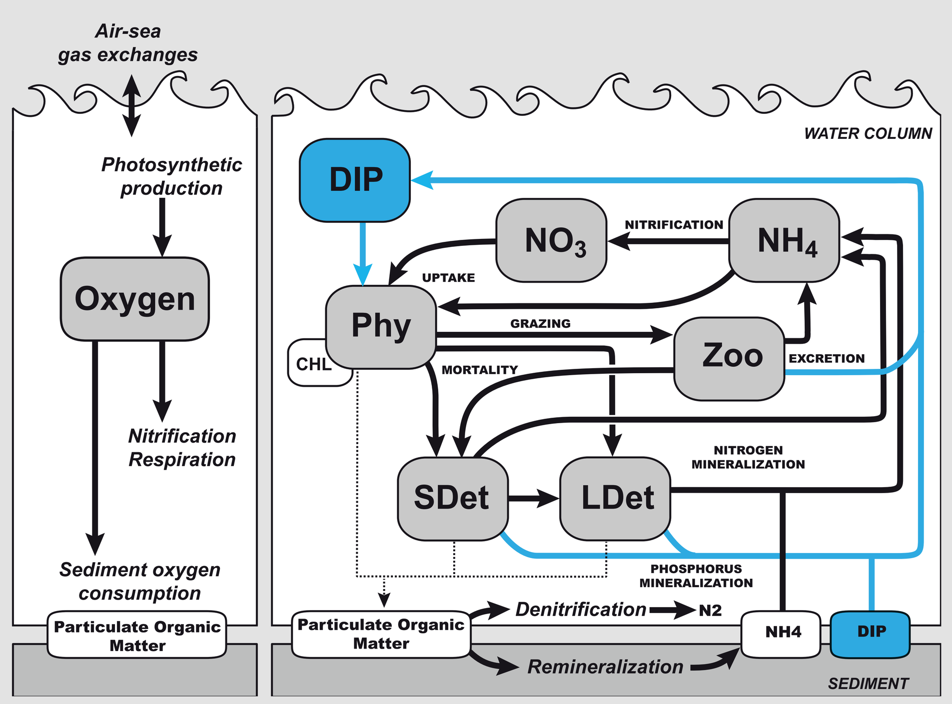

Figure 1. Schematic of the ecosystem model. Black arrows indicate the original nitrogen cycle model of Fennel et al. (2011) and blue arrows the added phosphorus processes (Laurent et al. 2012). Sedimenting particulate organic matter (dashed arrows) is instantly remineralized into ammonia and phosphate at the sediment-water interface. Part of the nitrogen is lost into nitrogen gas (N2) through denitrification. Oxygen sources and sinks are represented on the left-hand side panel.

Biological model

The nitrogen cycle model of Fennel et al. (2011) is modified to include a dissolved inorganic phosphorus (DIP) compartment (Fig. 2). Phosphorus interacts with the nitrogen cycle model through phytoplankton growth (μ; d^{-1}), which is limited by light and temperature ($\mu(E,T)$; d^{-1}) and by either dissolved inorganic nitrogen (DIN) or DIP as follows:

$$L_{\mathrm{DIN}} = \frac{NO3}{k_{NO3}+NO3}\cdot\frac{1}{1+NH4/k_{NH4}} + \frac{NH4}{k_{NH4}+NH4}$$

$$L_{\mathrm{DIP}} = \frac{PO4}{k_{PO4}+PO4}$$

$$\mu = \mu(E,T)\cdot\min(L_{\mathrm{DIN}},\ L_{\mathrm{DIP}})$$

Simulations: The model is run for the period 2001-2007. Six simulations are carried out:

- The control simulation; results are compared with observations using the L_{DIN} and L_{DIP} formulations.
- A simulation with the original N cycle model to determine the effect of P limitation.
- Additional simulations with ±50% DIP and/or DIN concentration in the Mississippi and Atchafalaya rivers.

Conceptual framework

The effect of P limitation on phytoplankton is similar among river-induced eutrophicated systems; P limitation displaces phytoplankton biomass toward downstream waters due to the transport of excess N (Figure 7). However, there is currently no consensus on whether this displacement amplifies or weakens hypoxia. P limitation is generally viewed as a mechanism that relocates or spreads hypoxia and thereby considered detrimental. Any relocation of primary production due to P limitation will also relocate O2 sinks, which could potentially lead to the development of hypoxic conditions in waters that would be normoxic without P limitation.

In flow-through systems, which are characterized by strong freshwater-induced stratification and transport akin to a simple translation along their upstream-downstream axis, a shift of primary production along this axis may well result in a linear effect on hypoxia.

However, excess nutrients in river plumes are being diluted when plumes interact with coastal circulation forced by topography, winds and tides. In these open systems, a "downstream" relocation may spread elevated primary production over a larger area while lowering the maxima of primary production in the affected area, in effect "diluting" the imprint of eutrophication (Fig. 7). Hypoxia is reduced upstream, but does not increase significantly downstream, resulting in an overall reduction of the hypoxic area.

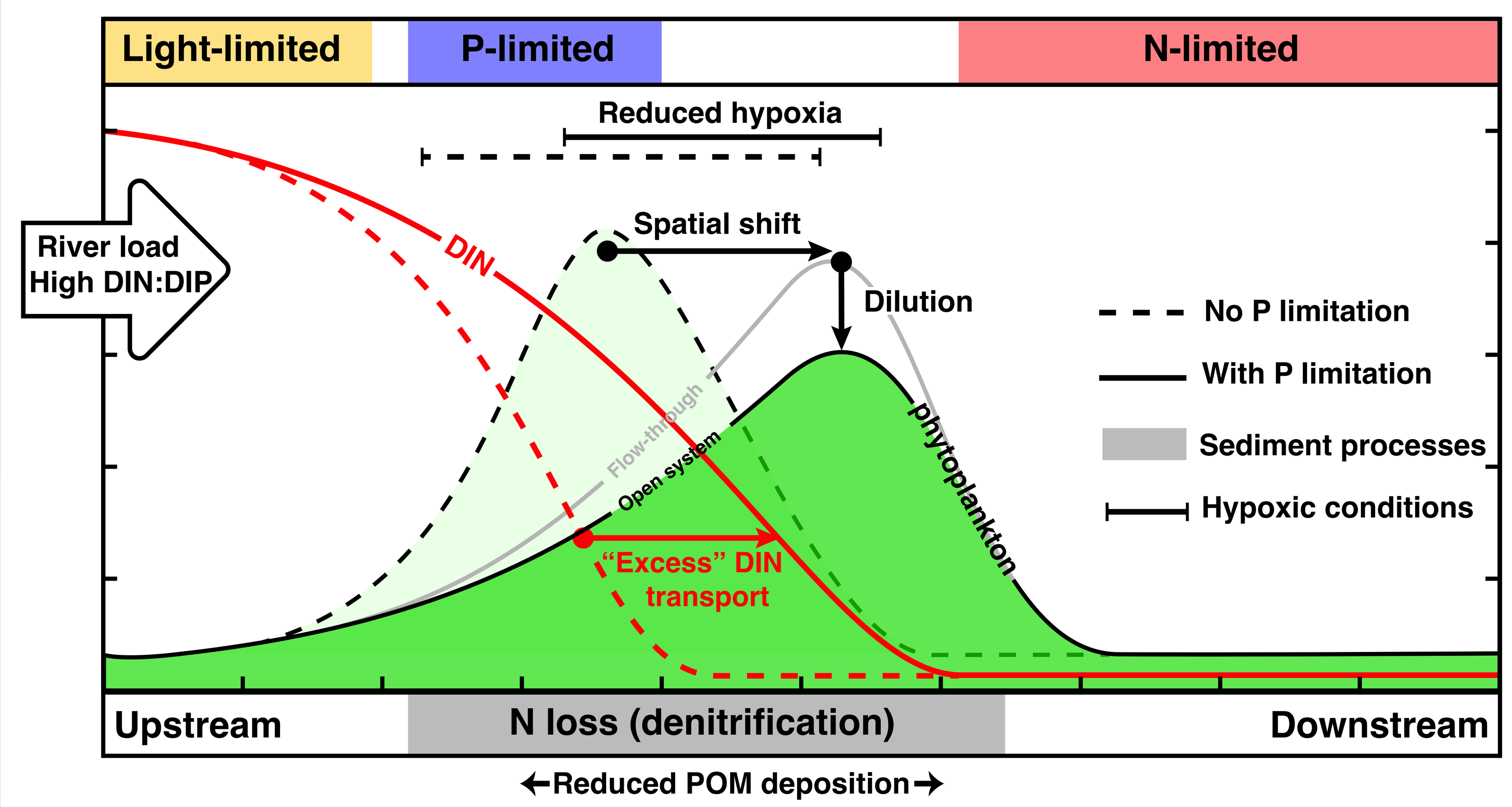

Figure 7. Conceptual model showing the spatial effects along an upstream-downstream transect of river-induced P limitation on DIN concentration (red), phytoplankton biomass (green) and hypoxia (black horizontal lines, top) in an open systems such as the Louisiana Shelf. The difference in phytoplankton biomass in flow-through systems is also indicated (grey line). The type of resource limitation is represented at the top. Along the transect, N is partly removed by denitrification in the sediment. As an indication, spatial distributions are also represented for systems where P is not limiting (dashed lines).

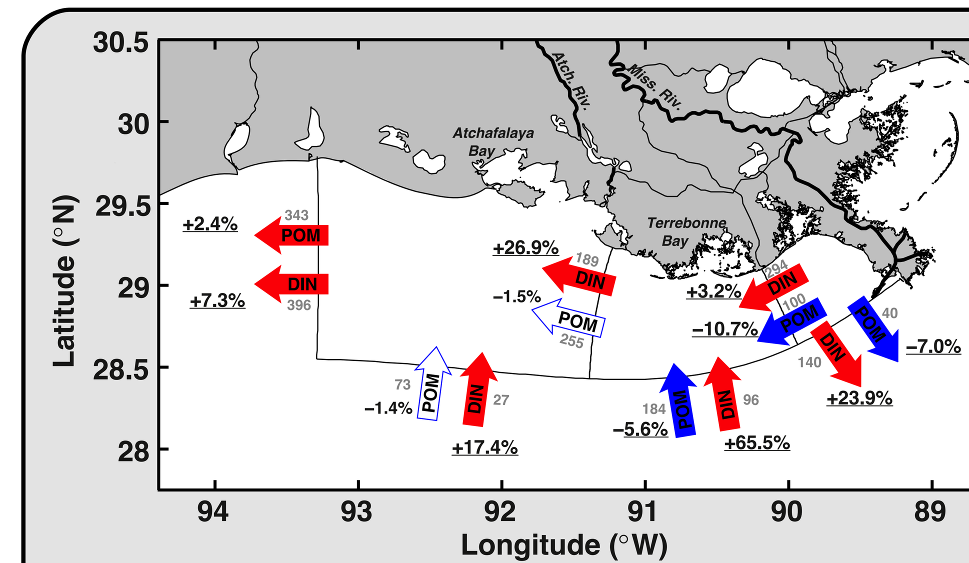

Figure 4. Changes in average POM and DIN transport over the Louisiana shelf due to P limitation. Transport is calculated from the simulations of Laurent and Fennel (2014) for three boxes representative of the shelf, their boundaries shown with a thin black line. The southern boundaries follow the 50 m isobath. Arrows indicate the direction of the transport and their color an increase (red), a decrease (blue) or a limited change (white) due to P limitation (also indicated in percent). The grey number beside each arrow indicates the magnitude of the transport (in 10^3 mmol N s^{-1}).

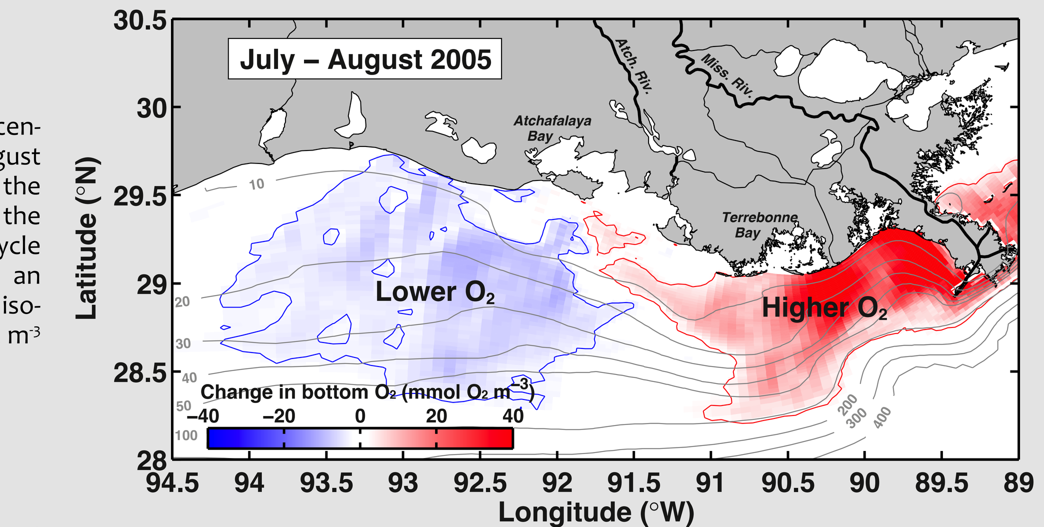

Figure 5. Average change in bottom O2 concentration due to P limitation in July and August 2005 on the Louisiana shelf, calculated as the results of the simulation with DIP minus the results from the simulation with the N cycle model only. Positive values (red) indicate an increase in O2 concentration. Red and blue isolines are indicative of the -3 and +3 mmol O2 m^{-3} limit, respectively.

3. The dilution effect

Changes in bottom water O2 associated with P limitation are asymmetrical over the Louisiana Shelf with a significant increase on the eastern shelf, but only a small decrease on the western shelf (Figure 5). This spatial asymmetry is explained by two additive effects, namely the westward shift of organic matter respiration against the backdrop of weakening vertical stratification and the net shift of respiration from the sediments to the water column.

The intensity of water column stratification varies along the freshwater gradient of the Mississippi River plume. Water column stratification is strongest on the eastern shelf and decreases toward the western shelf, away from the Mississippi River delta (Hetland and DiMarco 2008). Since bottom O2 concentration is highly correlated with stratification intensity on the Louisiana shelf (Fennel et al. 2013), a westward shift in organic matter respiration results in a reduction of hypoxia. In addition, P limitation leads to a redistribution of respiration between sediment and water column (Figure 3b,c). The westward shift of primary production occurs on a broadening shelf thus spreading primary production over a larger area and essentially diluting phytoplankton and detritus. Smaller concentrations of phytoplankton and suspended detritus reduce coagulation and POM deposition; hence more organic matter is respired in the water column and less in the sediment. This leads to an asymmetric effect of P limitation on respiration between the eastern and the western Louisiana shelf (Figure 3b,c). Given the role of SOC on hypoxia development on the Louisiana Shelf (Fennel et al. 2013), the net shift of respiration from sediments to the water column reduces the overall extent of hypoxia (by 29% on average; Laurent and Fennel 2014).

Results

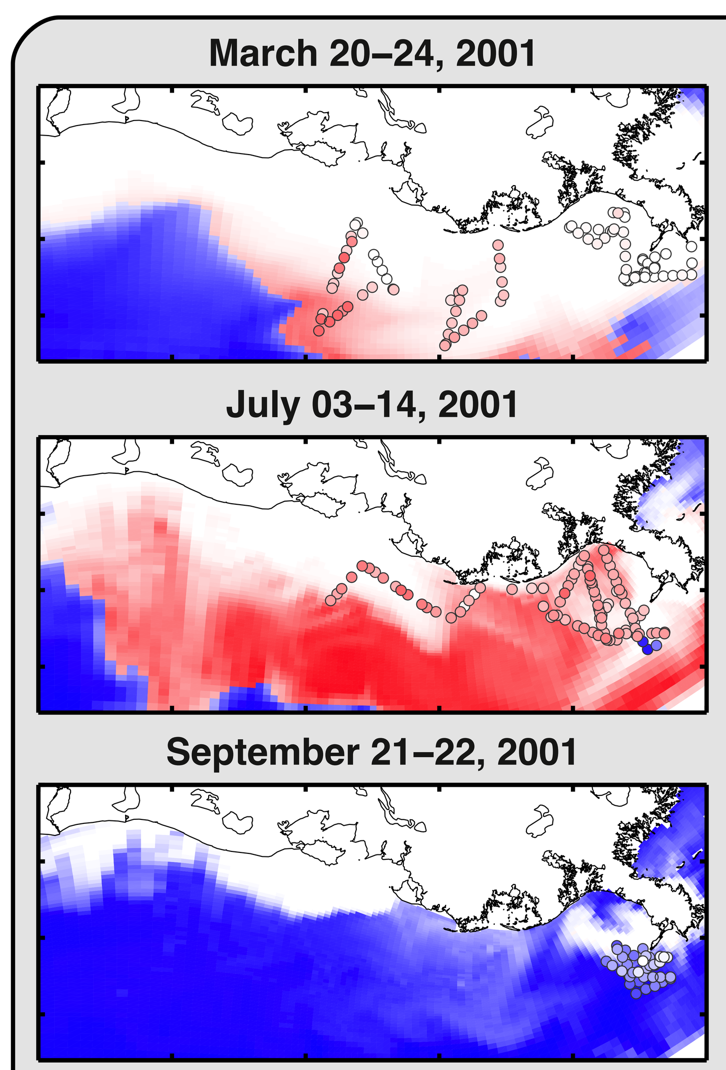

Figure 2. Simulated (maps) and observed (Sylvan et al 2006, dots) nutrient limitation on the Louisiana shelf in March, July and September 2001. The colour scale corresponds to L_{DIN} (blue, N limitation) and L_{DIP} (red, P limitation). The white areas are not nutrient-limited. Dark colours indicate high limitation.

1. Nurient limitation

The simulated annual cycle of nutrient limitation is as follows: no nutrient limitation in winter (Fig. 2a), P limitation in the mid-salinity waters of the Mississippi River plume in early summer (Fig. 2b) and N limitation over the shelf in late summer and fall (Fig. 2c). Open ocean waters are always N-limited. These patterns agree well with the observations (Fig. 2) and bioassays of Sylvan et al. (2006). Interestingly, P limitation does not occur in the Atchafalaya River plume. The shallow depth in this region (<20 m) results in rapid P turnover and N loss through denitrification, which limits the potential for P limitation.

2. Shift in primary production

P limitation reduces primary production by 26% near the Mississippi delta between May and July (Fig. 3a). The excess DIN is transported downstream (i.e., westward, Fig. 4), where it fuels primary production in otherwise N-limited waters (Fig. 3a). This induces a time delay and a westward relocation of part of primary production. Since this relocation occurs over a large area, the overall primary production is diluted over the shelf (see conceptual framework). POM deposition is a quadratic function of primary production in the model and therefore the dilution in primary production results in an overall reduction of POM deposition flux.

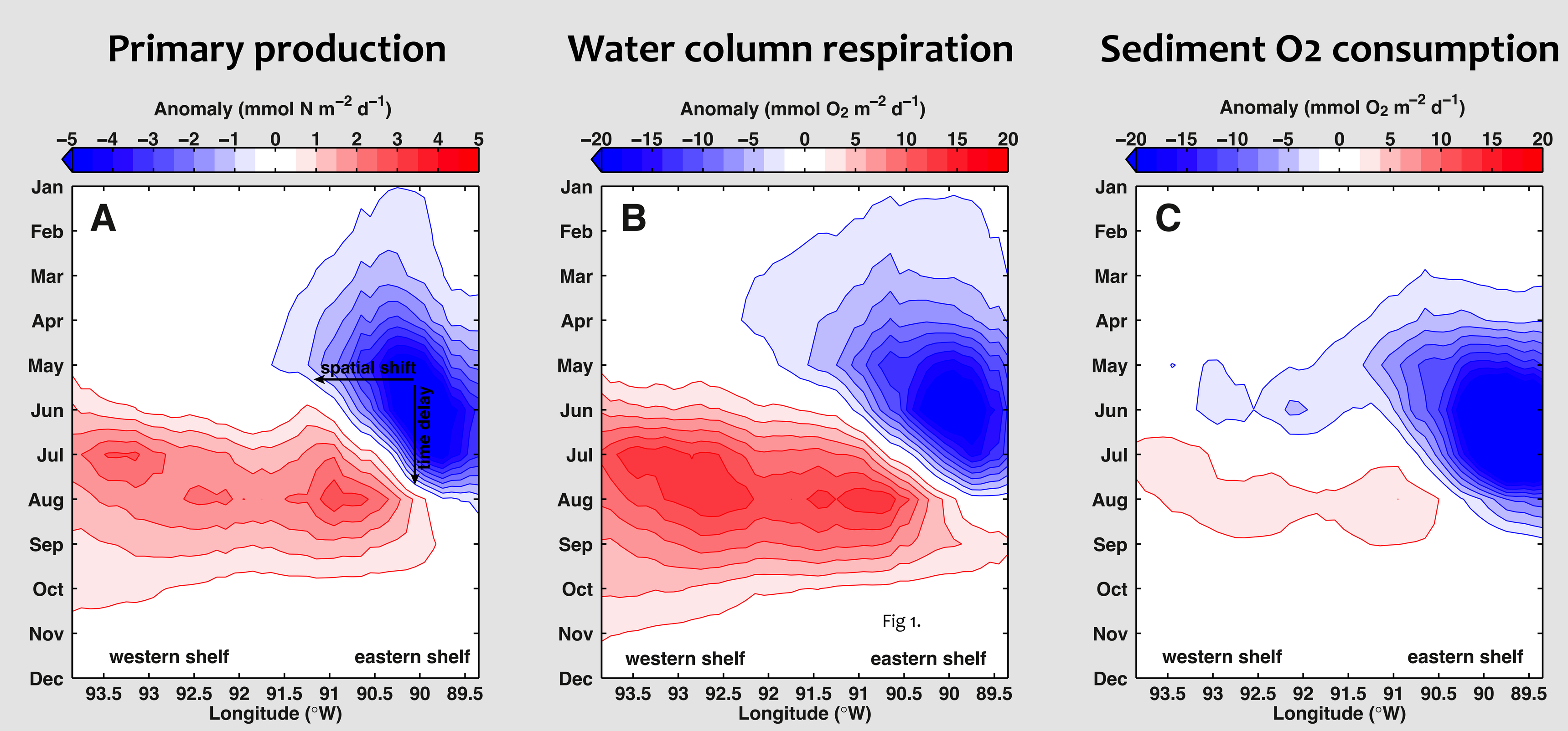

Figure 3. Anomaly plots showing spatial and temporal changes in primary production (A), water column respiration (B) and SOC (C) due to P limitation on the Louisiana shelf. Values represent monthly and latitudinal averages for the Louisiana shelf (z ≤ 50 m). Anomalies are calculated as the results of the simulation with DIP minus the results from the simulation with the N cycle model only.

4. N and P load mitigation

Four nutrient reduction scenarios were tested to assess their effect on summer hypoxia (Laurent & Fennel 2014): 50% decrease of river DIN (–N), 50% decrease of river DIP (–P), 50% decrease of river DIN and DIP (–NP) and a 50% increase in river DIN with a simultaneous 50% reduction of river DIP (+N–P). The dual N and P load reduction (–NP) maximizes the decrease in hypoxia size and duration (Figure 6). Decreasing N load only (–N) reduces hypoxia on the western shelf but the hypoxic area is larger than with a dual nutrient reduction. Reducing P only (–P) reduces the hypoxic area but not hypoxia duration on the western shelf. Finally, decreasing P but with a simultaneous increase of N (stronger P limitation) lead to a small reduction of the hypoxic area, but also to a longer hypoxia duration on the western shelf (Figure 6). A dual N and P load reduction strategy is therefore recommended to mitigate hypoxia on the Louisiana Shelf.

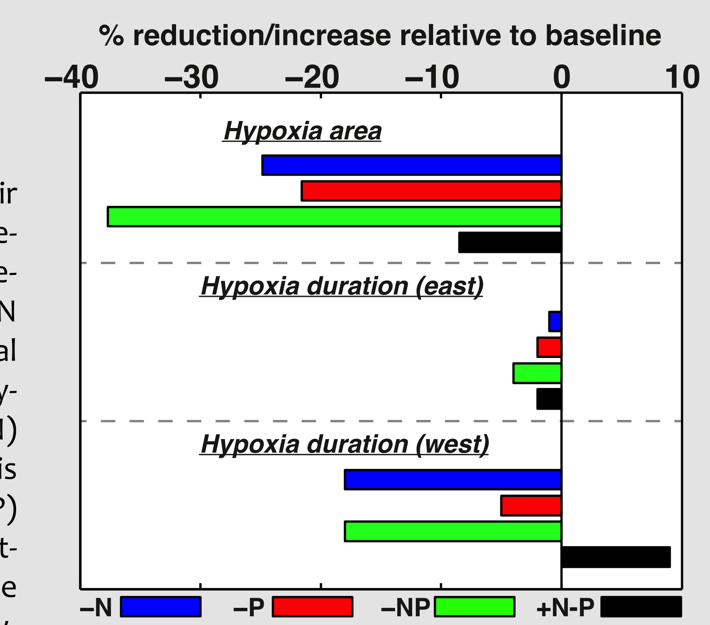

Figure 6. Results from nutrient load experiments showing the relative change in summer 2004 hypoxic area and hypoxia duration at an eastern and western shelf station, associated with a modification in nutrient river load as follow: –50% DIN (–N), –50% DIP (–P), –50% nutrients (–NP) and +50% DIN, –50% DIP (+N–P).

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