Response to the Referees comments - 01

Comment on bg-2021-101
Anonymous Referee #1

Referee comment on "Riverine nitrogen supply to the global ocean and its limited impact on global marine primary production: a feedback study using an Earth System Model" by Miriam Tivig et al., Biogeosciences Discuss., https://doi.org/10.5194/bg-2021-101-RC1, 2021

This is an interesting article exploring the long-term impact of riverine nitrogen inputs on the global ocean nitrogen inventory and associated primary production. The authors show that in simulations that have reached equilibrium, impacts on the global N inventory and primary production are highly limited due to feedbacks on N fixation and denitrification. I appreciated the candidness of the discussion on the modelling approach's strengths/weaknesses and how the results differ from those previously published in this area. The main discussion that I think might be expanded upon is how indicative simulations that have reached equilibrium are for policy relevant timescales (interannual to decadal). **Put another way, how do the authors' main conclusions change over the course of these 10000-year simulations? Are the implications different for watersheds that are experiencing rapid increases or decreases in nitrogen export at present?** Most of my comments and suggestions relate to how the manuscript text could be better structured and the figures could be made much easier to interpret. Subject to these changes, I would be happy to recommend for publication.

→ Thank you for your recommendation and positive feedback.
Regarding your question, how the main conclusions change over the whole simulation, we will include additional text in the revised manuscript, indicating that the main changes in the global marine nitrogen inventory appear in the first 4000 years of the simulation. After this time, the global nitrogen budget is almost in equilibrium. After the perturbation by additional nitrogen input via the rivers, marine primary production increases globally in all our simulations, but only for less than 2000 years. The most prominent changes have been found in the regions, where rivers currently export higher amounts of nitrogen, like for example in the East China Sea.

Minor comments

L23. "atmospheric" –should probably be dissolved/aqueous.
→ Biological dinitrogen (N2) fixation refers here to atmospheric N_2, dissolved in the ocean, which is reduced to ammonia

L26. Aren't these "model concepts" observationally /experimentally derived? Some reference to the empirical evidence would be useful here. Maybe also its limitations if it's heavily based on given species (eg Trichodesmium).
→ We will include more references, like:

- Karl et al. (2002): Dinitrogen fixation in the world's oceans, Biogeochemistry 57/58: 47–98.

- Landolfi et al. (2018) Global Marine N2 Fixation Estimates: From Observations to Models.Front. Microbiol. 9:2112. doi: 10.3389/fmicb.2018.02112
- Zehr and Capone (2020): Changing perspectives in marine nitrogen fixation, Science 15 May 2020, Vol. 368, Issue 6492, eaay9514, DOI: 10.1126/science.aay9514

and indicate that a part of our knowledge of N2-fixation is still based on the original limited assumptions based on given species especially Trichodesmium.

L31. concentrations "of" fixed N → will be corrected
L32. "the consumption of O2"- Do you mean the consumption of O2 during remineralisation? If so, be explicit. → "heterotrophic O2 consumption during organic matter remineralization"
L47. The Séférian et al. 2020 reference is perhaps worth citing here as it summarises the inclusion of riverine inputs in recent models. → This reference will be included
L51. "real" should probably be realistic or observed. → "without observed nutrient fluxes"
L59. Maybe clarify what is meant by N export here. Riverine delivery? For many in the ocean biogeochemistry community export is instinctively a vertical flux. → "Their focus was on pre-industrial nutrient input from the rivers"
Figure 1. More detail is needed on the tracers in the figure legend. → Yes, it will be included in the caption in the revised manuscript. This text will read, "Ecosystem model schematics for the NPZD model with the prognostic variables (in square boxes) and the fluxes of material between them, indicated by arrows. The prognostic variables include two nutrients, nitrate (NO_3) and phosphate (PO_4), two phytoplankton (nitrogen fixers P_D and other phytoplankton P_O) as well as zooplankton (Z), sinking detritus (D), and dissolved oxygen (O_2). nitrate (NO_3) and phosphate (PO_4) are linked through exchanges with the biological variables by constant (Redfield) stoichiometry."
L100. "atmospheric" –should probably be dissolved/aqueous. → "Nitrogen gas dissolved in seawater "

L101. Are they limited by a max NO3 concentration? I know much of this will be in the cited references but more detail is required on N-fixation in the model. Highlight perhaps that most models don't have explicit diazatrophs and this is an advantage of using uvic. What is the diazatroph PFT based on? How does N-fixation compare to observations where they exist?
→ We will include a statement like this in the revised manuscript: "Diazotrophs are not limited by NO3 concentrations, nor by a maximum NO3 concentration. The explicit integration of diazotrophs permitting the estimation of nitrogen fixation, is not given in all ocean models but makes UVic a good choice to study nitrogen cycle feedbacks. The maximum potential growth rate of diazotrophs is not only based on temperature as in most models, but also on dissolved iron, which is necessary e.g. for photosynthesis or the reduction of nitrate to ammonium (Keller et al., 2012; Galbraith et al, 2010). Keller et al. (2012) found that the global nitrate fixation rates were within the range of global nitrate fixation rates from estimations and the patterns of N_2 fixation from the new model were mostly consistent with observations, as far as they are known (Sohm et al. 2011).

L105-110. As with the above comment, some comparison on how denitrification in the model compares to observations would be very useful. I think a global map of N-fixation and denitification in the model CTR is required.

→ In the revised manuscript we will include some more maps with global distribution of denitrification and N_2-fixation.

L140. It should be made clearer on first use that NEWS etc are simulation names. → We will include a sentence about the simulation names at this place.

Table 1. For clarity I would remove UVic from the simulation names as this is not repeated in the main text. I would also add a CTR row. → Yes, absolutely right. This has been done for the revised manuscript.

L156. "vary a little" – please quantify this → "Global average NO3 concentrations only vary by 1-5 mmol m^{-3} between the simulations

L151. This should really be called a "Results and Discussion" section. → Yes, some of the final discussions have been directly included in the results chapter, so we will rename this section as you suggest.

L160. The wording here needs to be clearer. "At smaller scales…globally higher." This reads like it contradicts L167-168. → In the revised manuscript we change this sentence to "Nevertheless, in all three simulations (NEWS, DIN+DON, and 2xDIN), NO3 concentrations are globally higher compared to the control simulation (CTR)…"

Figure 3. Axes are missing labels and units here. → This has been corrected in the revised Figure

Figure 5. I find it very difficult to see differences between positive and negative anomalies using this colorbar. I suggest changing to something far more distinctive (e.g. red for negative anomalies). The same applies to other figures using this scale. → All Figures concerned have been updated with a new colorbar (in blue and red). We have chosen a delta colorbar with blue for negative and red for positive values.

L175-177. This is difficult to see in Figure 5 maybe cite figure 6 here. → Citation of Figure 6 included here.

Figure 6. The depths given in the figure don't match the legend. → Figure 6 has been updated for the revised manuscript.

L181-183. This sentence is confusing and needs rephrasing.
→ We have improved the text to read: "But in the deeper northern Indian Ocean basin down to approximately
2000 m, NO3 concentrations are significantly lower in NEWS than in CTR. Considering the zonal average of the Indian Ocean, NO3 concentrations are lower by -0.7 to -0.9 mmol N $m^{-3,}$ and even more if only the zonal average of the Bay of Bengal is considered."

Figure 7. Label missing from panel c. → Figure 7 has been updated for the revised manuscript.

L187. typo. "amounts to an increase of only 1.1…" → corrected

L209. I'm not sure the language here is accurate. Presumably the model is not explicitly trying to compensate anything. Wouldn't this be better described as enhanced denitrification sinks promoting conditions that favour N-fixers over the other PFT type and consequently global N-fixation rates are higher?
"To compensate for this additional N sink, the model estimates higher fixation rates." changed to:
→ "The additional N sink in form of benthic denitrification promotes conditions that favor N-fixers, i.e., diazotrophs, leading to higher nitrogen fixation rates."

L210-213. The discussion of other literature here before properly explaining your model results is confusing. Where these papers have used the same model this should be clear.
→ We will try to avoid confusion here and change the paragraph to: "Previous studies with UVic have shown, … (Somes et al., 2016)" The other studies cited here have shown similar results but with other models, so we will come to them later in the discussion.

L216. "where NO3 concentrations are substantially reduced relative to the CTR" → The text has been updated, thanks for the rephrasing.

Figure 8- See earlier comments on how it would be nice to see global Nfix in the control.
→ Thanks for the suggestion, this has been done in the revised Figure.

Figure 9. Suggest using different color palettes for mean states and anomalies. → Thanks for the suggestion, this has been done in the revised Figure (see also response to Figure 5)

L219-227. The balance between results of the model simulations and the discussion of other literature needs to be more organised. The presentation of discussion before results is quite confusing.
→ To address this critique, the whole paragraph (previously l. 190-241) has been restructured and divided in two subsections: "3.1.2. Denitrification and nitrogen fixation" and "3.1.3 The N-cycle feedback mechanisms"). (See whole paragraph at the end of this document)

L221-222. This is a bit rushed and therefore confusing. I think more detail is needed here on this mechanism, the difference between the stoichiometry of N-fixation and denitrification and how spatial and temporal coupling is important for the positive feedback to occur.
→ Sorry that this was confusing we have updated the text to read, "This is due to the stoichiometry imbalance created by the combination of these processes. Denitrification occurs in anoxic or suboxic environments, where nitrate or nitrite can be used as a substitute terminal electron acceptor instead of oxygen. Denitrification consumes 7 mol of NO3 for every mole of organic N provided by N2-fixation, when these processes equilibrate with each other over long timescales. This imbalance generates a net loss of fixed N, even if N is continuingly added via N2 fixation."

Table 3. Benthic denitrification appears to be twice the magnitude of that in the water column. This doesn't seem to be reported and discussed in the manuscript. Does this have

implications for models lacking benthic denitrification?

→ I don't see, where benthic denitrification appears to be twice the amount of water column denitrification (WCD), but indeed benthic denitrifications (BD) is an important process (e.g. Somes et al., 2016; Somes et al., 2013) and for both global estimates vary considerable: for WCD estimates are between 50 and 150 Tg N yr-1, for BD between 100 and 300 Tg N yr-1 (Galloway et al., 2004; Gruber, 2004; Bohlen et al., 2012; Somes et al., 2013). In the revised manuscript we will address this point. Our global results for N2 fixation, WCD and BD stay in the range assumed for a balanced fixed-N budget in the preindustrial ocean e.g. by Somes et al. (2013). BD is more evenly distributed than WCD. Therefore, to study regional effects, it is helpful to include both processes. Nevertheless, models can have a balanced nitrogen budget without benthic denitrification.

L246. "…and vary little between…" → corrected

L251. "smaller scales" is ambiguous. Here and elsewhere I recommend being more specific e.g basin/watershed/coastal scales etc.
→ Yes, at this place we changed the vague formulation to "Nevertheless, with rivers supplying N to the ocean, differences are visible at coastal scales: NPP increases locally, close to the river mouths

L257-259. Differences in spatial patterns between these simulations are difficult to discern it looks more like the magnitude of change is the only difference. → We will include this remark to the text: "The main differences are in the magnitude of NPP, however, some regions with higher NPP can only be found in the simulation 2xDIN in the open ocean basins." Furthermore, we will change the colorbar of the figure in blue and red like stated for Figure 5, in order to make the differences clearer.

L259. Are these subtropical and tropical regions where N-fixers are predominately confined to?
→ Yes, these are quite exactly the regions, where in UVic diazotrophs can be found. We will include a comment on this in the manuscript and refer to the new plot on figure 8.

L297. Maybe "exported again" should be "recycled" here. → yes. "recycled" is what was meant.

L301. And presumably not all the N can be consumed via local primary production due to other constraints.
→ Yes, we will include: "N is transported to the Indian basin but is not consumed by local primary production nor does it trigger the vicious cycle described before".

Table 6. Maybe the increase in NPP per quantity of additional N would be a useful metric to add to this table given each watershed provides different total N delivery.
→ Yes, this is a good idea. This has been calculated already and can be easily added to the existing table.

L325. For clarity I think "inhibiting additional NPP" should be "limiting increases in NPP".
→ Thanks for your suggestion, it will be changed.

Section 4. Given the extensive discussion of the Lacroix et al. 2020 paper, I think a few more details are required to compare the studies properly. What was their model resolution, did they have explicit N-fixers and benthic denitrification?

→ We will include this information: "This is due partly to the coarser resolution of UVic. The grid configuration used by Lacroix et al. (2020) (GR15) consists of a bipolar grid which resolves the ocean horizontally at around 1.5° and through 40 unevenly spaced vertical layers. Although N is simulated as fixed percentage of P, dynamic nitrogen fixation by cyanobacteria is included as well as nitrogen deposition and denitrification."

L358. The emphasis here and in the conclusions (L376) doesn't really match the findings. I would say the feedbacks do much more than "partly compensate" the riverine fluxes. Maybe this would be clearer if you gave the % of added N that is retained in the inventory at equilibrium or some other metric of feedback strength.

→ Yes, you are right. We will add: "Compared to the total amount of N added by the rivers at the end of the simulation, only 2,3 % (NEWS) to 2,6 % (2xDIN) is retained in the global inventory. The feedbacks compensate for much of the nitrogen addition and in some regions even overcompensate them."

The sentences in the conclusion were formulated this way, because some of the additional N is still accumulated in the deeper ocean.

L388-389. I'm not sure this "upper limit" conclusion would hold if N fertilisation were targeted spatially and temporally in regions of N limitation. Perhaps this should be toned down a little.

→ On short time scales target N fertilization might work, but once the vicious cycle has a chance to start, then the findings would probably be the same, as shown e.g. by Somes et al. (2016). But further research would need to be done for targeted spatial and temporal N additions at different levels in N limited regions.

Restructured Section (See comment on page 4)

3.1.2 Denitrification and nitrogen fixation (previously L. 190 – 241)

Denitrification is known to be the main sink for fixed N in the ocean (Gruber, 2004; Codispoti et al., 2001). It occurs both in marine sediments and in the water columns under suboxic conditions, like for example in the simulated Bay of Bengal. As a result of these dynamics, if N is added via river discharge, UVic simulates globally higher water column and benthic denitrification rates (Table 3).

While the global pattern of denitrification is very similar in the simulations with additional riverine N compared to CTR, in proximity to river discharge points, total denitrification rates are higher (by up to 35 nmol N m-2 s-1). Somewhat off the coasts however, total denitrification appears lower in the simulations with riverine nutrient supply (by up to -5 nmol N m-2 s-1) (Figure will be added to the revised manuscript).

At the same time, total global N2 fixation rates decrease in all three simulations compared to CTR (Table 3). Nitrogen fixation is a significant process in the marine nitrogen cycle and a major source of nitrogen in the open ocean. Nitrogen fixing organisms are able to convert dissolved nitrogen gas (N2) into ammonia, but are limited in their growth by phosphate and iron (Deutsch et al., 2007; Moore and Doney, 2007; Karl et al., 1997; Redfield et al., 1963).

The global rate and geographical distribution of nitrogen fixation are still uncertain. Observations remain sparse and highly variable in space and time. Combined with insufficient understanding of the controls of marine N2 fixation, this results in high uncertainties in the global pattern of marine nitrogen fixation (Wang et al., 2019; Landolfi et al., 2018; Somes et al., 2013). Deutsch et al. (2007) and Luo et al. (2012) estimated a global nitrogen fixation rate of 140 Tg N yr−1 and most recent studies stay in this range, although some studies suggest, that the global rates could be much higher (Wang et al., 2019; Landolfi et al., 2018; Somes et al., 2013; Karl et al., 2002).

The global rates calculated from our experiments with UVic (Table 3) are also higher than the estimates from Deutsch et al. (2007) and Luo et al. (2012). Although previous studies with UVic have given rates of N2 fixation between 128 and 150 Tg N yr-1 (Landolfi et al., 2017; Keller et al., 2012), the CTR simulation in our configuration estimates global N2 fixation rates of 219 Tg N yr-1. In our case, this is due to the additional integration of benthic denitrification, which has not always been considered in previous UVic studies. The additional N sink in form of benthic denitrification promotes conditions that favor N-fixers, i.e., diazotrophs, leading to higher nitrogen fixation rates.

In the UVic CTR simulation, N2 fixation is mostly confined to the tropical and subtropical oceans and is especially concentrated in the northern Indian Ocean, the eastern Pacific and the eastern Atlantic Ocean (Fig. 8a). This is comparable to the distribution in Keller et al. (2012) and Somes et al. (2010a), both using UVic in different configurations. The patterns of N2 fixation are therefore consistent with observations, as far as they are known, with the same limitations as for Keller at al. (2012) and Somes et al. (2010a). For example, in the subtropical North Atlantic, where some of the highest rates of N2 fixation have been measured (Capone et al., 2005), UVic simulates almost no N2 fixation at all.
The simulation NEWS, DIN+DON and 2xDIN show, that adding riverine N leads to a net decrease in N2 fixation in nearly the whole area, where it occurs, but especially near the river mouths (Fig. 8b-d). The main regions, where N2 fixation is significantly decreasing are the Gulf of Guinea, the Gulf of Bengal and near the Amazon River mouth.

In a previous study with UVic, Somes et al., 2016 have shown that increasing atmospheric N deposition could lead to a reduction in N2 fixation, due to non-nitrogen-fixing phytoplankton being more competitive than N fixers, when key nutrients like iron and phosphate are limiting. Here, it is the input of riverine nitrogen that stimulates the reduction in N2 fixation locally, where N reaches the ocean.

Reductions in N2 fixation can then partly explain the lower NO3 concentrations at the surface of the tropical and subtropical oceans in NEWS, even though these areas are far from riverine N input (see 3.1.1. and Fig. 6 first row). We remind here that these results show the distribution at steady state after 10 000 years of riverine nitrogen supply. Not all fixed nitrogen is consumed by biological activity, but part of the additional N is also transported with ocean circulation and can "replace" N from nitrogen fixation in regions far off the coast, leading to decreasing N2 fixation at the surface of the tropical and subtropical oceans.

~~Figure 8 shows that N2 fixation is only slightly lower in the NEWS simulations than in CTR in the tropical and subtropical oceans, with some exceptions in the Pacific and the South Atlantic Ocean. However, N2 fixation is reduced significantly in the regions, where NO3 is also substantially lower, as seen before in the Bay of Bengal and near the Amazon River (Fig. 8 compared to Fig. 6).~~

3.1.3. The N-cycle feedback mechanisms

The interaction between the mechanisms described just before, N2 fixation, denitrification, and riverine nitrogen supply, can also explain the significant loss in NO3 in some regions localized before: the Gulf of Guinea, the Gulf of Bengal and the western coast of Central America (Fig. 5 and Fig. 7). In addition, these three regions have also in common that they are known to have very low oxygen concentrations. In the Bay of Bengal, oxygen concentrations even though higher at the surface in NEWS than in CTR, are very low in the NEWS simulations in the subsurface waters and the whole deeper basin (Fig. 7). These suboxic waters are furthermore located in proximity to riverine N input and high denitrification rates (Fig. 9). While total denitrification rates (benthic and water column denitrification) are already quite high in CTR, they are further increased in NEWS, DIN+DON and 2xDIN in the northern Bay of Bengal, adjacent to the river delta.

Landolfi et al. (2013) found that the negative feedback mechanism between N2 fixation and denitrification, generally stabilizing the marine N inventory, can turn into a destabilizing positive feedback, generating runaway N loss, if a close spatial association of N2 fixation and denitrification occurs. This is due to the stoichiometry imbalance created by the combination of these processes. Denitrification occurs in anoxic or suboxic environments, where nitrate or nitrite can be used as a substitute terminal electron acceptor instead of oxygen. Denitrification consumes 7 mol of NO3 for every mole of organic N provided by N2-fixation, when these processes equilibrate with each other over long timescales. This imbalance generates a net loss of fixed N, even if N is continuingly added via N2 fixation.

The 'vicious cycle' described by Landolfi et al. (2013) is triggered in the Bay of Bengal by the input of new N from riverine export near oxygen minimum zones, explaining the NO3 deficit found in the simulated Bay of Bengal (Fig. 5). Note that UVic, similar to most other biogoechemical ocean models, misplaces the main oxygen minimum zone from the Arabian Sea to the Gulf of Bengal (Séférian et al., 2020). In reality, high water column denitrification has been observed in the Arabian Sea, while in the Gulf of Bengal highly variable oxygen concentrations seem to inhibit denitrification (Johnson et al., 2019; Bange et al., 2005).

At the end of the simulation, the global marine N inventory is higher by 5278 Tg N in NEWS compared to CTR, which corresponds to 1.12 % of the global N inventory in CTR and 2.3 % of the total riverine N input over the 10000 years of the simulation. Even for the highest scenario (2xDIN), the total increase in global N represents only +2.53 % of the reference N inventory. Most of the additional N input through river discharge is thus compensated for by the feedbacks of the N cycle.

However, relative to the total additional input, the N increase in 2xDIN is higher than in NEWS (+2.6 % compared to +2.3 %), which means that the negative feedbacks do not compensate in 2xDIN as much as in NEWS. A possible reason for this result could be, that the main negative feedbacks, resulting in loss of N, take place in very localized low-oxygen areas, that cannot expand further (e.g. Bay of Bengal), while riverine N is supplied through river mouths scattered over the world.

Additional literature

Capone, D. G., Burns, J. A., Montoya, J. P., Subramaniam, A., Mahaffey, C., Gunderson, T., Michaels, A. F., and Carpenter, E. J.: Nitrogen fixation by Trichodesmium spp.: An important source of new nitrogen to the tropical and subtropical North Atlantic Ocean, Global Biogeochem. Cy., 19, GB2024, doi:10.1029/2004GB002331, 2005.

Galbraith, E. D., Gnanadesikan, A., Dunne, J. P., and Hiscock, M. R.: Regional impacts of iron-light colimitation in a global biogeochemical model, Biogeosciences, 7, 1043–1064, doi:10.5194/bg-7-1043-2010, 2010

Sohm J. A., Webb E. A., and Capone D. G.: Emerging patterns of marine nitrogen fixation, Nature Reviews Microbiology, 9, 499-508, 2011.

Somes, C. J., Schmittner, A., and Altabet, M. A.: Nitrogen isotope simulations show the importance of atmospheric iron deposition for nitrogen fixation across the Pacific Ocean, Geophys. Res. Lett., 37, L23605, doi:10.1029/2010GL044537, 2010a.