RC2:

This study implements phosphorus cycle processes into the JULES land surface model. The authors calibrate and test their model using observation from the Amazon Fertilization Experiment site and perform a theoretical elevated OC2 experiment. The inclusion of the P cycle in models is critical to our ability to predict ecosystem responses to elevated CO2 and climate change in low-P systems such as the tropics and subtropics, and the majority of land surface models are now adding these processes.

We thank the reviewer for their positive comments and suggestions. We have addressed the comments as described below.

My main concern about this paper is not with the model development per se, which is largely robust, but with the very extensive calibration. The authors calibrate their model very intensively using data from a very well instrumented site, which leaves me wondering if JULES CNP can be applied to any other site. In particular, the leaf C:P ratio, which the authors themselves show is a very sensitive parameter (Fig. 4) can be highly spatially variable and I do not see how the model can be run at sites where this data is not available, not to say anything about globally. Ideally, I would like to see the model validated at a site at which it has not been calibrated, but I understand this can be very difficult as it would involve obtaining more data. Alternatively, the authors could perform a more comprehensive parameter sensitivity analysis and include a discussion of the generality of their model.

We agree with the reviewer that our study would benefit from testing model at other sites with available data. However, as the reviewer mentioned, obtaining detailed measurements (similar to study under AFEX project) is challenging. We created a model suitable for global application, and it is appropriate to first test it at a site-level where data are available. At site-level it is standard practise to parameterise and calibrate the model where possible, to be able to then evaluate model performance for key variables. In order to run the JULES CNP at the global scale we need to define PFT-specific: plant stoichiometries (that can be obtained from Zechmeister-Boltenstern et al. (2015)), soil stoichiometries (can be obtained from Zechmeister-Boltenstern et al. (2015) and Tipping et al. (2016)), sorption and weathering ratios (can be obtained based on lithological class specific from the GliM lithological map (Hartmann and Moosdorf, 2012) and soil shielding from Hartmann et al., (2014)). Following preparation and scaling this information to read in JULES CNP, we can run at the global scale. There are also approaches to extend model application to the regional scale, e.g. relating soil properties with leaf level traits. However, this is not currently in the scope of this study. Nevertheless, our ongoing project aims to apply JULES CNP to the Amazon region using existing soil (Quesada et al., 2011) and foliar structural and nutrient (Fyllas et al., 2009) data for the above-mentioned parameterisation. This is added in lines 827-833 in the discussion section 4:
"Our new developments include major P processes in both plant and soil pools and can be applied to the Amazon region using existing soil (Quesada *et al.*, 2011) and foliar structural and nutrient (Fyllas *et al.*, 2009) data for parameterisation. Moreover, JULES CNP can be applied at the global scale and for future projections using global soil P data (Sun *et al.*, 2021) for model initialization and PFT-specific plant stoichiometries (Zechmeister-Boltenstern et al. 2015), soil stoichiometries (Zechmeister-Boltenstern et al. 2015; Tipping et al. (2016), sorption and weathering ratios (based on lithological class specific from the GliM lithological map (Hartmann and Moosdorf, 2012) and soil shielding from Hartmann et al., (2014))."

As suggested by the reviewer we performed an extended parameter sensitivity analysis on the P-related parameters as outlined below. The extended model sensitivity was performed on C:P stoichiometry, P uptake scaling factor, organic and inorganic P adsorption coefficients, and maximum organic and inorganic sorbed P. Since the occluded and weathered P pools are prescribed in the simulations of this study, the occluded and weather P coefficients (other two P-related model parameters) were not included in these sensitivity tests. The R scripts and output files are uploaded on the Zenodo as well.

Modifications in methods section lines 595-604:

"To test the sensitivity of the P and C related processes to the model P parameters, six sets of simulations were conducted with modified plant C:P stoichiometry (Plant C:P: *SENS1*), P uptake scaling factor (K_P) (Kp: *SENS2*), inorganic (KP_sorb_in: *SENS3*) and organic (KP_sorb_or: *SENS4*) P adsorption coefficients

($K_{sorp-or}$, $K_{sorp-in}$), and maximum inorganic (KP_sorb_in_max: *SENS5*) and organic (KP_sorb_or_max: *SENS6*) sorbed P (K_{or-max}, K_{in-max}). These values were prescribed to vary between ±50% of the observed values and their effect on C pools (plant and soil C) and fluxes (NPP and excess C), and P pools (plant, soil, and soil sorbed P) was assessed. As the occluded and weathered P pools are prescribed for this model application, the occluded and weather P coefficients (other two P-related model parameters) were not part of sensitivity tests."

Modifications in results section 3.1.4 on model sensitivity lines 670-690 and added Figure S5 to supporting document:

"3.1.4 Model sensitivity

The results indicate that among all the corresponding C and P pools and fluxes, the excess C flux – which demonstrates P limitation to growth – shows the highest sensitivity to changes in C:P ratios, K_P and K_{or-max}, K_{in-max}. A decrease in plant C:P results in a large increase in excess C. This is due to the higher plant P demand as a result of lower plant C:P ratios. An increase in the uptake factor and maximum sorbed organic and inorganic P also results in an increase in excess C. This is due to the higher uptake demand through higher uptake capacity (due to higher K_P) and lower available P for uptake due to higher organic and inorganic sorbed P (due to higher K_{or-max}, K_{in-max}). Since the total P in the system is lower than the plant demand, the uptake capacity and sorbed P, higher P limitation is placed on growth (decreasing BP) which results in an increase in excess C and decrease in plant C, but also soil C which is a result of lower litter input (Figure 4). Total soil P shows low sensitivity to changes in plant C:P and uptake factor but high sensitivity to maximum inorganic sorbed P. Moreover, sorbed P shows middle to high sensitivity to maximum organic and inorganic sorbed P respectively (Figure. S5). Nevertheless, organic and inorganic P adsorption coefficients ($K_{sorp-or}$, $K_{sorp-in}$) show no sensitivity to C and P pools and fluxes. This is due to limiting the organic and inorganic P sorption terms controlled only by maximum sorption, hence no effect applied by organic and inorganic adsorption coefficients.

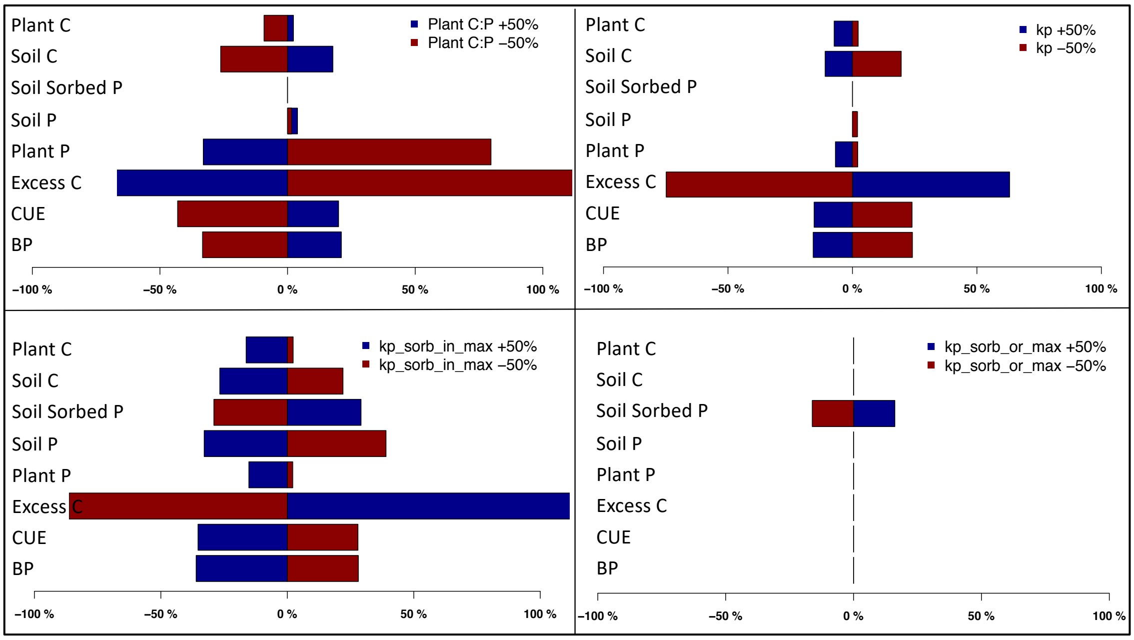

Figure. 4- Model sensitivity test results and corresponding C and P pools and fluxes under ambient CO_2.

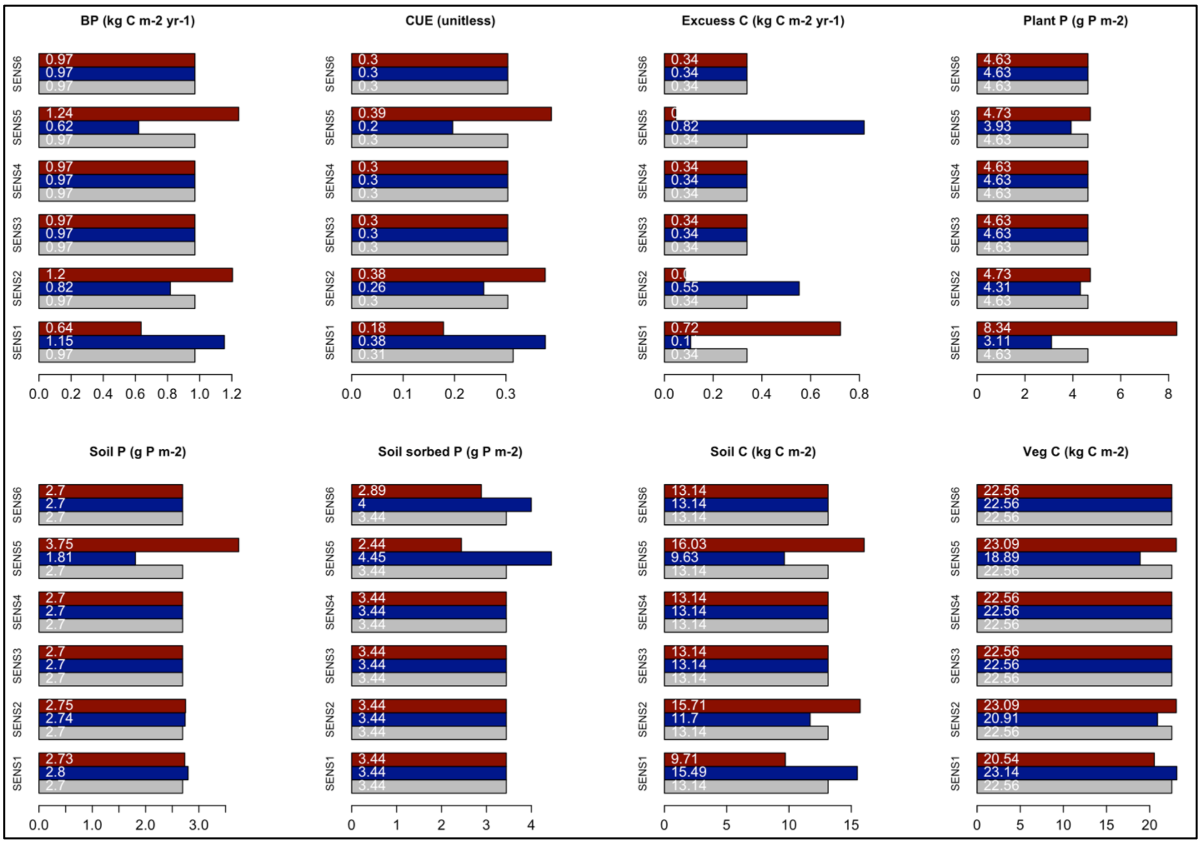

Fig. S5- Model parameters absolute sensitivity values”

Additionally, I think the paper would benefit from a more extensive discussion of the implementation of exudates and the knock on effect on CUE. The question of what to do with excess carbon under nutrient limitation is one that all models face and there have been a variety of solutions: respire it (what JULES CNP does too), down-regulate photosynthesis, decrease tissue nutrient content etc. I am not saying that the choice made here is necessarily wrong, but it does have implications for the model results. In particular, changes in carbon use efficiency are a direct result of this modeling choice and do not necessarily have an interpretable meaning.

As suggested by reviewer we revised the text and added the following part to the discussion on CUE in lines 812-826:

“As soil P availability is low in the majority of Amazonia (Quesada *et al.*, 2012), the competition for nutrients by both plant and soil communities is high (Lloyd *et al.*, 2001). The responses of these communities to eCO$_2$ under P limited conditions remains uncertain (Fleischer *et al.*, 2019). These responses in P enabled models are represented in different ways regarding the excess C which is not used for plant growth due to P limitation. Either growth is directly downregulated taking the minimum labile plant C,N and P (Goll *et al.*, 2017), or photosynthesis is downregulated via V_{cmax} and J_{max} (Comins and McMurtrie, 1993; Yang *et al.*, 2014; Zhu *et al.*, 2016) and finally models like JULES CNP downregulate NPP via respiration of excess carbon that cannot be used for growth due to plant nutrient constraints (Haverd *et al.*, 2018). The estimated CUE depends on the modelling approach. Models that down regulate the photosynthetic capacity and GPP consequently (Comins and McMurtrie, 1993; Yang *et al.*, 2014; Zhu *et al.*, 2016), simulate a positive CUE response to CO$_2$ fertilization while models that down regulate the NPP and respire the excess C (Haverd *et al.*, 2018) simulate a negative CUE response (Fleischer *et al.*, 2019) which is in line with the studies showing lower CUE when nutrient availability declines (Vicca *et al.*, 2012). However, this remains a major uncertainty in understanding the implication of P limitation on terrestrial biogeochemical cycles.”

Detailed comments:

L 241 As far as I understand from the description here, what the authors term ‘exudates’ is just excess C that is respired by the plants. However, the term normally refers to carbohydrates released by plants into the soil for a potential benefit in additional nutrients. This is a complex process and extremely difficult to include in models, so I am not suggesting the authors include it here, but maybe a different term for this flux can be used here. I am also not clear what ‘spread’ refers to here.

To avoid this confusion, we have replaced “exudates” term with “excess C” throughout the whole text, tables and figures, as also suggested by RC1.
The spread term refers to the increase in vegetation cover due to reproduction and recruitment. We further clarify it in the revised version as follows:
“NPP in JULES is calculated as the difference between GPP and autotrophic respiration. In JULES-CNP, potential NPP represent the amount of C, available for tissue growth (C density increase) on a unit area, and spreading (vegetation cover increase as a result of reproduction and recruitment), ie to increase the area covered by the vegetation type, assuming no nutrient limitation.”

L 367 Table 2 Check the notations here - doe eta_CP refer to litter or soil CP?

This refers to soil C:P. As suggested by reviewer #3, we replaced eta_CP with $C{:}P_{soil}$ in the revised version in line 358-359:
“C:P ratios of plant (i) (DPM/RPM) $(C\!:P_{plant})$ and soil (HUM/BIO) $(C\!:P_{soil})$”

L 460 by 1000 times, do you mean 1000 years?

We modified the spin-up description in the revised version in lines 553-558 as follows
“The JULES CNP simulations were initialized following the same methodology as in Fleischer et al., (2019), by the spin-up from1850 recycling climatology to reach equilibrium state (Figure S1) and spin up was performed separately for three versions of JULES (C/CN/CNP) following the same procedure. Furthermore, the transient run was performed for the period 1851-1998 using time-varying CO_2 and N deposition fields. Finally, for the extended simulation period (1999-2019) two runs were performed, the first with ambient the second elevated CO_2 concentrations”

L 564 Figure 3 Would it be possible to label the panels more clearly? I have to assume that the one on the left is fluxes and the one on the right, pools?

The left plot includes fluxes (BP and Litter C), CUE and pools (leaf and root C (0.2 – 0.4 kg C m^{-2})) (wood, veg and soil C (13-24 kg C m^{-2})). Due to the scale size of C pools (leaf and root will not be visible if they are next to other C pools). However, in order to make it clearer, we modified it and separated the units on two Y axis as follows:
“

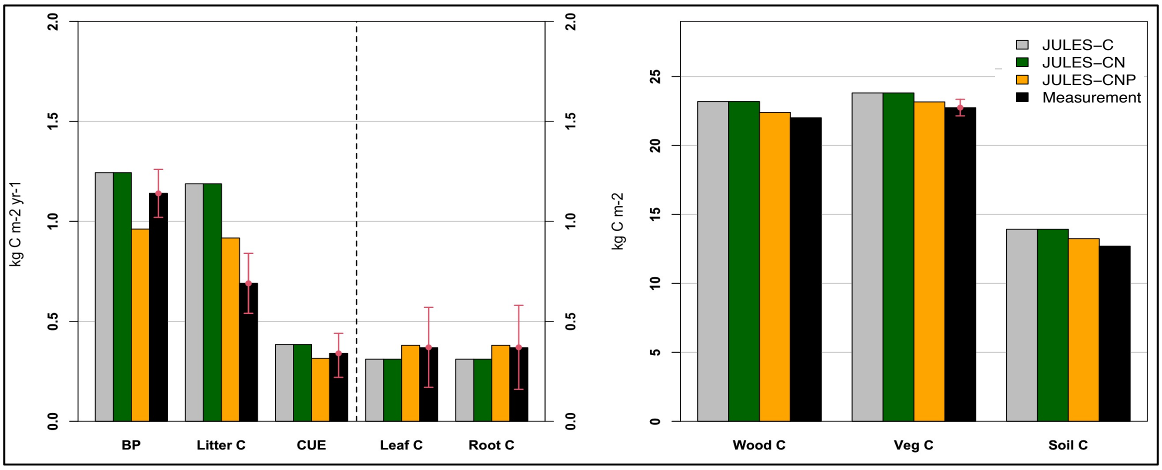

Figure. 3- JULES C, CN, CNP modelled vs measured C pools (Leaf, root, wood, Veg and Soil C) (in kg C m^{-2}) and fluxes (BP and Litter C) (in kg C m^{-2} yr^{-1}) and CUE under ambient CO_2. Note that CUE is unitless.

L 581 Figure 4 Could you discuss why a change in biomass production does not result in a change in plant C?

As mentioned above, this figure and discussion is now replaced.

Reference:

Comins, H. N. and McMurtrie, R. E. (1993) 'Long-Term Response of Nutrient-Limited Forests to CO"2 Enrichment; Equilibrium Behavior of Plant-Soil Models', *Ecological Applications*, 3(4), pp. 666–681. doi: 10.2307/1942099.
Fleischer, K. *et al.* (2019) 'Amazon forest response to CO2 fertilization dependent on plant phosphorus acquisition', *Nature Geoscience*. doi: 10.1038/s41561-019-0404-9.
Fyllas, N. M. *et al.* (2009) 'Basin-wide variations in foliar properties of Amazonian forest: phylogeny, soils and climate', *Biogeosciences*, 6(11), pp. 2677–2708. doi: 10.5194/bg-6-2677-2009.
Goll, D. S. *et al.* (2017) 'A representation of the phosphorus cycle for ORCHIDEE (revision 4520)', *Geoscientific Model Development*, 10(10), pp. 3745–3770. doi: 10.5194/gmd-10-3745-2017.
Haverd, V. *et al.* (2018) 'A new version of the CABLE land surface model (Subversion revision r4601) incorporating land use and land cover change, woody vegetation demography, and a novel optimisation-based approach to plant coordination of photosynthesis', *Geoscientific Model Development*, 11(7), pp. 2995–3026. doi: 10.5194/gmd-11-2995-2018.
Lloyd, J. *et al.* (2001) 'Should Phosphorus Availability Be Constraining Moist Tropical Forest Responses to Increasing CO2 Concentrations?', in *Global Biogeochemical Cycles in the Climate System*. Elsevier, pp. 95–114. doi: 10.1016/B978-012631260-7/50010-8.
Quesada, C. A. *et al.* (2011) 'Soils of Amazonia with particular reference to the RAINFOR sites', *Biogeosciences*, 8(6), pp. 1415–1440. doi: 10.5194/bg-8-1415-2011.
Quesada, C. A. *et al.* (2012) 'Basin-wide variations in Amazon forest structure and function are mediated by both soils and climate', *Biogeosciences*, 9(6), pp. 2203–2246. doi: 10.5194/bg-9-2203-2012.
Sun, Y. *et al.* (2021) 'Global evaluation of the nutrient-enabled version of the land surface model ORCHIDEE-CNP v1.2 (r5986)', *Geoscientific Model Development*, 14(4), pp. 1987–2010. doi: 10.5194/gmd-14-1987-2021.
Vicca, S. *et al.* (2012) 'Fertile forests produce biomass more efficiently', *Ecology Letters*, 15(6), pp. 520–526. doi: 10.1111/j.1461-0248.2012.01775.x.
Yang, X. *et al.* (2014) 'The role of phosphorus dynamics in tropical forests – a modeling study using CLM-CNP', *Biogeosciences*, 11(6), pp. 1667–1681. doi: 10.5194/bg-11-1667-2014.
Zhu, Q. *et al.* (2016) 'Multiple soil nutrient competition between plants, microbes, and mineral surfaces: model development, parameterization, and example applications in several tropical forests', *Biogeosciences*, 13(1), pp. 341–363. doi: 10.5194/bg-13-341-2016.