RC1:

This is a straightforward paper evaluating the inclusion of P cycle processes in JULES. The work is obviously important for the importance of P in estimating the global C sink and the important role of JULES in the modelling community. I have several comments to hopefully help further strengthen the manuscript.

We thank Dr Mingkai Jiang for his positive comments. We have addressed the comments as described below.

Given that the site is a nutrient fertilization experiment, it seems to be a missed opportunity to not evaluate the model performance in response to nutrient fertilization. The evaluation of the CO2 response is obviously still important, but I don't see enough rationale to do it given that there is limited data available to actually evaluate the simulated CO2 responses. Can we learn more by simulating the nutrient fertilization response where there is actual data?

We agree with the reviewer that additional evaluation of JULES-CNP against treatment (fertilization) data from the Amazon nutrient fertilization experiment (AFEX) is of high value. AFEX is an ongoing project and only changes in fine root dynamics have been published so far, so we don't have all the datasets needed for model evaluation. Therefore, it is not possible evaluate the model against the nutrient addition response yet but this is planned in a future model application study.

Given the fact that rightly two reviewers have asked about this, to avoid confusion, we have decided to simply refer to our 'study site' in Amazonia where we have access to key soil and plant data, rather than explicitly elaborate that this is the control site from AFEX.

We have modified lines 119-125 at the end of the introduction accordingly:
"Here, we describe the development and implementation of the terrestrial P cycle in the Joint UK Land Environment Simulator (JULES) (Clark *et al.*, 2011), the land component of the UK Earth System Model (UKESM), following the structure of the prior N cycle development (Wiltshire *et al.*, 2021). The model (JULES-CNP) is parameterized and calibrated using novel in situ P soil and plant data from a well-studied forest site in Central Amazon near to Manaus, Brazil with soil P content representative of 60% of soils across the Amazon basin. We then evaluate the model against carbon stocks and fluxes from data sets from our study site and the nearby K34 field site"

We also modified the following lines in the methods section 2.3; study sites in lines 460-471
"This study uses data from two nearby sites in Central Amazon in Manaus, Brazil. The main site from here on termed *study site* (2°35′′21.08′′ S, 60°06′′53.63′′ W) (Lugli *et al.*, 2020) is for model development and evaluation. The second site is the Manaus K34 flux site (2°36′′32.67′′ S, 60°12′′33.48′′ W) which provides meteorological station data for running the model but also provides data for model evaluation.

We use detailed novel soil and plant P pool data from the *study site* (Lugli *et al.*, 2020, 2021) for model parameterisation and calibration and carbon stock data for model validation. The *study site* has a very similar forest, geomorphology, soil chemistry and species composition to the well-known and studied K34 eddy covariance flux site (Araújo *et al.*, 2002)."

Some details of the model description is not available. For example, how P interacts with N to affect allocation, plant growth, stoichiometry and nutrient uptake?

Many thanks for spotting this. This was omitted due to the lack of N limitation at our study site. Details of the N and P interaction in JULES CNP in the revised are described in the methods section in lines 284-318 as follows:

"Similar to other P-enabled models (Yang *et al.*, 2014; Goll *et al.*, 2017), JULES-CNP follows the same structure as its N model component. Description of the plant P and N demand follow Wang *et al.*, (2007) and are represented by the sum of demand ($\emptyset_t$) to sustain growth (P-related: ($\emptyset_{g_P}$), N-related: ($\emptyset_{g_N}$)) and vegetation spreading (to increment PFT fractional coverage) (P-related: ($\emptyset_{S_P}$), N-related: ($\emptyset_{S_N}$)) and is expressed in (P-related in kg P m^{-2} yr^{-1}; N-related in kg N m^{-2} yr^{-1}). The total demand for growth ($\emptyset_g$) and spreading ($\emptyset_s$) is controlled by the dominant demand between P ($\emptyset_{g_P}$) and N ($\emptyset_{g_N}$) as follows:

$$\emptyset_t = \emptyset_g + \emptyset_s \tag{eq.19}$$

$$\emptyset_{gP} = \frac{P_p}{C_V}\left(\Pi_c - \frac{dC_v}{dt} - \psi_g\right) \tag{eq.20}$$

$$\emptyset_{SP} = \frac{P_p}{C_V}\left(\Pi_c - \frac{dC_v}{dt} - \psi_s\right) \tag{eq.21}$$

$$\emptyset_{gN} = \frac{N_v}{C_V}\left(\Pi_c - \frac{dC_v}{dt} - \psi_g\right) \tag{eq.22}$$

$$\emptyset_{SN} = \frac{N_v}{C_V}\left(\Pi_c - \frac{dC_v}{dt} - \psi_s\right) \tag{eq.23}$$

$$\emptyset_g = \begin{cases} \emptyset_{gP} & \emptyset_{gP} \times \frac{C_V}{P_p} > \emptyset_{gN} \times \frac{C_V}{N_v} \\ \emptyset_{gN} & \emptyset_{gN} \times \frac{C_V}{N_v} > \emptyset_{gP} \times \frac{C_V}{P_p} \end{cases} \tag{eq.24}$$

$$\emptyset_s = \begin{cases} \emptyset_{SP} & \emptyset_{SP} \times \frac{C_V}{P_p} > \emptyset_{SN} \times \frac{C_V}{N_v} \\ \emptyset_{SN} & \emptyset_{SN} \times \frac{C_V}{N_v} > \emptyset_{SP} \times \frac{C_V}{P_p} \end{cases} \tag{eq.25}$$

where $\frac{P_p}{C_V}$ is the inverse of whole plant C:P ratio, $\frac{N_v}{C_V}$ is inverse plant C:N ratio, $\frac{dC_v}{dt}$ is rate of change in plant C (see Clark *et al.*, (2011) for more detail), Π_c is nutrient-unlimited, or potential, NPP (kg C m^{-2} yr^{-1}), ψ_g is excess C due to either P or N limitation for plant growth (kg C m^{-2} yr^{-1}) and ψ_s is excess C due to either P or N limitation for vegetation spreading (kg C m^{-2} yr^{-1}).

Equations 20 and 22 are solved by first setting $\psi_g = 0.0$ to find the total plant P (eq. 20) and N demand (eq.22). If the P and N demand for growth are less than the available P and N and fractional coverage (λ) (NPP fraction used for fractional cover increment; for detail see Wiltshire *et al.,* (2021)) at the considered timestep Δt, then there is no limitation to growth ($i.e. \emptyset_{gP} < \frac{(1-\lambda)P_{avail}}{\Delta t}$; $\emptyset_{gN} < \frac{(1-\lambda)N_{avail}}{\Delta t}$). Where there is limited P and/or N availability, the uptake equals the available P and N ($\emptyset_{gP} = \frac{(1-\lambda)P_{avail}}{\Delta t}$; $\emptyset_{gN} = \frac{(1-\lambda)N_{avail}}{\Delta t}$), and the plant growth which cannot be achieved due to nutrient constraints will be deducted from potential NPP, here termed excess C term (ψ_g), to give an actual NPP. Following Wiltshire et al., 2021, we assume excess C is respired by the plant.

Similarly, in order to estimate the P and N demand for spreading (eq. 21 and 23), initially the excess C from spreading is set to 0.0 ($\psi_s = 0.0$), i.e under the assumption that there is no nutrient limitation. If the P and N demand for spreading are lower than the available P and N and fractional coverage (λ) ($\emptyset_{SP} < \frac{(1-\lambda)P_{avail}}{\Delta t}$; $\emptyset_{SN} < \frac{(1-\lambda)N_{avail}}{\Delta t}$), then there is no limitation on spreading and in case of limited P and N availability, the uptake equals the available P and N ($\emptyset_{SP} = \frac{(1-\lambda)P_{avail}}{\Delta t}$; $\emptyset_{SN} = \frac{(1-\lambda)N_{avail}}{\Delta t}$), and the excess C for spread (ψ_s) is subtracted from potential NPP."

And lines366-388:

"The soil respiration from each soil layer ($R_{i,n}$) is estimated from potential soil respiration ($R_{POT_{i,n}}$) for the DPM, RPM pools and the litter decomposition rate modifier (F_{P_n}) as follows:

$$R_{i,n} = R_{POT_{i,n}} \times F_{P_n} \tag{eq.33}$$

where the description of F_{P_n} for P pools ($F_{P_{P_n}}$) follows Wang *et al.*,(2007) and is estimated based on the soil pool (BIO/HUM) mineralization ($minl_{P-BIO_n}$, $minl_{P-HUM_n}$) and immobilization ($immob_{P-BIO_n}$, $immob_{P-HUM_n}$) (in kg P m^{-2} yr^{-1}), soil inorganic P (P_{inorg_n}) (in kg P m^{-2}), and litter pools (DPM/RPM) demand (in kg P m^{-2} yr^{-1}) as follows:

$$F_{P_{P_n}} = \frac{(minl_{P-BIO_n} + minl_{P-HUM_n} - immob_{P-BIO_n} - immob_{P-HUM_n}) + P_{inorg_n}}{DEM_{DPM_n} + DEM_{RPM_n}} \tag{eq.34}$$

The net demand associated with decomposition of litter pools ($DEM_{k,n}$) represents the P required by microbes which convert DPM and RPM into BIO and HUM. The limitation due to insufficient P availability is estimated based on the potential mineralization ($minl_{p-pot}$) and immobilization ($immob_{p-pot}$) (in kg P m^{-2} yr^{-1}) of pools (k) as follows:

$$DEM_{k,n} = immob_{p-pot,k} - minl_{p-pot,k} \tag{eq.35}$$

The F_{P_n} estimated for N pools ($F_{P_{N_n}}$) follows the same formulation as P (see Wiltshire *et al.*, 2021 for detail) and the F_{P_n} is estimated based on a higher rate modifier between N and P as follows:

$$F_{P_n} = \begin{cases} F_{P_{P_n}} & F_{P_{P_n}} > F_{P_{N_n}} \\ F_{P_{N_n}} & F_{P_{N_n}} > F_{P_{P_n}} \end{cases} \tag{eq.36}"$$

Can the authors spend some efforts highlighting the novelty of this work? I understand that adding P cycle into JULES is a significant work, but some readers could take it as "yet another model with P cycle". Considering the spread of the simulated CO2 responses among CNP models in Fleischer et al. 2019, having yet another model doesn't necessarily reduce the model spread and our knowledge gap. Is there anything specific about having a P cycle in JULES would help to resolve? In other words, what unique features JULES-CNP can provide relative to other models?

In the most recent CMIP6, only one model includes P (ACCESSESM1.5 model) (Arora et al., 2020) and only few studies focused on P cycling in soil and between plant and soils for tropical forests particularly (Yang et al., 2014; Zhu et al., 2016; Goll et al., 2017). There are no dedicated model-data nutrient cycling studies specifically for the Amazon forest with poor soils and limited P availability that is hypothesized to be among the key limiting nutrients to plant growth (Vitousek et al., 1997, 2010; Hou et al., 2020). As acknowledged by RC2 the inclusion of the P-related processes in models is critical to our ability to predict ecosystem responses to eCO2 and climate change in low-P systems such as the tropics and some land surface models are now adding these processes. We created a model suitable for global application, and it is appropriate to first test it at a site-level where data are available. We included detailed P processes such as: litter production and decomposition, mineralisation, immobilisation, ad/desorption, occlusion, weathering and plant uptake and we use the actual site measurements from soil pools from our study site to constrain the model in contrast with other P model development which use soil-specific data (Goll et al., 2017) or simplified approach (fluxes estimation based on equilibrium state of other fluxes (Wang et al., 2018)). At this 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. This information is added in lines 119-125 as follows:

"Here, we describe the development and implementation of the terrestrial P cycle in the Joint UK Land Environment Simulator (JULES) (Clark *et al.*, 2011), the land component of the UK Earth System Model (UKESM), following the structure of the prior N cycle development (Wiltshire *et al.*, 2021). The model (JULES-CNP) is parameterized and calibrated using novel in situ P soil and plant data from a well-studied forest site in Central Amazon near to Manaus, Brazil with soil P content representative of 60% of soils across the Amazon basin. We then evaluate the model against carbon stocks and fluxes from data sets from our study site and the nearby K34 field site."

Also

JULES_CNP model structure was designed to match soil P pools for which data is available for the whole Amazon region, with a global data set also available for global applications. 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))."

Specific comments:

L31: Unclear – what does this 60% mean? Is it the 60th percentile of P availability (doesn't sound like a particularly P limited site)? Or does it mean the total P/available P at the site represents 60% of soil across the Amazon? Be good to make it clearer.

Indeed, our study soil P content is representative of 60% of soils across the Amazon basin. This is clarified in the revised version as follows:

"…a low fertility site, with a soil P content representative of 60% of soils across the Amazon basin."

L32: What is the eCO2 treatment? Show a number is useful.

This value is +200 ppm, over ambient [~400 ppm] We have added the value, see below:

"We then apply the model under elevated CO_2 (600 ppm) at our study site to quantify the impact of P limitation on CO_2 fertilization."

L32: The model is able to reproduce observed plant and soil P pools under ambient conditions – to what extent are these values provided as parameters and/or targeting values to tune the model?

Please note that, the plant P pools are calculated based on observations of C:P ratios, and soil P pools have been either prescribed (occluded and weathered) or calibrated via a single parameter (maximum sorption capacity) (sorbed organic and inorganic P) or evaluated (organic and inorganic P). Moreover, the model is able to reproduce observed fluxes and stock of C. We have now corrected Table 3 and clarified this in lines 32-34 as follows:

"Novel soil and plant P pool observations are used for parameterisation and calibration and the model is evaluated against C fluxes and stocks, and for those soil P pools not used for parameterisation/calibration."

And lines 515-517:

"JULES-CNP has fixed stoichiometry and C:P ratios of leaf and root (measured), and wood (estimated from fresh coarse wood (Lugli, 2013)) which were taken from the *study site* and prescribed in JULES to simulate P dynamics in the plant"

And lines 530-532:

"Thus, in order to cap P sorption and uptake capacity, the maximum sorption capacities (P_{in-max_n}, P_{or-max_n}, eq.37 and 39) (adopted from (Wang, Houlton and Field, 2007)) were prescribed using maximum observed sorbed inorganic and organic P."

And lines 533-535:

"Moreover, as the magnitude of changes in the occluded and parent material pools are insignificant over a short-term (20 years) simulation period (Vitousek *et al.*, 1997), these two pools were prescribed using observations."

Abstract: Given that you evaluated the model at a nutrient fertilization site, does it make sense to apply the nutrient treatment to the model and try to evaluate the model against observation? It's quite unclear what to learn from evaluating the model against a CO2 treatment where you don't have any data. The rationale about the CO2 effect isn't very clear in the abstract.

Having 1) developed and parameterised our P model with plant and soil observations from a site in the Amazon (Manaus) and 2) evaluated for C fluxes under ambient CO_2, the rationale behind the simulations under eCO_2 was to quantify the impact of P limitation on CO_2 fertilization in the Amazon in JULES-CNP and compare against the ensemble of models some of which include P cycle in Fleischer et al., 2019 which was performed as part of the AmazonFACE intercomparison, a nearby site to our study site.

In response to the four above specific comments, we have modified the abstract to read as follows in lines 30-36:
"We evaluate JULES-CNP using in situ data collected at a low fertility site in the Central Amazon, with a soil P content representative of 60% of soils across the Amazon basin, to parameterise, calibrate and evaluate JULES-CNP. Novel soil and plant P pool observations are used for parameterisation and calibration and the model is evaluated against soil P pools and C fluxes and stocks. We then apply the model under elevated CO_2 (600 ppm) at our study site to quantify the impact of P limitation on CO_2 fertilization. We compare our results against current state of the art CNP models using the same methodology that was used in the AmazonFACE model intercomparison study."

L42: net primary production.

Corrected.

L43: C, not carbon.

Corrected.

L47: It's not either or. There are other nutrients involved.

Corrected.

L99: Hou et al. 2019 – are you sure this is a DGVM?

The references are corrected in the revised version.

Figure 1. Do you have P leaching flux and biochemical P mineralization flux? What about atmospheric P deposition?

Due to the low P availability at this site, all the available P is considered to be returned to plants, thus leaching is to be minor within the timescales simulated (Went and Stark, 1968; Bruijnzeel, 1991; Neff, Hobbie and Vitousek, 2000). However, the current version of JULES CNP only includes the total mineralization. Nevertheless, even the models which include this process show no significant difference between biochemical P mineralization to total P mineralization (Goll et. al., 2017). Also, JULES-CNP does not include atmospheric P deposition which is envisaged in future model developments and applications. This information is now added to discussion in the revised version in discussion section 4.1 – lines 888-895:
""Moreover under low P availability, all available P is considered to be adsorbed or taken by plant and microbes for further consumption, with leaching considered to be minor within the time scales of our study period (Went and Stark, 1968; Bruijnzeel, 1991; Neff, Hobbie and Vitousek, 2000).
Due to the strong fixation of P in the soil (Aerts & Chapin, 2000; Goodale, Lajtha,Nadelhoffer, Boyer, & Jaworski, 2002), the P deposited is unlikely to be available to plants in the short term (de Vries et al., 2014), for this reason this version of JULES CNP did not include P deposition. However both P deposition and leaching are likely to have a very important role on sustaining the productivity of tropical forests in the Amazon over longer time scales (Van Langenhove et al., 2020) and needs to be considered in future studies."

From the equation it seems that you would have a continuous build-up of P in the system, because there is no way out from the occluded P pool.

In our simulations we deactivated the occluded flux and the reported occluded pool is prescribed in the model using the observed value. Thus, we have a closed P system balanced between vegetation and active soil pools. This is further clarified in the revised version as follows:
"Moreover, as the magnitude of changes in the occluded and parent material pools are insignificant over a short-term (20 years) simulation period (Vitousek et al., 1997), these two pools were prescribed using observations for these two pools."

L239: This exudate term is confusing. Can I consider it as part of autotrophic respiration? It's a missed opportunity where this exudate term isn't pumped into soil to facilitate plant-soil interaction, which could potentially be used to alleviate plant nutrient stress. See for example (Jiang et al., 2020).

The reviewer is right. Since in the model this excess does not have an explicit functional role in facilitating plant-soil interaction we now refer to it as "excess C" throughout the whole text, figures and tables. Following JULES-CN (Wiltshire et al., 2021) we simply assume it is part of the autotrophic respiration.

L284: What timestep does retranslocation occur?

The retranslocation occurs at a daily timestep. This is now added to the revised version in the 2.2.2 section in line 342-344 as follows:
"where λ is the leaf, root and stem re-translocation (at daily timestep) coefficient (Zaehle and Friend, 2010; Clark et al., 2011) and the related $C:P$ ratios for P fraction and γ is a temperature dependent turnover rate representing the phenological state (Clark et al., 2011)."

Table 2: Would be good to show P retranslocation coefficient.

We added these coefficients to the table2 in the revised version.

Method: Description on N-P interaction is missing. I suppose P is not entirely independent from N processes? I think it should be useful to describe how P affects N, and vice versa in the model.

We added detailed explanation on the N-P interaction as stated in the general comment part above and it can be found in the methods section (2.2.2) in lines 284-388

L404: What about N only model?

This is now clarified in the methods in lines 481-482 as follows:
"JULES vn5.5 (JULES CN in this study) estimates Vcmax (μmol m^{-2} s^{-2}) based on Kattge et al. (2009) using foliar N concentrations in area basis"

What about Jmax?

In JULES vn5.5 that JULES CNP was developed on, we use Collatz C3 and C4 photosynthesis model (Collatz et al., 1991; Collatz, Ribas-Carbo and Berry, 1992) which does not include the estimation of Jmax. This information is now clarified in the methods in lines 513-514 as follows:
"Note that JULES CNP uses C3 and C4 photosynthesis model from Collatz et al., 1991; Collatz, Ribas-Carbo and Berry, 1992, which does not include estimation of J_{max}."

L428: I may have missed this, but does the model assume fixed or variable CP ratios?

We have clarified this in lines 515-517 in methods section 2.4:
"JULES-CNP has fixed stoichiometry and C:P ratios of leaf and root (measured), and wood (estimated from fresh coarse wood (Lugli, 2013)) which were taken from the *study site* and prescribed in JULES to simulate P dynamics in the plant."

L450: What does the symbol -//- mean?

We have removed this symbol and complete the table for clarity as follows:

Table 3. Observations from study site (taken during 2017-2018) and from Manaus site K34 used for model parameterisation and evaluation

Process	Variables	Purpose of use	Reference and site
C associated	GPP	Evaluation	Fleischer et al., 2019, K34
	NPP	Evaluation	Fleischer et al., 2019, K34
	Soil C	Evaluation	Malhi et al., 2009, K34
	CUE	Evaluation	Malhi et al., 2009, K34
	Veg C	Evaluation	Study site
	Leaf C	Evaluation	Study site
	Stem C	Evaluation	Study site
	Root C	Evaluation	Study site
	LAI	Initialisation	Study site
	LMA	Parameterisation	Study site
P associated	Resin	Evaluation	Study site
	Pi Bic	Evaluation	Study site
	Po Bic	Evaluation	Study site
	Po NaOH	Calibration	Study site
	Pi NaOH	Calibration	Study site
	P residual	Parameterisation	Study site
	P HCL	Parameterisation	Study site
	Leaf N	Parameterisation	Study site
	Leaf P	Parameterisation	Study site
	Root P	Parameterisation	Study site
	Plant C:P ratio	Parameterisation	Study site

L469: What does a step increase mean?

Step increase refers to a sudden change (increase) in atmospheric CO_2 ie. going from ambient to elevated to CO_2 conditions in one model timestep. This is now clarified in the revised version as follows:
"with present-day CO_2 based on global monitoring stations, and an abrupt (step) increase in atmospheric CO_2 of +200 ppm on the onset of the transient period (i.e., 1999)."

L664: What is SMCL?

Soil moisture. It is corrected in the revised version:
"The estimated WUE and soil moisture content (SMCL) for the lowest GPP period"

L767: Jiang et al., not Jing :)

I am really sorry for the typo on your name. It has now been corrected.

Reference:

Araújo, A. C. *et al.* (2002) 'Comparative measurements of carbon dioxide fluxes from two nearby towers in a central Amazonian rainforest: The Manaus LBA site', *Journal of Geophysical Research*, 107(D20), p. 8090.

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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.

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