Response to comments on “GOLUM-CNP v1.0: a data-driven modeling of carbon, nitrogen and phosphorus cycles in major terrestrial biomes” by Y. Wang et al.

We thank the referee for reviewing our manuscript. Please find attached a point-by point reply to each of the comments raised by the referee with legible text and figures organized along the text.

Overall this is an interesting and detailed summary of an improvement to an existing model. Though not the first to put in a N cycle, the P cycle is relatively novel and there is clearly diligent work done by the authors to ensure values are appropriately backed up by data where possible. There are a few points that I think need clarifying and some aspects of the model that seem to me a bit odd, and therefore need provisos about the appropriate (or inappropriate) use of the model. Some of the conclusions about openness are a bit of a stretch given the model setup. But with some extra information discussing the limitations, this will be a worthwhile model description.

Response:

We would like to thank the referee for the valuable comments and suggestions for improving our manuscript. Following the reviewer’s comments, we carefully revised our manuscript. Please find below the point-to-point responses (in black) to all referee comments (in blue). For your convenience, changes in the revised manuscript are highlighted with dark red. All the pages and line numbers correspond to the original version of text. Of note GOLUM-CNP is not an improvement to an existing model, but an independent model that uses the outputs from CARDAMOM and incorporate the data-driven estimates of N and P cycles (see detailed response to Comment 3).

Major points

1. The issue of this being an equilibrium model for the present day/recent past is a concern to me. It isn’t sufficiently explained how an equilibrium estimate (including anthropogenic N deposition) is valid in equilibrium. I can see the justification if it’s preindustrial (excluding anthropogenic N deposition), but it doesn’t make sense to me as it is. In particular, the openness of the system seems to me to be almost completely determined by the assumption of equilibrium. If the outputs and inputs are balanced (i.e. the equations are solved to 0, as is stated on P7 L32), then surely the store size is at least partly determined by something we know to be wrong. Given that the equilibrium assumption should increase the carbon storage, it’s odd that in Table 2 (assuming these are present-day values), the NPP and the soil and vegetation pools are all smaller than many other models and global estimates suggest.

Response:

We develop a steady-state model as a first attempt of a CNP data-driven diagnostic model. The objective of this study is not to reproduce the present day state, but to provide a steady-state estimates of C, N and P cycle with current input of C, N and P, stoichiometry of

N:C and P:C ratios, and residence times of different pools, because there is a lack of data to constraint a transient state (see point 1). As a result, we choose to constrain an equilibrium state. Although it does not correspond in some aspects to the present day state, it is still useful for evaluating global models as these model are able to simulate a equilibrium state for present day conditions and a direct comparison is possible (see point 2 and point 3).

1) Although we described processes in the C, N and P cycles by a set of differential equations (Eqs. A1-A5, B1-B7, C1-C7), only few global long-term observations associated with N and P were available to constrain a transient simulation. For example, the synthesis of stoichiometries in different pools are based on published literature during the last four decades, and almost no data are available for preindustrial period; field-scale manipulation experiments have shown that warming, elevated atmospheric CO_2, and N and P fertilization can drive changes in stoichiometries and nutrient resorption in terrestrial ecosystems (Sistla and Schimel, 2012; Sardans et al., 2012; Sardans and Peñuelas, 2012; Mayor et al., 2014; Yang et al., 2014; Yuan and Chen, 2015; Sardans et al., 2016; Sardans et al., 2017), but these data are insufficient to infer these changes in terrestrial ecosystems during the past years. As a result, for a data-driven model framework, we computed the equilibrium estimates and this equilibrium corresponds to the state where the inputs of C, N and P (e.g. NPP for C cycle, N deposition and fixation for N cycle, P deposition and release of P by rock weathering for P cycle) and residence times equal to the estimates under present-day conditions.
2) Some previous studies that have investigated the changes in C, N stocks between pre-industrial period and present day. Thornton et al. (2007) investigated the C stock changes from pre-industrial times and present day (1976-2000) using CLM-CN model. They found the C stocks in vegetation, litter and SOM increased by 35, 1 and 10 Pg, which equal to only 5%, 6% and 3% of the respective initial C stocks in 1850. Zaehle et al. (2010) estimated the C stock changes and N stock changes in vegetation and SOM, using the O-CN terrestrial biosphere model. By excluding the impact by land use change, that vegetation C stocks increased by 62 Pg and soil C stocks increased by 39 Pg from 1860 to 2002, being 13% and 3% of initial C stocks for vegetation and SOM respectively. The N stocks increased by 376 Tg and 2836 Tg in vegetation and SOM, being 11% and 3% of initial N stocks. Zaehle et al. (2013) further accounted for the effect of land use change on the global C and N cycles. The results also showed that the cumulative effect of anthropogenic disturbance from preindustrial times are small (<5%) on the natural C and N cycles. The evidences for the change of global P cycling from pre-industrial times are quite limited and highly uncertain (Goll et al., 2012). At local scales, some places are experiencing significant anthropogenic disturbances, mostly through deposition and fertilizer (Jornard et al., 2015). However, the extent to which natural ecosystems are affected by these disturbances are not clear (Wang et al., 2017). Given these state-of-the-art estimates about the magnitude of anthropogenic disturbance on natural C, N and P cycles and large uncertainties, it is still useful to take steady-state estimates as a diagnostic to evaluate DGVMs in simulating global C, N and P cycling (Wang et al., 2010; Xu-ri et al., 2008; Yang et al., 2009; Lawrence et al., 2011). The estimates based on steady state assumptions listed above match well with a wide range of *in-situ* observations in recent years.

3) CARDAMOM is the only spatially explicit data-driven product of C cycle, which does not rely on a steady-state assumption. In this study, our aim is to develop a steady-state model (see point 1) in which a consistency between different datasets are achieved (which is a novelty). We chose to use the variables in the CARDAMOM products: NPP, residence times and fire fractions, which were constrained by global long-term observations of MODIS LAI and MODIS burned area. For other C variables whose direct constraints do not have a global coverage in CARDAMOM (such as biomass), we recalculated them based on the equilibrium assumption. With this steady state C cycle, we compute the associated N and P pools and fluxes. For example, the N and P in SOM pool equal to the product of N:C/P:C ratios and equilibrated C content.

In summary, given the three concerns mentioned above, we computed an equilibrium estimate of C, N and P cycle, where the inputs of C, N and P into the terrestrial ecosystems (NPP, N and P deposition, N fixation and release of P by rock weathering), stoichiometries of N:C and P:C ratios, the residence times of different pools and the land cover are held constant as the period 2001-2010. Although this steady-state estimates deviate from the actual state of present-day disturbed cycles, we compare the GOLUM-CNP with the original CARDAMOM to show that the steady-state estimates in GOLUM-CNP are still within the range of such large uncertainties from data on the present day state.

To address the referee's concern about steady-state assumption in a quantitative way, we compare the recomputed pool sizes for C with the original CARDAMOM estimates (Fig. S1 in the revised supporting information). The steady-state transformed pool sizes are within the [25, 75th] percentile range of the original CARDAMOM results at more than 90% forest grid cells. The major part of the deviation comes from the treatment of grassland in GOLUM and are not associated to the steady-state assumption: In GOLUM-CNP grasslands are considered as a distinct biome, while the original CARDAMOM did not use land cover information and provided some woody biomass pools for grassland dominated regions. As GOLUM does not consider woody biomass for grass, we transfer wood growth from CARDAMOM into non-woody tissue for grasslands. This makes our C pools more different from the original CARDAMOM at grassland-dominated pixels than at forest-dominated pixels. However, although the biomass at grassland grid cells in GOLUM-CNP are much lower than the biomass in CARDAMOM, the litter and SOM pool sizes at grassland grid cells in GOLUM-CNP are still within the [5, 95th] percentile range of the original CARDAMOM results (Fig. S1b and S1c in the revised supporting information). In addition, we also mention in the revised manuscript: although GOLUM-CNP is presented for steady state in this study, the methods and equations used to compute fluxes and pools are generic and could be extended to non-steady state. In the future, when more data will become available, a transient version of GOLUM-CNP will incorporate the new data and improved understandings in C, N and P cycles.

We outline in the revised paper that some variables like the *openness* do not strongly rely on the equilibrium assumption. The openness is defined as:

$$\mathrm{XO} = \frac{\mathrm{I_x}}{\mathrm{F_x} + \mathrm{RSB_x}} \qquad (1)$$

where I_x ($X \in \{N,P\}$) is the new nutrient inputs, i.e. deposition (N_d) and biological fixation (N_{fix}) for N cycle and deposition (P_d) and rock weathering (P_w) for P cycle. These variables are in fact the nutrient inputs to the system, which are derived from observations and are not estimated from equilibrium assumption. F_x+RSB_X represent the total uptake of nutrients by plant, which are determined by NPP, allocation fractions of NPP to different vegetation pools and stoichiometries in different vegetation pools. These variables are also the inputs to GOLUM-CNP and represent the non-steady state situation under current climate condition from original CARDAMOM without equilibrium assumption (as discussed above, only the C store sizes are computed based on equilibrium assumption). In consequence, this computation is actually based on a mass-balance framework and driven by fluxes as observed in present day transient state. However, we do assume that the stoichiometries of N:C and P:C ratios do not change significantly during the period considered (2001-2010), although small changes in stoichiometry in fast-turnover plant tissue is being observed on such a time scale (Jonard et al. 2015). Such an approach is common and is similar to that of Cleveland et al. (2013). In Cleveland et al. (2015), they computed NPP_{new} and $NPP_{recycle}$ where N:C and P:C ratios are the same in these two types of NPP. In our study, we use new nutrient input (i.e. I_x) and total nutrient uptake (i.e. F_x+RSB_X) rather than two types of NPP.

Under the equilibrium assumption, conceptually, the pool sizes do not represent the current stock. However, our estimates under equilibrium assumption are very close to observation-based estimates of NPP and C stocks (Table R1) and are all within the range of other estimates. In fact, our estimates of biomass and SOM stocks are a little bit larger than the state-of-the-art estimates listed in Table R1. In addition, the C stocks are not necessarily larger than the dynamic state. For example, Jones et al. (2009) showed that when the climate forcing was held constant after 2050, the equilibrated forest cover in a region of Amazon forest will be smaller than the dynamic state in 2050, resulting less equilibrated biomass than the dynamic biomass in this region. Given these evidences, we do not think that our results about the steady state are significantly underestimated.

Table R1 Computed NPP and C stocks under equilibrium assumption compared with published estimates.

variable	This study	Other
NPP (Pg yr^{-1})	52.5	54 (Zhao et al., 2005)
Terrestrial biomass (Pg)	493	450 [380-536] (Erb et al., 2018) 450 [375-540] (Bar-on et al., 2018)
SOM (Pg)	1421	1408 ±154[1] (Batjes et al., 2016)

[1] This value represent the C stock between the depth 0-100 cm, generally correspond to the biologically active depth

To address all the points raised by the referee, in the revised manuscript, we revised the manuscript:

- Page 2 line 37 – page 3 line 6: "We present a new global data-driven diagnostic of C, N and P pools and fluxes, called GOLUM-CNP (Global Observation-based Land-ecosystems Utilization Model of Carbon, Nitrogen and Phosphorus) which is based on the assumption that these cycles are equilibrated with present day conditions (see below for limitations of this approach). The goals of this study are to: 1) establish a global data-driven diagnostics of C, N and P fluxes and pools in order to compare nutrient use efficiencies, nutrient turnover rates and other relevant indicators across biomes; and 2) provide a new dataset that can be used to evaluate the results of global terrestrial biosphere models with consistent state of C, N and P cycles. In GOLUM-CNP, the C, N and P cycles are estimated for different biomes assuming steady state with present-day input of carbon (NPP), nitrogen (N deposition and N fixation) and phosphorus (P deposition and release from rock weathering) (see Sect. 3.2). The reason for this steady-state computation lies in the fact that only few global long-term observations associated with N and P cycles are available and are insufficient to constrain a transient simulation under the model framework. For example, field-scale manipulation experiments have shown that warming, elevated atmospheric CO_2, and N and P fertilization can drive changes in stoichiometries and nutrient resorption (Sistla and Schimel, 2012; Mayor et al., 2014; Yang et al., 2014; Yuan and Chen, 2015) in terrestrial ecosystems, but these data are insufficient to infer these changes in terrestrial ecosystems during the past decades. As more data becomes available the model framework can be adjusted to simulate a transient present day state. Although, the steady-state assumption hampers the comparison of stocks with present day observations, a direct comparison with simulated steady states of DGVM is possible as these model can simulate the steady-state for present day conditions.

Starting from a CARbon DAta MOdel fraMework (CARDAMOM) …we incorporated observed stoichiometric ratios (C:N:P) in each pool, N and P external input fluxes, transformations and losses in ecosystems and ~~losses and observation-based information for~~ the fraction of gaseous losses of N to total (gaseous and leaching) losses of N from a global dataset of ^{15}N measurements in soils. Although the diagnostics is presented for steady state, the methods used to compute fluxes and pools are generic and could be extended to non-steady state (see Sect. 2 and equations in Appendix A-C) when more data will become available in the future (see Sect. 5.3).”

- Sect. 5.3 page 12 lines 35-37: “… Our results are a first step for evaluating global biogeochemical cycles. Although our steady-state C pool sizes (given the NPP and residence time at the condition of current climate) were within the [25, 75th] percentile range of the original non-steady-state CARDAMOM results (Fig. S1) at most grid cells, the biomass C stocks at 5%-10% of forest grid cells exceed the uncertainty range of CARDAMOM. In addition, independent remote-sensing estimates for 30 °N to 80 °N were 4.76 ± 1.78 kg C m-2 for mean forest C density and 79.8 ± 29.9 Pg C for total forest C (Thurner et al., 2014), which were lower than the GOLUM-CNP estimates (6.51 kg C m-2 for mean forest C density across pixels defined as forest in Fig. 2, and 181 Pg C for total forest C) for this region. This inconsistency was largely due to the fact that northern temperate and boreal forests may deviate substantially from their equilibrium for the current NPP (Pan et al., 2011), because of climate change and elevated CO2. Residual overestimation could be also due to the fact that biomass removal by harvesting and from disturbance other than fires was not explicitly constrained in CARDAMOM and thus not represented in GOLUM-CNP. A transient simulation of N and P cycling will be needed in future studies…"

- We also specify the computation method for the output variables, to indicate whether these variables depend or not on the equilibrium assumption (Table 1 in the revised manuscript).

2. Reading between the lines, it seems that the N fixation is about 120Tg/year. How does this square with other estimates, e.g. Vitousek et al. 2013 (44Tg/year)? Since it's not discussed where this N fixation number came from (and the reference isn't available), or where the N deposition number came from, it makes it difficult to give much credibility to the openness discussions which rely on these.

Response:

The estimates of global BNF from synthesis and extrapolation are highly uncertain. Cleveland et al. (1999) estimated of biome- and global-level BNF based on scaling up of *in situ* measurements of BNF. They applied average plot-level BNF rates measured within each biome to the biome as a whole, assuming empirical range of values for the cover of plants with potential N-fixing symbioses. They estimated that global BNF by natural ecosystems was ~195 Tg N yr^{-1} (with a range 100-290 Tg N yr^{-1}) during pre-industrial. The estimates by Cleveland et al. (1999) were criticized by Galloway et al. (2004) and later Sullivan et al. (2014) as too high, in particular for tropical regions. Galloway et al. (2004) suggested a lower global BNF to be 128 Tg N yr^{-1}; Wang et al. (2007) made the estimate of BNF using the principle of resource optimization, and their global estimate for the year 1900 was 125 Tg N yr^{-1} (Wang and Houlton, 2009). Vitousek et al. (2013) incorporated information on N fluxes with ^{15}N relative abundance data and estimated pre-industrial N fixation was 44 TgN yr^{-1}. The large range (44-290 TgN yr^{-1}) in the estimates of BNF mentioned above reflects both a paucity of measurements of N fixation, as well as an incomplete understanding of the biophysical and biochemical controls on BNF.

In this study, we used estimates of biological N fixation from the CABLE model simulation by Peng et al. with a N fixation model developed by Wang et al. (2007), and used by Wang and Houlton (2009). This work by Peng et al. still is under review for Global Biogeochemical Cycles. We agree that there are considerable uncertainties about the magnitude of BNF. Vitousek (2013) estimated the total global N fixation from ranges from 40 to 100 Tg N yr^{-1} for the preindustrial time. Our estimated rate of 116 Tg N/yr^{-1} for the present days is still close to the upper limit of Vitouske (2013). Much of the difference may result from much higher rates used in this study for tropical forests than the recent estimate by Sullivan et al. (2014) that was based on the measurements at sites in southwest Costa Rica. However, estimates of BNF from Vitousek et al. (2013) are only available at global scale. BNF from CABLE, a process-based model validated for observations for diverse terrestrial biomes (Wang et al., 2007; Houlton et al., 2008) is to our best knowledge the only available global spatially explicit estimates of BNF besides the heavily criticized estimates by Cleveland et al. (1999), and is therefore used in this study. We discussed the uncertainties of BNF in the revised manuscript on page 5 line 7: "We used the spatially explicit estimates of N deposition (Wang et al., 2017) for 2001-2010, which were evaluated with globally distributed *in-situ* measurements. The spatially explicit N fixation was taken from the CABLE model simulation for 2001-2010 (Peng et al., submitted) with a N fixation model developed by

Wang et al. (2007). The simulation result matches the relative abundance of N_2-fixing legumes in different ecosystems. Globally, the N fixation was 116 Tg N yr^{-1}, within the range of empirical data (100-290 Tg N yr^{-1}; Cleveland et al., 1999; Galloway et al., 2004), but was larger than the estimate of 44 Tg N yr^{-1} by Vitousek et al. (2013) for pre-industrial. The large range (44-290 TgN yr^{-1}) in the estimates of nitrogen fixation reflects both a paucity of measurements of N fixation, as well as incomplete understanding of the biophysical and biochemical controls on N fixation. However, as mentioned in Sect. 2.2, our estimates of total N inputs (N deposition + N fixation) are consistent with the estimate from Houlton et al. (2018). And to our knowledge, CABLE simulation is the only product that has spatially explicit and processed-based estimates of N fixation, and is therefore used in this study. The resorption coefficients of leaves…"

3. The relationship between GOLUM-CNP and CARDOMON is opaque and needs to be clarified. It is particularly unclear with regard to what the relationship between the code provided and CARDOMON is. For example, does this code work independently? Or does it need CARDOMON to run? If CARDOMON is part of the code provided, which parts are new and which are CARDOMON?

Response:

The code of GOLUM-CNP is not just an extension of CARDAMOM, but a new model that used the outputs of CARDAMOM, i.e. data-driven C variables. The relationship between GOLUM-CNP and CARDAMOM are: 1) the C pools and fluxes in GOLUM-CNP follows that of CARDAMOM after steady state transformation, except that we group foliar and vegetation labile C into a single pool because labile C is not a measurable pool and no observation data were available to separate it from foliar in terms of stoichiometry. The N and P cycles in GOLUM-CNP were added on top of this C cycle model by adding two pools (soil inorganic N and P) and associated N and P fluxes; 2) GOLUM-CNP used some of the CARDAMOM results as inputs which are listed and explained in Table 1. These variables are the key parameters that describe the C cycle and influence the estimates of status of nutrient cycles. For instance, the residence time of C pools were used in the calculation of N and P fluxes (Eqs. E15, E16, E26 and E27).

To precise the relationship between GOLUM-CNP and CARDAMOM in the manuscript, we made the following revisions:

- We added on page 3 line 8: "~~The~~ GOLUM-CNP ~~framework~~ describes the C, N and P cycles in natural (i.e. non-agricultural) terrestrial ecosystems (Fig. 1). We used the same C pools and fluxes as in ~~The C cycle follows the model structure of~~ the CARDAMOM diagnostic (see Sect. 2.1 for details) to describe the C cycle and we computed associated N and P pools and fluxes. Biomass is divided into three pools: foliage, fine roots and wood…"
- We revised the sentence on page 4 line 35: "…the N and P contents in soil control the decomposition of soil C and thus the soil C pool observed (Manzoni et al., 2010). In this sense, it is appropriate to use C cycle from CARDAMOM as inputs to estimate the pool and fluxes of N and P."

The code must be run with variables from CARDAMOM (and also other required datasets, see "Inputs" in Table 1). Following the referee's suggestion, we comment the code thoroughly. Please refer to the code resubmitted for detail.

4. It’s not explained what the intended use of this model is. It’s essential early on in the paper to have some examples of use, as well as specific limits on what it shouldn’t be used for, (particularly given the limitation of it being an equilibrium model). This is slightly covered right at the end of the paper, but needs to be earlier and more extensive.

Response:

Thank you for this suggestion to improve the manuscript. We agree with the referee this information is quite important for the readers. In the revised manuscript, we explained the objects of this study in the introduction and discussed the equilibrium assumption in Sect. 5.3 (see answer to Major comment 1).

We remind the readers that current GOLUM-CNP results are steady-state estimates, when comparing our results with other DGVMs, it is better to run the DGVMs to steady state with present-day inputs of C, N and P. We revised the manuscript by:

- Adding a paragraph in Sect. 5.3 about this point: “The model structure of GOLUM-CNP is mainly described by the inputs (NPP for C cycle, N deposition and fixation for N cycle, P deposition and release from rock weathering for P cycle) and residence times. Most DGVMs (e.g. Goll et al., 2012, 2017a; Medvigy et al., 2009; Parton et al., 2010; Thornton et al., 2007; Wang et al., 2010; Weng and Luo, 2008; Xu-Ri and Prentice, 2008; Yang et al., 2009; Zaehle et al., 2014; Zaehle and Friend, 2010) can be summarized by these two components, although these models have more processes and use complex equations to describe the dynamics controlling carbon and nutrient distribution among pools and the turnover of each pool. In this context, the output of the GOLUM-CNP provides a traceable tool that can be used in the future to compare the results between GOLUM-CNP and different DGVMs. As DGVMs are capable of computing the steady state of the biogeochemical cycles for present conditions, a direct comparison between GOLUM-CNP estimate and DGVMs’ estimates is possible.”
- Revising page 12 line 38 to page 13 line 3: “At last, ~~The~~the sensitivity matrix presented in Sect. 4.4 provides a useful tool for assessing the uncertainties in model outputs by propagating the uncertainties in the model inputs. We applied this method to quantitatively assess the sources of uncertainties in the estimated nutrient-use efficiencies (Sect. 5.1 and Fig. 8), but we also found that the uncertainties for some other quantities were currently difficult to obtain, because the estimates of uncertainties were not available for all spatially explicit input data. This sensitivity analysis can be used in future studies to quantify the contribution of each input data set to the uncertainty in other model outputs, to characterize the dominant sources of uncertainties in the estimated C, N and P processes, to identify the major differences between different models (e.g. GOLUM-CNP versus DGVMs) and thus to identify priorities for future data syntheses to fill the largest gaps in uncertainty. Future studies that provide global data sets will need to include systematic evaluations and spatially explicit estimates of uncertainties in their data sets.”
- Revising the conclusion on page 13 lines 10-17: “… The structure of GOLUM-CNP is analogous to most other process-based ~~LSMs~~ DGVMs describing carbon and nutrient interactions ~~(e.g. Goll et al., 2012, 2017a; Medvigy et al., 2009; Parton et al., 2010;~~

~~Thornton et al., 2007; Wang et al., 2010; Weng and Luo, 2008; Xu-Ri and Prentice, 2008; Yang et al., 2009; Zaehle et al., 2014; Zaehle and Friend, 2010), although these models have more processes and use complex equations to describe the dynamics controlling carbon and nutrient distribution among pools and the turnover of each pool.~~ The output of the GOLUM-CNP provides a traceable tool and~~, in which a consistency between different datasets of global C, N and P cycles has been achieved. Such a framework~~ can ~~thus~~ be used in the future to test the performance of ~~these~~ complex ~~LSMs~~ DGVMs in the simulation of interactions between C, N and P cycling."

5. The code is very dense, making it very difficult to read. Code should have comments every 1 - 10 lines, depending on how interpreted/dense, etc. the code is. Ideally, code should be commented so that, if you stripped out the actual code or if you didn't know python at all, you could re-write it in another language just from the comments. I was also a bit surprised not to see any functions used.

Response:

We write detailed comments in the new code. In fact, we have the main code "Globe_ss_Anal.py" and another two files incorporating three modules: 1) ncload.py, in which the module "ncload" reads the netcdf4 files and associated variables very efficiently; 2) ss_Anal.py, which make the computation at each grid cell. In ss_Anal.py, two functions ("tree" and "grass") making the computation for forest and grassland are defined separately. In the main code Globe_ss_Anal.py, "ncload" are called at the beginning of the code to read all the variables; "tree" and "grass" are called according to the dominant biomes of each grid cell.

Minor points

1. P.2 L6-7. Yes, but also water, light etc. are essential controls - if there's no light and water it doesn't matter how much N or P there is, nothing will grow.

Response:

Thank you for noting this inappropriate expression. We revised the sentence as: "…in terrestrial ecosystems. N and P availability affects vegetation productivity, growth and other processes (Norby et al., 2010; Sutton et al., 2008; Vitousek and Howarth, 1991)."

2. P.2 L17 - 30. This seems to mix up P and N fertiliser. It would be better to keep the two issues separate wherever possible.

Response:

Thank you for the suggestion. We rephrase this paragraph: "… Many of the underlying processes are not fully understood, and comprehensive data for evaluation are lacking to constrain the representation of some key processes (Zaehle et al., 2014), so model structure, the processes included and the prescribed parameters differ widely among DGVMs (Zaehle and Dalmonech, 2011). For example, some models assume constant stoichiometry (N:C and P:C ratios) in plant tissues (Thornton et al., 2007; Weng and Luo, 2008), but others have a flexible stoichiometry (Wang et al., 2010; Xu-Ri and Prentice, 2008; Yang et al., 2009; Zaehle and Friend, 2010). For the N cycle, for instance, some models do not include losses of gaseous N ~~due to~~ from denitrification (Medvigy et al., 2009), some use the "hole-in-the-pipe" approach to simulate the denitrification flux (Thornton et al., 2007; Wang et al., 2010), assuming it is proportional to net N mineralization, and others calculate this flux as a function of soil N-pool size and soil conditions (temperature, moisture, pH, etc.) (Parton et al., 2010; Xu-Ri and Prentice, 2008; Zaehle and Friend, 2010). For models of the terrestrial P cycle, for instance, Jahnke (2000) estimated a global amount of soil P of 200 Pg and that P contained in plants was 3 Pg, based on empirical P content of soils (0.1%) and soil thickness (60 cm). These estimates were questioned by Wang et al. (2010) and Goll et al. (2012), who estimated that P in plants ranged between 0.23 and 0.39 Pg and that P in soil was only 26.5 Pg based on P:C ratios derived from more comprehensive stoichiometric data sets. Furthermore, ~~these models~~ terrestrial ecosystem models are usually only evaluated for specific ecosystems or at a limited number of sites (Goll et al., 2017a; Yang et al., 2014). The application of these models for simulations with global coverage is thus highly uncertain (Goll et al., 2012; Wang et al., 2010; Zhang et al., 2011)."

3. P18. L28. Reference to Peng missing.

Response:

Please see the response to the 2nd major point. And we added the reference accordingly.

4. P21. Table 2. When is this table referring to? (Pre-industrial? Present day?) It needs to be specified.

Response:

We revised the caption of Table 2 into: "Global annual mean C-pool sizes, NPP and heterotrophic-respiration fluxes in the C-cycle model assuming steady states under the climate conditions of 2001-2010." We also revised the text in the manuscript on page 8 line 3: "Table 2 shows the global C-pool sizes and main fluxes of the steady-state C cycle transformed from CARDAMOM under the climate conditions of 2001-2010, which are compared with the means and percentile ranges from the original non-steady-state CARDAMOM results during 2001-2010. The differences between the steady-state transformed pool sizes…"

5. P22. Figure 1. The caption would be more useful if the terms at the top of the figure were defined first, and then worked downwards.

Response:

Thank you for the suggestion. We reorganized the sentences in the caption: "**Figure 1** Schematic representation of the pools and fluxes in the C, N and P cycles within GOLUM-CNP. The gray, blue and red arrows represent C, N and P fluxes, respectively. Plants are divided into foliar, fine root and wood pools, where the wood pool includes woody stems and coarse roots. Litter and soil are two separate pools. The inorganic pool represents the nutrient sources in the soil that are available for plant uptake. Arrows between the pools represent the directions of C, N and P flow between pools. External inputs of N are atmospheric deposition (N_d) and biological N fixation (N_{fix}). External inputs of P are atmospheric deposition (P_d) and P released by rock weathering (P_w). F_C is net primary production (NPP). F_N and F_P are plant uptake of N and P from the inorganic N and labile soil P pools, respectively. R_h is release of C due to heterotrophic respiration. Mineralization of N and P is modeled along with litter and SOM decomposition, and N and P immobilization is modeled by a flux from the inorganic pool to SOM. External losses of N occur by fire, leaching and denitrification. External losses of P occur by fire, leaching and transfer to occluded P in the soil."

6. P24. Figure 3. This is a very difficult to read. A table or a series of bar plots would be much better.

Response:

We tried to use tables or bar plots (Fig. R1) as the referee suggested. There are many variables involved, and we want to separate the seven biomes to see their major differences in the C, N and P cycle. As shown in Fig. R1, such figures will need 6 y-axis, and a very long space to put 6 figures. Even though we tried to optimize the spacing between figures, it is hard to put it on one A4 page and the texts are small. In addition, with the original plots, we depict the full C, N and P cycles including the pool sizes, residence times of different pools and fluxes. But with bar plots, only a small subset of the variables could be shown in limited space so that the readers will lose the whole pictures of the C, N and P cycles when reading these bar plots only. It is the same case to use a series of tables, because readers would need to link the variables from the tables in their own mind. At last, we decide to use the same figure, but rearrange them. We put the figures in a 3 by 3 grid so that all figures and numbers in the figures are larger and more easily to be read (please see the revised manuscript). And for readers who are more interested in reading bar plots, we also provide these bar plots in the supplementary material.

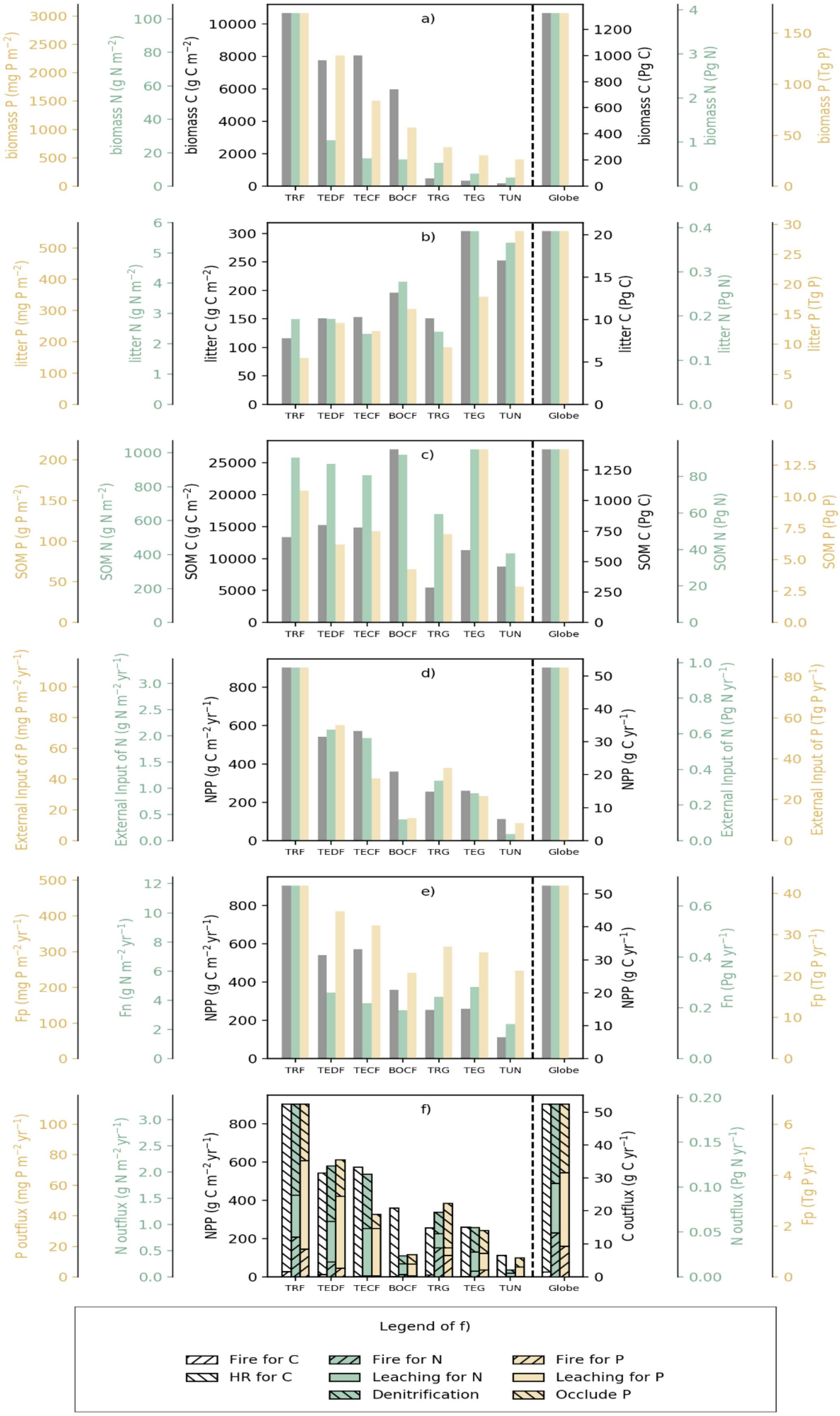

Figure R2 Pool sizes and fluxes of C (black), N (green) and P (yellow) computed from

GOLUM-CNP. The targeted biomes are tropical rainforests (TRF, a), temperate deciduous forests (TEDF, b), temperate coniferous forests (TECF, c), boreal coniferous forests (BOCF, d), tropical/C4 grasslands (TRG, e), temperate/C3 grasslands (TEG, f) and tundra (TUN, g).

7. P28. Figure 7. Two points need to be addressed for this figure. First that the text is so small that it is impossible to read printed A4. That's true of the ones in the SI too. Second that it's ironic that a red-green color scheme is used, despite one of the authors being color-blind. I just… Other color schemes are available.

Response:

Following the referee's suggestion, we revise this figure and the corresponding figures in the SI. The two plots are placed up and down, so that the circles and texts are enlarged. We also changed the color schemes for all the figures in the paper. With these modifications, we also want to mention that the color in these figures are indicative enough to show the different order of magnitude in the sensitivity. The numbers in each grid cell gives the same information as the colors but gives the precise values corresponding to the colors.

8. P29. Figure 8. It would be a courtesy to your readers to include in the key what YC1, etc. are. It could literally just go beneath the current labels.

Response:

Thank you for your comments. We revised the figure accordingly.

References:

Bar-On, Y. M., Phillips, R. and Milo, R.: The biomass distribution on Earth, PNAS, 201711842, doi:10.1073/pnas.1711842115, 2018.

Batjes, N. H.: Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks, Geoderma, 269, 61–68, doi:10.1016/j.geoderma.2016.01.034, 2016.

Cleveland, C. C., Townsend, A. R., Schimel, D. S., Fisher, H., Howarth, R. W., Hedin, L. O., Perakis, S. S., Latty, E. F., Von Fischer, J. C., Elseroad, A. and Wasson, M. F.: Global patterns of terrestrial biological nitrogen (N2) fixation in natural ecosystems, Global Biogeochem. Cycles, 13(2), 623–645, doi:10.1029/1999GB900014, 1999.

Cleveland, C. C., Houlton, B. Z., Smith, W. K., Marklein, A. R., Reed, S. C., Parton, W., Grosso, S. J. D. and Running, S. W.: Patterns of new versus recycled primary production in the terrestrial biosphere, Proc. Natl. Acad. Sci., 110(31), 12733–12737, doi:10.1073/pnas.1302768110, 2013.

Erb, K.-H., Kastner, T., Plutzar, C., Bais, A. L. S., Carvalhais, N., Fetzel, T., Gingrich, S., Haberl, H., Lauk, C., Niedertscheider, M., Pongratz, J., Thurner, M. and Luyssaert, S.: Unexpectedly large impact of forest management and grazing on global vegetation biomass, Nature, 553(7686), 73–76, doi:10.1038/nature25138, 2018.

Galloway, J. N., Dentener, F. J., Capone, D. G., Boyer, E. W., Howarth, R. W., Seitzinger, S. P., Asner, G. P., Cleveland, C. C., Green, P. A., Holland, E. A., Karl, D. M., Michaels, A. F., Porter, J. H., Townsend, A. R. and Vöosmarty, C. J.: Nitrogen Cycles: Past, Present, and Future, Biogeochemistry, 70(2), 153–226, doi:10.1007/s10533-004-0370-0, 2004.

Goll, D. S., Brovkin, V., Parida, B. R., Reick, C. H., Kattge, J., Reich, P. B., van Bodegom, P. M. and Niinemets, Ü.: Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling, Biogeosciences, 9, 3547–3569, doi:10.5194/bg-9-3547-2012, 2012.

Jonard, M., Fürst, A., Verstraeten, A., Thimonier, A., Timmermann, V., Potočić, N., Waldner, P., Benham, S., Hansen, K., Merilä, P., Ponette, Q., Cruz, A. C. de la, Roskams, P., Nicolas, M., Croisé, L., Ingerslev, M., Matteucci, G., Decinti, B., Bascietto, M. and Rautio, P.: Tree mineral nutrition is deteriorating in Europe, Global Change Biology, 21(1), 418–430, doi:10.1111/gcb.12657, 2015.

Jones, C., Lowe, J., Liddicoat, S. and Betts, R.: Committed terrestrial ecosystem changes due to climate change, Nature Geoscience, 2(7), 484, 2009.

Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence, P. J., Zeng, X., Yang, Z.-L., Levis, S., Sakaguchi, K., Bonan, G. B. and Slater, A. G.: Parameterization improvements and functional and structural advances in Version 4 of the Community Land Model, Journal of Advances in Modeling Earth Systems, 3(1), doi:10.1029/2011MS00045, 2011.

Mayor, J. R., Wright, S. J. and Turner, B. L.: Species-specific responses of foliar nutrients to long-term nitrogen and phosphorus additions in a lowland tropical forest, Journal of Ecology, 102(1), 36–44, doi:10.1111/1365-2745.12190, 2014.

Peng, J, Wang Y-P and Houlton B.Z. Estimates of biological nitrogen fixation and implication of land carbon uptake from 1901 to 2100. under review in Global Biogeochemical Cycles.

Sardans, J. and Peñuelas, J.: The role of plants in the effects of global change on nutrient availability and stoichiometry in the plant-soil system, Plant Physiology, pp.112.208785, doi:10.1104/pp.112.208785, 2012.

Sardans, J., Rivas-Ubach, A. and Peñuelas, J.: The C:N:P stoichiometry of organisms and ecosystems in a changing world: A review and perspectives, Perspectives in Plant Ecology, Evolution and Systematics, 14(1), 33–47, doi:10.1016/j.ppees.2011.08.002, 2012.

Sardans, J., Alonso, R., Janssens, I. A., Carnicer, J., Vereseglou, S., Rillig, M. C., Fernández‐Martínez, M., Sanders, T. G. M. and Peñuelas, J.: Foliar and soil concentrations and stoichiometry of nitrogen and phosphorous across European Pinus sylvestris forests: relationships with climate, N deposition and tree growth, Functional Ecology, 30(5), 676–689, doi:10.1111/1365-2435.12541, 2016.

Sardans, J., Grau, O., Chen, H. Y. H., Janssens, I. A., Ciais, P., Piao, S. and Peñuelas, J.: Changes in nutrient concentrations of leaves and roots in response to global change factors, Global Change Biology, 23(9), 3849–3856, doi:10.1111/gcb.13721, 2017.

Sistla, S. A. and Schimel, J. P.: Stoichiometric flexibility as a regulator of carbon and nutrient cycling in terrestrial ecosystems under change, New Phytologist, 196(1), 68–78, doi:10.1111/j.1469-8137.2012.04234.x, 2012.

Thornton, P. E., Lamarque, J.-F., Rosenbloom, N. A. and Mahowald, N. M.: Influence of carbon-nitrogen cycle coupling on land model response to CO2 fertilization and climate variability, Glob. Biogeochem. Cycles, 21(4), GB4018, doi:10.1029/2006GB002868, 2007.

Vitousek, P. M., Menge, D. N. L., Reed, S. C. and Cleveland, C. C.: Biological nitrogen fixation: rates, patterns and ecological controls in terrestrial ecosystems, Philos Trans R Soc Lond B Biol Sci, 368(1621), doi:10.1098/rstb.2013.0119, 2013.

Wang, Y. P., Law, R. M. and Pak, B.: A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere, Biogeosciences, 7(7), 2010.

Xu-Ri and Prentice, I. C.: Terrestrial nitrogen cycle simulation with a dynamic global vegetation model, Glob. Change Biol., 14(8), 1745–1764, doi:10.1111/j.1365-2486.2008.01625.x, 2008.

Yang, X., Wittig, V., Jain, A. K. and Post, W.: Integration of nitrogen cycle dynamics into the Integrated Science Assessment Model for the study of terrestrial ecosystem responses to global change, Glob. Biogeochem. Cycles, 23(4), 2009.

Yang, Y., Fang, J., Ji, C., Datta, A., Li, P., Ma, W., Mohammat, A., Shen, H., Hu, H., Knapp, B. O. and Smith, P.: Stoichiometric shifts in surface soils over broad geographical scales: evidence from China’s grasslands, Global Ecology and Biogeography, 23(8), 947–955, doi:10.1111/geb.12175, 2014.

Yuan, Z. Y. and Chen, H. Y. H.: Decoupling of nitrogen and phosphorus in terrestrial plants associated with global changes, Nature Climate Change, 5(5), 465–469, doi:10.1038/nclimate2549, 2015.

Zaehle, S., Friend, A. D., Friedlingstein, P., Dentener, F., Peylin, P. and Schulz, M.: Carbon and nitrogen cycle dynamics in the O-CN land surface model: 2. Role of the nitrogen cycle in the historical terrestrial carbon balance, Global Biogeochemical Cycles, 24(1), doi:10.1029/2009GB003522, 2010.

Zaehle, S.: Terrestrial nitrogen–carbon cycle interactions at the global scale, Philos. Trans. R. Soc. Lond. B Biol. Sci., 368(1621), 20130125, doi:10.1098/rstb.2013.0125, 2013.

Zhao, M., Heinsch, F. A., Nemani, R. R. and Running, S. W.: Improvements of the MODIS terrestrial gross and net primary production global data set, Remote Sensing of Environment, 95(2), 164–176, doi:10.1016/j.rse.2004.12.011, 2005.