R: reviewer's comment

A: authors' response

C: changes made in the manuscript (the tracked-change version)

Responses to Reviewer Comment 1

R: Yu et al reported the development and evaluation of the microbially-explicit SOM BGC model Jena Soil Model at a temperate beech forest stand. The model was found able to reasonably reproduce the measured profile of SOM stocks and radiocarbon. It also explained why microbial residue plays an important role in SOM cycling. Further, the nutrient dynamics resulting from plant-microbial interactions simulated by the model appeared reasonable, although important nitrification-denitrification dynamics are missing. Overall, I found the paper interesting and generally well written. I think the paper will become a good read provided the authors address the following comments.

A: we thank the reviewer for the positive comment and recognition of our work

R: In section 2.3, subsection model protocol and calibration. I followed the authors without any problem on the model initialization, however, it is unclear how the 200 years are aligned with the time. Did the model pretend to start from 1850? Also the 14C of litter input in last 60 years was mentioned to match the observed 14CO2 atmospheric pulse, how was this done exactly? Further, I think the inorganic P pool from Yang et al. (2013) is closer to contemporary (say year 2000) than 1850. Was this criterion appropriate? I have no answer to this last question myself, and we also struggled when doing the P cycle in our TBM. Nonetheless, I would like to know more about the authors' opinion on this.

A: we ran the model for 200 years and compared the simulated results with the present-day measurement; therefore the initialization should represent the condition of ca.1820, and the bomb pulse we mimicked occurred around 1960, which is ca. 60 years before the end of simulation. The pulse was fitted to the observed atmospheric peak, by simply modifying the 14C content of litter fall.

C: Page7, Line16-18: "To mimic the history of ^{14}C input, we increased litter ^{14}C content for the final 60 years before the end of the simulation, assuming that the Δ^{14}C in gross primary productivity in response to the observed CO_2 atmospheric pulse propagates directly into litterfall without any delay."

A: The inorganic P pool we used to initialize the model was the data set that Yang et al. published in 2014 (Yang X, Post WM, Thornton PE & Jain AK 2014: Global Gridded Soil Phosphorus Distribution Maps at 0.5-degree Resolution. ORNL Distributed Active Archive Center.), but we made a mistake in the reference and will revise it in the resubmission. The data set we used has no explicit *temporal component, but data were nominally for the pre-industrial period ca. 1850 as recommended by the authors. So we don’t think it is a problem to use it to represent the condition of 1820. As we stated in the discussion that the uncertainties in inorganic P cycling and initialization are very high. We have made some progress in reducing these uncertainties, and will hopefully publish the results in a separate study soon.*

C: Page7, Line9-10: “The soil inorganic P pools were initialised using the soil P dataset from Yang et al. (2014a), …”

R: Another question is how the SOM 14C profile is initialized? It is not very clear from current description.

A: We initialize the whole SOC profile with a pre-industrial 14C value for all the carbon pools and then let the 14C values develop from there following COMISSION model (Ahrens et al. 2015). We will include the 14C initialization in the resubmission.

C: Page7, Line8-9: “All SOC profiles were initialised with a pre-industrial $\Delta^{14}C$ values for all C pools, from which the ^{14}C values were developed.”

R: In the model formulation, I saw nitrate was part of the N dynamics. However, I did not see any description of other N related biogeochemistry. My impression is that the model does not have a nitrification-denitrification process. Is this why no abiotic ammonium adsorption is considered in the model?

A: Yes, the N dynamics in the current version is much simplified but will be implemented into the model in a later stage. In this paper, we mainly focus on the different roles of inorganic and organic nutrients in regulating the microbial/SOM dynamics and processes; therefore we think the simplified N processes won’t alter the main conclusions of this study. However, we do realize this is an important point to mention and will clarify it in the summary section.

C: Page18, Line15-20: “Concerning the model's description of N dynamics, in the current version, N processes such as nitrification/denitrification and abiotic ammonium adsorption are not yet implemented. Although the simplified N dynamics will probably not alter the main findings of this study, it is important to investigate these in the future since plants often have a preference for ammonium uptake (Masclaux-Daubresse et al., 2010). Finally, given the good quality of the input data, JSM could adequately reproduce the soil stocks and flux rates at the selected study site; however, its capacity to extrapolate to other climate and soil conditions needs to be further investigated in the future.”

R: Further, the model predicted a number of interesting features, such as the importance of microbial residue, and that root input will result in different depolymerization dynamics. Given one purpose of modeling is to inform new empirical experiments, I think the authors can make the paper more interesting by explicitly asking what new experiments will help constrain their model.

A: Thanks for recognition of our work. We will include some implications for experiments in the resubmission. A few examples are: how the microbial carbon use efficiency will change when the nutrient availability changes? how the microbial enzyme production will respond to changes of litter input?

C: Page19, Line11-15: "To better represent microbial dynamics, we would need detailed and advanced understanding of microbial processes from experiments for implementation and testing in the model. For example, how will microbial C use efficiency change in response to changes in C sources (e.g. DOM or litter addition) and nutrient availability (e.g. N & P addition)? How starkly does the microbial community adjust its stoichiometry, change its element use efficiency or alter extracellular enzyme synthesis under dynamic external conditions?"

R: Finally, I think the English of the paper should be further improved. I collected some of these problems below, but I recommend the authors do a more thorough check.

A: Thanks for helping with the language. We will do a grammar check before resubmission.

C: The language was edited by a professional editor before resubmission. Please find it in the tracked-change version.

Other comments:

R: P1 Line 3, remove the redundant "potential" from "predict potential future climate feedbacks".

A: this part was deleted in the resubmission.

C: Page1, Line1-3.

R: P1 Line 14, remove "of" from "ample of".

A: Corrected

C: Page1, Line20: "There is ample evidence from both ecosystem monitoring data …"

R: P1 Line 17, replace "major nutrients" with "macronutrients".

A: Corrected

C: Page1 Line24-Page2 Line1: "… on terrestrial ecosystems are driven by the constraints imposed by macronutrients such as nitrogen (N) and phosphorus (P)"

R: P1 Line 24, replace "reproduce the response" with "reproduce the ecosystem response".

A: Corrected

C: Page2 Line8-9: "…, these nutrient-enabled TBMs largely fail to reproduce the responses of ecosystems to elevated atmospheric CO_2 concentration, …"

R: P2 Line 1, replace "their representation" with "their poor representation".

A: Corrected

C: Page2 Line11-12: "An important shortcoming of the current generation of models is their poor representation of plant–soil interactions, …"

R: P2 Line 2, please be specific about what "plant uptake".

A: Revised

C: Page2 Line13-14: "… to altered plant inputs and ultimately plant uptake of mineral nutrients (Hinsinger et al., 2011; Drake et al., 2011; Zaehle et al., 2014)."

R: P2, Line 5, remove "the" from "In these models, the nutrient".

A: Corrected

C: Page2 Line16-17: "In these models, nutrient mineralisation and immobilisation fluxes …."

R: P2, Line 7, expand "the CENTURY approach" into "the sufficiency of the CENUTRY approach".

A: Revised to "the adequacy of"

C: Page2 Line18-19: "Recent insights in soil science have questioned the adequacy of the CENTURY approach …"

R: P2, Line 8, remove "the representation of".

A: Corrected

C: Page2 Line21: "such as the substrate limitation of soil microbial growth …"

R: P2, Line 10, "one other important limitation" is awkward, please consider revision. And replace "most of the current SOM" with "most current SOM".

A: Revised

C: Page2 Line24-25: "Another limitation of many current SOM models in TBMs is that they represent soil as a 'bucket', …"

R: P2, Line 20, the sentence reads a little bit awkward, please consider revision.

A: Revised

C: Page3 Line3-6: “The main challenge in coupling C and nutrient cycles in microbially explicit models is to account for the large stoichiometric imbalances between the microbial decomposers (i.e. soil microorganisms) and their resources (i.e. plant litter and SOM) (Xu et al., 2013; Mooshammer et al., 2014).”

R: P2, Line 30, remove “this” from “this competition”. Also, the sentence seems incomplete, even though it is syntactically correct.

A: Revised

C: Page3 Line29-30: “Regarding P, in particular, the soil mineral surface adsorbs inorganic P to compete with plants and microbes (Bünemann et al., 2016; Spohn et al., 2018).”

R: P2, Line 33, remove “for representing them”.

A: The sentence is rewritten

C: Page3 Line19-24: “As the above-mentioned processes/phenomena are receiving more attentions, an increasing number of emerging microbially explicit models have started to tackle these challenges by accounting for the N cycle, enzymatic biosynthesis and rhizosphere priming (Abramoff et al., 2017; Sulman et al., 2017; Huang et al., 2018; Sulman et al., 2019) using certain novel approaches”

R: P3, Line 2. “kinetic” should be “kinetics”.

A: The sentence is rewritten

C: Page3 Line30-33: “The equilibrium chemistry approximation (ECA) approach has been proposed to simulate the competition of substrate uptake kinetics in complex networks where the uptake kinetics of one substrate affects the others (Tang and Riley, 2013).”

R: P3, line 6, replace “cycle process” with “cycling process”.

A: The sentence is rewritten

C: Page4 Line1-2: “…, we present the structure and basic features of a novel microbially explicit and vertically resolved SOM model that integrates with the N and P cycles—the Jena Soil Model (JSM).”

R: P3, line 13, remove “and was”

A: Corrected

C: Page4 Line13-14: “JSM is a soil biogeochemical model built on the backbone of the vertically explicit C-only SOC model COMISSION (Ahrens et al., 2015)”

R: P3, line 17, replace “a maximum” with “the maximum”.

A: Corrected

C: Page4 Line14-15: “The COMISSION model was further developed from the conventional one by introducing a scalable maximum sorption capacity”

R: P3, line 18, add “while” before “the mathematical”.

A: Corrected

C: Page4 Line19-20: “A schematic overview of JSM is presented in Fig. 1, and the mathematical description of the processes is provided in Appendix A.”

R: P3, line 19, replace “of the QUINCY” with “QUINCY”.

A: Corrected

C: Page4 Line20-21: “The model is integrated into the QUINCY (Thum et al., 2019) TBM modelling framework …”

R: P3, Line 20, replace “can be” with “can either be”.

A: Corrected

C: Page4 Line22: “… and can either be applied as a stand-alone soil model or …”

R: P4, line, 24, “a loam topsoil” should be “a loamy topsoil”.

A: Corrected

C: Page6 Line11: “…, with loamy topsoil and sandy loamy subsoil, …”

R: P4, line 27, is the unit “g/kg” meaning “g C/kg soil”?

A: Yes. Corrected in all appearances

C: Page6 Line20 and so on: “The soil C content decreases from 510 g C/kg soil in the forest floor to 126 g C/kg soil …”

R: P5, line 3, replace “the observations” with “observations”.

A: Corrected

C: Page6 Line31: “… were obtained from observations at the VES site”

R: P5, line 19, replace “we assumed increased” with “we increased”.

A: Corrected

C: Page7 Line17: “…, we increased litter ^{14}C content for the final 60 years …”

R: P6, line 5, replace “the model experiments” with “model experiments”.

A: Corrected

C: Page8 Line5: “All model experiments used the same parameterization …”

R: P6, line 18, Table S4 should be “S2”.

A: Corrected, should be “S1”

C: Page9 Line4: “We selected 28 parameters from calibration (Tab.S1) and …”

R: P7, line 10-11, the sentence is hard to understand due to unclear definition of organic P and stocks. Does this mean include all P from all organic SOM pools? Nor the definition of stocks is clear. Please define them clearly.

A: Revised and clarified.

C: Page10 Line1-3: “The modelled results agreed well with observed stock sizes and vertical patterns, indicating that the stocks [here we define the term `stock' as the total amount of all (model) pools within a larger set] of C, N and P pools …”

R: P7, line 14, perhaps Fig. 7 and Fig. 3 should be swapped, so the paper’s logical flow is more continuous.

A: Corrected

C: all the displayed items in the manuscript are re-numbered in their order of appearances.

R: P8, line 24, remove “the fact”

A: The sentence is rewritten

C: Page12 Line4: “This difference is because that geophysical processes, …”

R: P8, line 27-34, I think “actual enzyme allocation” is not a proper name here because you don’t know what is happening in reality. Perhaps a better name is needed.

A: Revised. The word “actual” is removed

C: Page12 Line9-10: “We compared the enzyme allocation curve of polymeric litter …”

R: P9, line 9, maybe “resistant” should be replaced with a more appropriate word.

A: Revised to “insensitive”

C: Page12 Line29: “N mineralisation was surprisingly insensitive while …”

R: P10, line 23, replace “The fact that” with “that”.

A: Corrected

C: Page14 Line24: “The simulated plant N and P uptakes …”

R: P11, line 13, perhaps "N&P" should be replaced with "N and P" for it to be consistent with the writing style of the paper. Similar changes should be made in other places.

A: Corrected. We followed the advice from the language editor and use "N & P" throughout the manuscript.

C: Page15 Line20: "…, although the N & P stocks and fluxes were greatly influenced."

R: P11, line 13, "resulted" should be "resultant".

A: Corrected

C: Page15 Line21: "…, the resultant SOM C:N and C:P ratios became lower and higher, …"

R: Fig 5, some red annotation of depth overlapped with the y-stick label.

A: Revised

C: The new figure number is Fig 8.

R: For all figures, some annotation text should use large font size, because they may become unreadable when included in the published version.

A: Revised

C: the annotation text in Fig.8 and Fig.9 are enlarged.

Responses to Reviewer Comment 2

R: This manuscript describes the Jena Soil Model, a new soil organic matter model that includes microbial processes, mineral sorption of organic matter, and vertically-resolved soil processes. I thought overall the manuscript was well-written, clear, and easy to follow, and the model integrates new methods for simulating microbial and mineral influences on carbon and nutrient cycling and will be a useful contribution to the biogeochemical modeling field. The introduction did an excellent job of describing the relevant issues and the context for the model. The description of the model was generally clear, although most of the details were left in supplemental material. I do have a few suggestions of areas where the clarity of the manuscript could be improved.

A: we thank the reviewer for the positive comment and recognition of our work

R: I think some additional detail about the sources of the measurements that the model was driven with and compared to would be helpful for understanding the results. The site description only covers the characteristics of the site itself (vegetation and soil types, and some soil profiles) and does not include what kind of data collections were available and the methods used to collect key data resources such as C, N, and P profiles and meteorological data. Some presentation of seasonally-varying factors such as soil moisture, temperature, and litter inputs would help with interpretation of the simulated seasonal cycles. While some of these data collections are presumably described in detail in other publications, a summary in the methods section (an expansion of section 2.2) would help make the measurement context of the simulations clearer.

A: we have included a summary of the measurements in the method section to give a bit more information on the data collections.

C: Page6 Line15-18: “The soil was sampled up to 1 m, with layer depths of 5–10 cm, for the measurements of total C, N and organic and inorganic P and basic physical properties such as bulk density and soil texture. Soil from the A horizon alone was extracted for the estimation of microbial C, N and P pools. Detailed sampling and measurement approaches are described in Lang et al. (2017).”

R: The description of model processes in the text is quite short and is very focused on a few details about stoichiometry and enzymatic processes. There is a lot of detail in the model equations (in supplemental material) that is not explained in the main text. I think some expansion of the process explanation would help readers to understand some of the results. In particular, the seasonal cycles of fluxes shown in Figures 3-5 are largely controlled by moisture and temperature functions, and possibly by the seasonal phenology of vegetation forcing in model simulations, which are not explained in the text.

A: we agree that the seasonal patterns are strongly controlled by the temperature and the seasonal variation of the litter forcing. Although the main focus of this paper is not to look at the causes of seasonal pattern, we do agree it is better to mention them in the method and discussion sections.

We have added some brief descriptions of other processes, such as the temperature and moisture sensitivities used and the microbial response to nutrient availabilities in the model description to help readers better understand our results.

C: Page5 Line6-9: "It assimilates organic forms of C, N and P from DOM with fixed element use efficiencies and inorganic forms of N and P from soluble mineral pools. Microbes are assumed to aim to maximise their growth by maintaining high C use efficiency; however, when growth is limited by nutrients, microbes reduce their C use efficiency and increase nutrient mineralisation accordingly (See Sect.S1.5)."

C: Page5 Line31-Page6 Line2: "The impacts of soil conditions on biogeochemical processes are also represented in JSM. The temperature response of different processes (e.g. microbial growth, decay, and nutrient uptake in Sect.S1.4) are represented by Arrhenius equation with different activation energies. Moisture responses are described by two rate modifiers—one representing the effects of oxygen limitation (e.g. litter turnover in Sect.S1.2) and the other representing the effects of diffusion limitation (e.g. depolymerisation in Sect.S1.3). JSM also considers the effects of SOM content to correct bulk density (Sect.S3), which in turn affects other processes such as organic matter (Eq.S7) and phosphate (Eq.S25) sorption."

Specific comments:

R: Page 1, Line 5-6: Some microbial-explicit decomposition models have included nutrient cycle coupling for example, Abramoff et al., 2017; Sulman et al., 2017; Huang et al, 2018.

A: Thanks for the information. We have corrected it.

C: Page1 Line7-8: "…, they lack a full coupling to the nitrogen (N) and phosphorus (P) cycles with the soil profile."

R: Page 2, Line 31-32: Likewise, there are some TBMs that have included more mechanistic SOM cycling and there are some microbial SOC models that include nutrient cycling.

A: We have corrected it.

C: Page3 Line19-24: "As the above-mentioned processes/phenomena are receiving more attentions, an increasing number of emerging microbially explicit models have started to tackle these challenges by accounting for the N cycle, enzymatic biosynthesis and rhizosphere priming (Abramoff et al., 2017; Sulman et al., 2017; Huang et al., 2018; Sulman et al., 2019) using certain novel approaches"

R: Page 4, line 13: The "See Sect. 5" may be a mistake. Section 5 is the Conclusions. I think this should be SI section 5? Also, I would suggest explaining these processes in

more detail in the main text rather than referring readers to the complex set of equations to understand how the model works.

A: Corrected. We will add a brief description of these processes to the model description, as mentioned in the previous response.

C: Page5 Line24-27: “JSM tracks three potential fractions of enzyme allocation, which represent cases in which microbes only maximise depolymerisation release of C, N or P, respectively, and then updates the microbial enzyme allocation fraction by acclimating gradually to the potential fraction of most limiting element (See Sect.S1.5.2).”

R: Page 4, line 21: "DFG" should be spelled out or defined

A: Corrected.

C: Page6 Line9-10: “…, the VES site has also been one of the main study sites in the German Research Foundation (DFG) funded the priority programme 1685 …”

R: Page 4, line 27: "C content of SOM" is a bit confusing as it could suggest that SOM has been separated from bulk soil and the C content of only organic matter has been determined. Based on the numbers, I think this is C content of the bulk soil in those layers. I would just say “soil C content”

A: Thanks for pointing it out. Corrected.

C: Page6 Line20: “The soil C content decreases from 510 g C/kg soil in the forest floor to 126 g C/kg soil …”

R: Page 5, lines 26-30: It’s not clear from the description whether calibration was an iterative processes. Was this two-step process repeated until results were satisfactory? Was there a particular statistical method used to assess how well the model fit the data?

A: Thanks for pointing it out. No, the calibration is not done iteratively, but indeed, during the second step, we slightly revised some of the parameter values of the first step based on our previously experience.

Also, we only evaluated the model fit visually and did not use a particular statistical method. Because we did not run a Monte-Carlo type calibration, instead all the parameters were varied gradually between two selected values. By calibrating in this way, we learnt how the individual parameter/process would affect other processes/pools, and it also makes the visual judgment sufficient to choose the better model fit.

C: Page8 Line21-25: “The two steps were not performed iteratively; however, during the second step, we revised the parameters from the first step as necessary. Other observed soil profiles, such as the soil organic N and the bulk density, were used as additional criteria to select parameterisation, although not specifically used to calibrate the model. During the calibration processes, parameter values were gradually changed and the goodness of model fit was visually evaluated on the basis of observations.”

Page 7, lines 18-25: Since 14C measurements were an important part of the model evaluation, with some interesting interpretations, I would suggest moving the 14C comparison figure to the main text.

A: The 14C signal is indeed a very important feature of our model, but we did not include the comparison in the main text for two reasons: first, the main focus of this paper is to include nutrient cycles and discuss the features more relevant with carbon-nutrient interactions; second, we did not run the model long enough to match the 14C measurement due to the very high uncertainty in long-term inorganic P cycling and in model initialization. We did test the model for 10,000 years at two other sites with more extreme soil P content, and found out that current inorganic P cycling does not work well in long-term simulation, therefore we have no clue how to initialize the soil mineral P pools, such as primary P pool and secondary P pool, over such a long time. Please find more information in the response to reviewer 3.

C: We include a new paragraph in the discussion regarding the problem of 14C and inorganic P cycling.

Page17 Line26-Page18 Line6: “Nonetheless, certain caveats of this study and JSM should be discussed. A main challenge is the different simulation times for different purposes. Our results indicated that in the upmost 30 cm of soil, SOM content stabilises after 150 years while in the upmost 1 m SOM stabilises after 1000 years of simulation (Fig.2), regardless of the initial SOM content (Fig.S2). However, with respect to the radiocarbon profile, as indicated by Ahrens et al. (2015), a very long simulation time (13500 years) was required to match both the measured $\Delta^{14}C$ and SOC profiles at a nearby Norway spruce forest site. In our study, a 10000-year simulation time was still not sufficient to match the measured $\Delta^{14}C$ profile, indicating that an even longer simulation time is required. Although JSM is very stable in the long term in term of SOM development and storage, long-term simulation of soil P balance as a result of continuous weathering and occlusion remains a significant challenge (Fig.2, Tab.1). Such a long simulation time is unrealistic for the P cycle due to the unknown conditions of the initial soil P pools and the un-equilibrated soil inorganic P cycling processes (Yang et al., 2014). Although we used a much shorter simulation length in this study, noticeable uncertainties remain due to inorganic P cycling parameters (Tab.2). Additionally, the long simulation time required to match the radiocarbon profiles is also problematic for future coupling to TBMs because these models typically examine centennial time scales. A possible solution is to spin-up radiocarbon (>10000 years) independent of the plant--soil spin-up (1000 years), although this approach needs to be properly tested in the future.”

R: Page 7, lines 30-31: Were there changes in microbial growth rates over the season that could explain changes in microbial N demand? I also would suggest adding some explanation for the large spike in microbial N uptake in November. Is this something to do will autumn litterfall, like a short-term increase in N immobilization due to deposition of a large amount of fresh litter?

A: No, we did not find a strong correlation between microbial growth and microbial demand for inorganic N, but of course the total microbial N (organic N + inorganic N) demand is always linear with the growth rate. As we explained in the paper, the microbial inorganic N uptake is largely affected by the N content in DOM.

The peak in microbial N uptake in November seems only existing when ECA approach is turned on, indicating that it might be caused by the simulated competition between roots and microbes.

C: We did not make specific changes regarding this point, as it was already further discussed in the Discussion section "N cycle vs. P cycle". However, we did improve the English in relevant sections to make the result and discussion easier to follow.

R: Page 8, line 10: What does "TW" mean?

A: Removed. It was a comment by co-author we forgot to delete.

C: Page11 Line17-19: "The simulations showed that microbes outcompeted roots for inorganic P uptake in JSM at all depths."

R: Page 8, line 27-page 9, line 5: I had trouble following this explanation of the figure, particularly how the potential allocation curves were calculated and how they should be interpreted.

A: Revised by linking the output in the figure to the variable names and equations. Additionally, a simple description has also been added in the model description. To understand the details of calculation, we would invite the readers to go to the mathematic description in the appendix.

C: Page12 Line9-11: "We compared the enzyme allocation curve of polymeric litter (Enz_{frac}^{poly} in Eq.S17) with three potential allocation curves (α_{poly}^{X} where X stands for C, N, and P, in Eq.S15), which represent cases in which microbes only maximise C, N or P release from depolymerisation."

Page5 Line24-27: "JSM tracks three potential fractions of enzyme allocation, which represent cases in which microbes only maximise depolymerisation release of C, N or P, respectively, and then updates the microbial enzyme allocation fraction by acclimating gradually to the potential fraction of most limiting element (See Sect.S1.5.2)."

R: Page 9, line 7-8: Microbial N uptake and N losses were not centered around the mean. And there is no Table S4, only S1 and S2.

A: Corrected.

C: Page12 Line25-27: "The interquartile range of outputs (Fig.10) from model sensitivity analysis revealed that all outputs were well centred around the results of the parameterisation of the base scenario (Tab.S2), except microbial inorganic N uptake and N losses."

R: Page 10, lines 4-9: This seems like an important part of the model structure and results, and should be introduced earlier than the Discussion section. I think this

modification to the model should be described in the methods. And since making the parameter depth-dependent makes a difference to the results, it might make sense to include it as a separate set of model simulations (as with the SEAM-off and ECA-off simulations) so its effect could be shown.

A: Indeed, the depth-dependent microbial recycling of P is really important for this study site to yield the realistic C:P ratio and Po-to-Pi ratio, and is also what we expect to happen in reality (Rousk and Frey, 2015). We did run a simulation with uniform microbial P recycling along depth but excluded it in the final submission. The reasons to exclude it is that, it is not a standard model feature as SEAM and ECA, which do have theoretical basis. Instead, we suspect that the depth-dependent microbial P recycling should be an emerging model feature if we separate bacteria from fungi.

However, we attach the comparison figure here (in the end) and hand it to the editor to decide if it needs to be included or not.

C: No changes are made yet. Please find the comparison figures below.

R: Page 10, lines 23-24: At steady state, plant N and P uptake would have to be close to litterfall inputs, unless there were large losses due to leaching or other loss pathways.

A: The major reason for not reaching a real equilibrium is, as we stated in the manuscript, the model does not have the feedback from vegetation. That said, we prescribed our litter forcing, and the plant uptake is only determined by the soil conditions regardless of how much plant really requires. As shown in Tab.1, there is no significant loss of N and P from the ecosystem, but N and P are accumulated slowly in the soil due to the fact that 5% of litter fall is accumulated in the soil as SOM.

C: We have added more results and discussion for the long-term stability of JSM. Please find them in Fig.2, Page9 line15-29, and Page17 Line26-Page18 Line6.

R: Page 11, Lines 7-8: Is the fact that plants mainly take up N and not mineralized P specific to this ecosystem? In a more P-limited ecosystem, would the results differ?

A: We do not know the exact answer to this question. However, in our ongoing work where we run the model with multiple sites along a soil P availability gradient, this pattern still holds true. To our understanding, it is the very different stoichiometry of plant tissue and microbe that yield such a pattern, and it should be even stronger in P poor ecosystem than P rich ecosystem, as indicated by Lang et al. 2017.

C: No changes are made.

R: Page 11, line 11-12: The global microbial stoichiometry simulations should be described in the methods.

A: Added.

C: Page8 Line26-Page9 Line2: “To test the effects of different microbial stoichiometry, we ran a *Glob Mic Stoi* scenario in which the global average microbial stoichiometry (42:6:1, Xu et al., 2013) was used to parameterise the model instead of the observed microbial C:N:P ratio (10.3:0.8:1, Lang et al., 2017). ”

R: Figure 1: It would be helpful if the notation in this figure matched the notation in the equations in supplementary material.

A: Revised.

C: Please find the changes in Fig.1.

R: Figure 8: This figure is difficult to understand because there is not a clear explanation of what the different variables mean.

A: Revised by linking the variables in legend with their process name and including the order of displayed processes.

C: Please find the new figure (and caption) of Fig.7

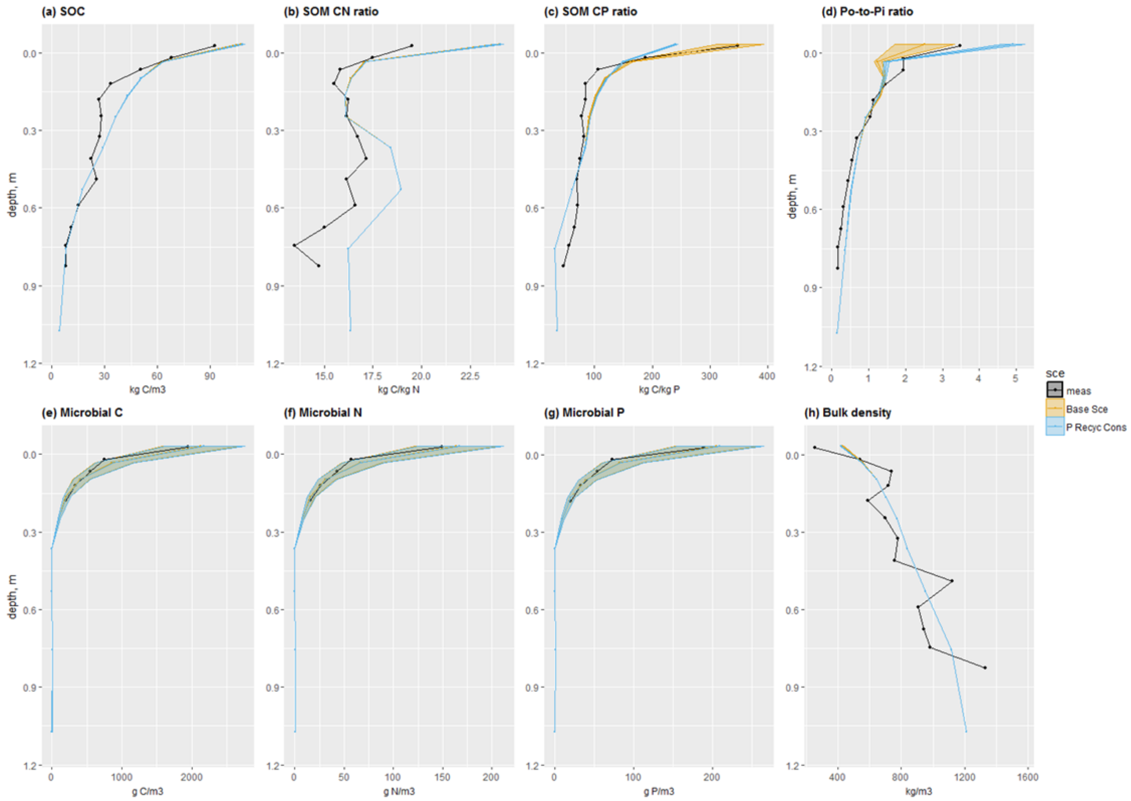

Fig 1. Simulated and observed (a) SOC content, (b) C:N ration in SOM, (c) C:P ratio in SOM, (d) organic P to inorganic P ratio in soil, microbial C, N, and P content ((e) to (g)), and (h) soil bulk density at the study site up to 1m soil depth. Black lines and dots: observations; Color lines and shades: simulated mean values and ranges of standard deviation by different model experiments. The microbial C, N, and P are only measured in top 30cm soil. Simulated means and standard deviations are calculated using data of the last 10 years from the model experiments.

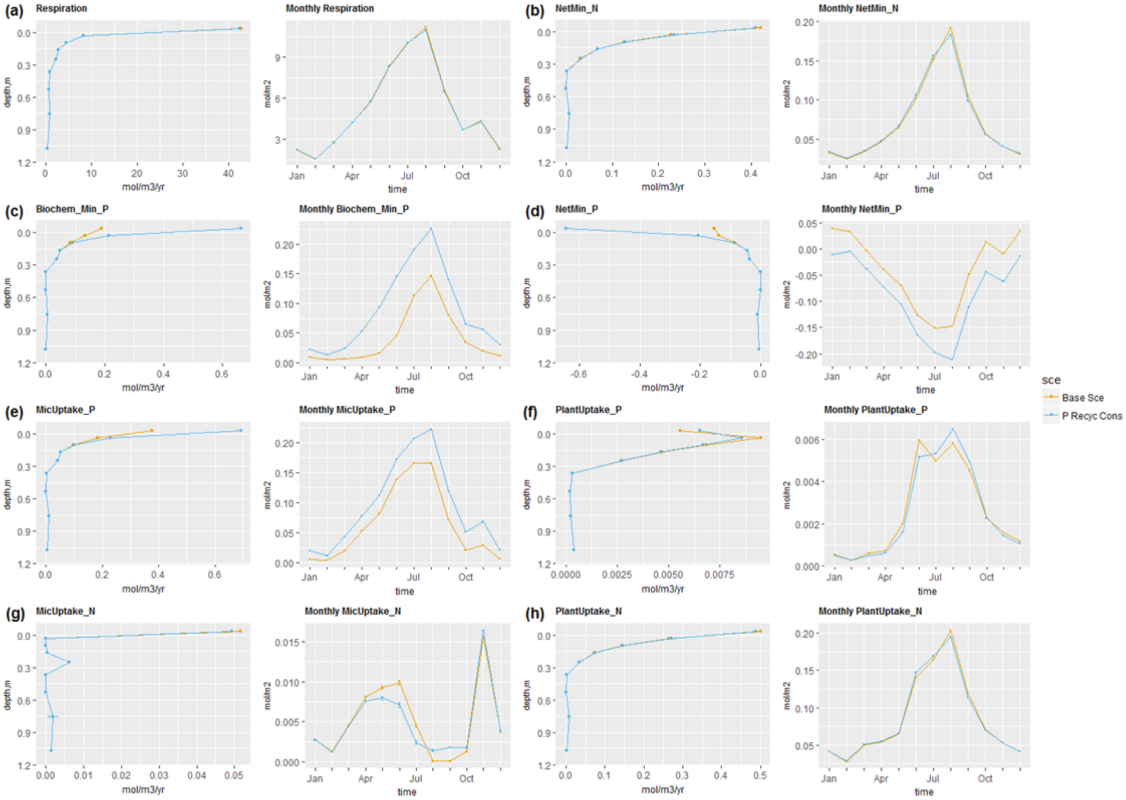

Fig 2. Simulated seasonal and vertical distribution of (a) respiration, (b) net N mineralisation, (c) biochemical P mineralisation, (d) net P mineralisation, (e) microbial inorganic P uptake, (f) plant P uptake, (g) microbial inorganic N uptake, and (h) plant N uptake at the study site up to 1m soil depth. Points represent the mean values and error bars represent the standard deviations, both calculated using data of the last 10 years from the model experiments.

Responses to Reviewer Comment 3

General comments

R: Yu and coauthors present a conceptually robust model that looks at soil biogeochemical processes that explicitly represents microbial activity and CNP stoichiometry in a vertically resolved model. The work presented here does a very thorough job documenting the model configuration and performance at a well-studied site. What's less clear is why it matters? A few suggestions are described in the specific comments below.

A: Thanks for the recognition of our effort.

R: My other major concern with the model is that it doesn't reach steady state equilibrium, instead soil C pools are accumulating at a rate that's roughly 5% of NPP (Table 1). It seems longer spin up times were tried, but since results aren't presented I'm assuming this issue persists, if so, what do soil CNP profiles look like after 10ˆ4 years, do they still match observations well? If the model just has long-term oscillations this may be less of a concern than a constant drift (as I currently understand). The spin up issues, however, seems like a significant issue that has to be addressed if models that more explicitly represent microbial activity and coupled biogeochemical cycles are ever going to be applied in TBMs, as seems to be the aim of this work. The 'lack of plant feedbacks' argument seems unsupported. Moreover, I don't really understand why / how constant 'loss' of P into 'occluded pools affect the C dynamics simulated belowground? This spin-up issue is also one I don't know how to handle in review and my overall assessment of this work. For this reason I'm signing this review and welcome an open conversation with the authors on this concern. I appreciate all the effort that the authors have made do make a very interesting contribution to this line of work- but a model that never really reaches steady state seems very challenging to use for more than short term-studies and sites where the model can be adequately parameterized. This may be the aim of this research group, but it seems unlikely given the introduction, conclusion, and history of strong work from this research group looking at global scale C and nutrient responses for climate change projections.

A: Thanks for the reviewer to point this out. First of all, in our opinion, the soil system should not reach a real equilibrium due to the fact that soil has to develop from bare soil to certain SOC content, and this accumulation process should not stop as long as the soil is not C-saturated when there are continuous C inputs. However, we do agree in an ideal model simulation, the accumulation rate should be constrained within a very small rate. This is actually the case in the top as well as the near surface subsoil in our model after a few hundred years, while small accumulation continue to take place in the deeper soil. We chose the 200-year simulation length for the manuscript, because the surface soil has already reached equilibrium after 200 years, but the deeper soil continues to accumulate C. In our long-term simulation (5000 yr), the annual accumulation of NPP as C in the soil is only 0.07%, compared with 5% in the 200 yr simulation. There is no evidence of the model application to result in oscillations at longer time-scales, as seen in Fig.1 in which we present the top- and sub-soil C content for the 10000 year simulation. We agree with the reviewer that this has been unclear from the previous version of the manuscript, nor did we include the data in the results. To *elaborate this, we will include a new figure in the resubmission to demonstrate how the SOC accumulates in surface and deep soil over a very long time period. We still believe that the results of our study can reasonably be interpreted, because the top 30 cm showed near equilibrium conditions already after 200 years (demonstrated in Fig.S1 and S2).*

A general issue with the development of stand-alone nutrient enabled soil biogeochemical models is that the assumed plant uptake demand does not adequately reflect long-term soils development. When the model was ran for a very long time (e.g. 10,000 years), there were some cases in which the primary P in surface layers got depleted and a large fraction of the sorbed P got occluded. While microbes detect this change and as a result levels down its biomass because it takes up less P, the root biomass and associated plant P uptake in our model is prescribed at the level of mature healthy forest. That said, the root biomass does not change under P limited growth condition, nor does the root distribution over soil layers change. The lack of the phosphorus-root growth feedback implies that under such conditions fine roots become more competitive than microbes in taking up inorganic P, and there is always living roots trying to take up P even if they only take up little P for a very long time. The inorganic P cycling problem is a common problem for the community of terrestrial biosphere modelers, especially at very P-poor ecosystems.

C: We have added more results and discussion for the long-term stability of JSM. Please find them in Fig.2, Tab.1, Page9 line15-29, and Page17 Line26-Page18 Line6.

Specific comments

R: In my opinion there's a bit too much emphasis in the introduction in playing up the novelty of this work. This is not the first model to think about vertical resolution, microbes, nutrients or ECA. It may be the first to do all these together, which can be stated, but then move on. The current review of the literature is nice, but I'd encourage the authors to avoid language that's unnecessarily dismissive of previous work. To address my first issue of 'why this work matters' I can three of three options to consider:

A: We are grateful for all the previous work that makes this model possible and we do realize our wording has caused misunderstandings. We'll carefully rephrase them in the resubmission.

C: We have made several changes to acknowledge other researchers' work in the introduction, such as Page 2 Line 26, Page2 Line29-32, Page 3 Line21-23.

1. **Idealized experiments: While the justification for including nutrients and microbial feedbacks in a model like the Jena soil model is well established in the abstract and first paragraphs of the introduction I also fear it sets up somewhat unrealistic expectations for readers. Notably, none of the results presented illustrate how the model may respond to environmental perturbations. I'm not suggesting these have to be compared to results, but instead simple idealized experiments that illustrate how the different model configurations respond to increases in litterfall inputs, root exudates, warming, or changes in precipitation.**

A: We really appreciate the suggestions by the reviewer for more interesting model experiments, and we are also interested in carrying out such experiments in the future. However, performing such model experiments themselves in a meaningful way would require substantial additional model evaluation and discussion to discuss whether the simulated feedbacks are commensurate with current understanding. Because established model benchmarks do not exist for this model behaviour, this would require an in-depth discussion of the available observations, which in our opinion is beyond the scope of a model description paper. Simply showing sensitivity study without comparing these to suitable observations would be fairly meaningless.

C: no changes are made regarding this point.

2. **Model validation: Alternatively, it seems lots of data were needed to initialize the model. This is fine for development, but how well does the model do simulating other sites? Are there other well studied sites that can be used for independent model validation? I realize this potentially an objective for future work, but it seems like typical activity for model development papers (especially in GMD) that would help illustrate the broader generalizability of the approach outlined here?**

A: Thanks again for the suggestions. Simulation on multiple sites, e.g. a gradient study involves specific biogeochemistry scientific questions to be addressed, and we believe that this is beyond the scope of this paper. Simply showing that the model could be calibrated in other sites will not give much additional value to this paper.

C: no changes are made regarding this point.

3. **Sensitivity analysis: A third alternative would be to consider illustrating model sensitivities to initial conditions? Much like the idealized experiment suggestion (above), I kept finding myself wondering how sensitive the model behaves to initial conditions that are being input to the model (e.g. litterfall and microbial stoichiometry, soil texture / mineralogy, water fluxes and temperature profiles). The parameter sensitivity analysis is nice, what about other assumptions that are being made regarding inputs to what seems like a highly parameterized model? This would open up the discussion for consideration of how to run JSM in regional or global simulations (clearly the intent), where we have less certainty of how the define these characteristics (especially with multiple elements and with depth).**

A: Thanks for the comment. We did test how model performs under different initial conditions, and we have also done some other experiments, such as how the model responds to different microbial carbon-use-efficiency and nutrient-use-efficiencies, plant/microbe uptake rates of mineral nutrients, DOM uptake rates etc.. The reasons for not showing all of them are very similar as the ones for previous two: first, there is a limit on how much we can try to include in a model description paper; second, some of the experiments are very interesting topic to formulate new studies, and we don’t want to dilute the importance of them by including them into this paper.

We will include the model results under different initial conditions in the resubmission, and discuss it together with the spin-up, equilibrium state, and stability issues.

C: we have included the model test of different initial conditions: method description at Page 8 Line28-Page9 Line2, result displayed in Fig.S2 and presented at Page 9 Line16-19 and discussed at Page 17 Line28-29.

R: The authors have actually done #3 with the microbial stoichiometry section that squeezed into the discussion. Maybe the most direct path forward to satisfy this concern would be to actually flush out these findings in the methods and results (see technical comment below).

A: Thanks for the recognition and we will make it more visible in the resubmission.

C: Page8 Line26-28: "To test the effects of different microbial stoichiometry, we ran a *Glob Mic Stoi* scenario in which the global average microbial stoichiometry (42:6:1, Xu et al., 2013) was used to parameterise the model instead of the observed microbial C:N:P ratio (10.3:0.8:1, Lang et al., 2017). "

Technical corrections

R: Page 2, Line 10, I might include Lehmann and Kleber 2015 here.

A: Thanks, included.

C: Page2 Line23-24: "…the nutrient immobilisation and physical stabilisation of organic matter through organo-mineral association (Schmidt et al., 2011; Lehmann and Kleber, 2015)."

R: Page 2, Line 11, Vertically resolved models are becoming more common (McGuire et al. 2018)

A: Thanks, included.

C: Page2 Line25-26: "… thus ignoring the strong variance of SOM cycling within a soil profile (Koven et al., 2013; Arora et al., 2013;McGuire et al., 2018)."

R: Page 2, Line 18, I'm not sure the assertion (made here and in the following paragraph) that microbial explicit models don't represent coupled biogeochemical cycles is accurate (Averill & Waring 2017; Schimel & Weintraub 2003; Sistla et al. 2014; Sulman et al. 2017, 2019).

A: Thanks. We will carefully revisit related literature and revise the introduction, as both reviewer 2 and 3 have pointed out the problem.

C: Page3 Line19-24: "… accounting for the N cycle, enzymatic biosynthesis and rhizosphere priming (Abramoff et al., 2017; Sulman et al., 2017; Huang et al., 2018; Sulman et al., 2019) using certain novel approaches."

R: Page 3, Line 4. I'm pretty sure the ECA approach is applied in E3SM land model, which I wouldn't call a prototype model.

A: Corrected.

C: Page3 Line33-35: “ECA has also been applied to resolve mineral nutrient sink (plant–microbe uptake or mineral adsorption) competitions in other modelling studies (Zhu et al., 2016, 2017).”

R: Page 3, line 16. & Page 4. Where’s section 5?

A: Should be Sect. S2, corrected.

C: Page5 Line29: “…, following the ECA approach (See Sect.S2.2).”

R: Methods. I know COMISSION already has radiocarbon, but should there be any focus on documenting how JSM implements radiocarbon in the text or appendix?

A: We will include the 14C initialization in the model protocol section. But we don’t intend to include the radiocarbon in the supplementary material since they are not the new development of this paper.

We will clearly state it in the revision that the model explicitly traces 14C, see Ahrens et al. 2015 and Thum et al. 2019, and the 14C values of litter forcing were generated using QUINCY, see Thum et al. 2019.

C: Page5 Line17: “JSM explicitly traces ^{13}C, ^{14}C and ^{15}N following Ahrens et al. (2015) and Thum et al. (2019).”

Page7 Line16: “… and vertically resolved litterfall that includes ^{14}C values) …”

R: Page 7 and Fig 2 the model calculates its own bulk density?! That’s pretty interesting, should this be described in the methods?

A: We will include it in the model description, together with the descriptions of some other processes, as mentioned in the response to reviewer 2.

C: Page6 Line1-2: “JSM also considers the effects of SOM content to correct bulk density (Sect.S3), which in turn affects other processes such as organic matter (Eq.S7) and phosphate (Eq.S25) sorption.”

R: Page 7, Line 10-15. It seems odd to jump from presentation of Fig 2 to 7. Should the display items reflect the order that information is covered in the text?

Throughout, display items should be numbered in the order they are introduced in the text.

A: Thanks for pointing out the problem. We will revise the order of our displayed items in the resubmission.

C: all the displayed items in the manuscript are re-numbered in their order of appearances.

R: Fig 8 and Table 1 are never referenced in the results, should they be? I'd prefer these display items not be first introduced in the discussion of the findings of this study.

A: Thanks for pointing it out. We will reorganise the results and discussions according to the order of display items. However, we do think these findings are interesting enough given the fact it is a model description paper. More elaboration can be found in the response to comments of "Discussion".

C: Page9 Line22: "… , but the complete soil profile had not yet reached a steady state (Tab.1) …"

Page11 Line5-7: "The sources and sinks of soluble inorganic N and P also show very different patterns (Fig.7). The main source and sink for inorganic N in solution are gross mineralisation and plant uptake ofNH4, respectively; whereas for P, microbial uptake is the main sink and biomineralisation is a larger source than gross mineralisation in each scenario."

R: Fig. 7 Bottom panels of should be % modern. I also couldn't help but notice that you just have 14C data for the site. Why not run the model for longer and show result, or put the radiocarbon observations up on the plot shown here even if they're just illustrative for 14MOC (which should be most of what makes up the bulk 14C values at depth? Wait, the 14C data are presented in the SI (page 7, line 20- sorry I'm on a plane and don't have access to the SI material). It seems this would be a powerful constraint for the model to try and hit (and should be included in the main text). I'm struck that we can learn a good deal about the model, even if the model is not able to match radiocarbon profiles! If longer spin-up runs have already been done I can't think of any reason not to compare results to observations where they are available.

A: Since this study does not involve any development of radiocarbon calculation, we did not focus on presenting the 14C results. The main message of the 14C results in this paper is that, the inclusion of N and P cycling and other processes do not affect the capacity of the carbon core of JSM (i.e. COMISSION model) to capture/approach the soil profile radiocarbon.

Admittedly, we have stated in the paper that due to the uncertainty in initialization and P cycling processes, the model will have P depletion problem in the long-term simulation (>10,000 years). As a demonstration, we show the change of non-occlude inorganic P for 10,000 year below (Fig.2). The P content in top- and sub-soil fluctuates before 2500 years due to the combined effects of transport and immobilization/mineralization, but after that both of them decrease continuously. We did reach P depletion in other long-term (10,000 year) tests during the calibration processes although this one is not yet there.

We agree that a long simulation time is the perquisite to hit the 14C soil profile, but in order to run the model stably for such a long time, we might need to switch off some inorganic P cycling processes in the spin-up. We will discuss about this more in detail in the resubmission.

C: Page17 Line26-Page18 Line6: "Nonetheless, certain caveats of this study and JSM should be discussed. A main challenge is the different simulation times for different purposes. Our results indicated that in the upmost 30 cm of soil, SOM content stabilises after 150 years while in the upmost 1 m SOM stabilises after 1000 years of simulation (Fig.2), regardless of the initial SOM content (Fig.S2). However, with respect to the radiocarbon profile, as indicated by Ahrens et al. (2015), a very long simulation time (13500 years) was required to match both the measured $\Delta^{14}C$ and SOC profiles at a nearby Norway spruce forest site. In our study, a 10000-yearsimulation time was still not sufficient to match the measured $\Delta^{14}C$ profile, indicating that an even longer simulation time is required. Although JSM is very stable in the long term in term of SOM development and storage, long-term simulation of soil P balance as a result of continuous weathering and occlusion remains a significant challenge (Fig.2, Tab.1). Such a long simulation time is unrealistic for the P cycle due to the unknown conditions of the initial soil P pools and the un-equilibrated soil30inorganic P cycling processes (Yang et al., 2014b). Although we used a much shorter simulation length in this study, noticeable uncertainties remain due to inorganic P cycling parameters (Tab.2). Additionally, the long simulation time required to match the radiocarbon profiles is also problematic for future coupling to TBMs because these models typically examine centennial time scales. A possible solution is to spin-up radiocarbon (>10000 years) independent of the plant–soil spin-up (1000 years), although this approach needs to be properly tested in the future."

R: Figs 3-4, Page 7. From the text it sounds like there are observations of soil nutrient transformation (at least N mineralization). If so, can these be included on the appropriate panels, or am I misunderstood?

A: Sorry for the confusion, but we don't have observed nutrient fluxes that can be comparable to our simulations.

C: no changes are made.

R: Page 8, line 10, what is TW in JSM? Section 3.2. Is the strong microbial competition for P (and not N) caused by the C:N:P ratios that are prescribed for the site (and notably skewed).

A: The content within the bracket in line 10 is a co-author's comment which should have been removed.

The reviewer 2 also has similar concern about the strong microbial P competition of the site, but as what we have seen in simulations of other sites (for another study) it is a consistent pattern in all sites. However, the C:N:P ratios of this study site is not far from other sites we have (Lang et al. 2017), but very far from the global average value. The scenario using global average microbial stoichiometry also shows that microbe outcompetes roots, but not as strong as the base scenario.

C: Page11 Line17-19: "The simulations showed that microbes outcompeted roots for inorganic P uptake in JSM at all depths."

R: Page 8, line 24, the difference among models mentioned here regarding depth profiles of N-mineralization is not obvious, at least to my eye. Regardless, avoid using 'significant' when no statistical results are presented.

A: Thanks for the suggestion. It will be corrected in the resubmission.

C: Page12 Line3-4: "…, but decrease in net N mineralisation with soil depth is marginally stronger (Fig.5). "

Page 8, line 27, it's not clear from the methods how the actual and potential enzyme allocation curves are being calculated from the methods, or did I miss this description. I'm also still hung up on how or why this is being done if the model doesn't explicitly represent enzymes (by the way this decision not to explicitly represent enzymes makes sense to me from a purely practical / numeric standpoint)

A: The detailed processes descriptions are presented in the supplementary material. For the enzyme allocation, we made an assumption that the total enzyme is always proportional to the microbial biomass and used the enzyme richness in the Michaelis-menton equation. Therefore we did implicitly model the enzyme production, and explicitly model the enzyme allocation. We will clarify this in the model description in the main manuscript.

C: Page5 Line24-27: "JSM tracks three potential fractions of enzyme allocation, which represent cases in which microbes only maximise depolymerisation release of C, N or P, respectively, and then updates the microbial enzyme allocation fraction by acclimating gradually to the potential fraction of most limiting element (See Sect.S1.5.2)."

R: Page 8 line 33, if P depolymerization is completely demand driven why is microbial P uptake so much lower in the ECA-off simulations (Fig 4a)? I thought these were supposed to be the 'demand based' simulations (methods)? Please clarify.

A: In the ECA approach, we do not calculate the demand, but the potential uptake depends not only on the uptake capacity per carbon roots/microbes, but also on the biomass of roots and microbes. The ECA approach mainly regulates the competition of uptake capacity per carbon, but eventually the total uptake still depends on the microbial biomass. That is why it looks like "demand-based" simulation.

To simply explain what happened when we turned off ECA: we initialize all the scenarios the same, but the microbes take up less P per biomass carbon than the base scenario, therefore the microbes develop less biomass than the base scenario. Both the lower microbial biomass and lower uptake capacity per unit carbon in the ECA-off scenario has caused the much lower microbial P uptake than the base scenario.

C: No changes are made.

R: Page 9, line 5. Reference Fig 7 here?

A: Corrected.

C: Page12 Line23: "…, resulting a systematic difference in the radiocarbon profiles between the two scenarios (Fig.4)."

R: Page 9, Line 25 these values are for soil stoichiometry? Also, what are N:P ratios for soils? Finally, to my eye it looks like the model may overestimate observed soil C:N

ratios in upper soil horizons (Fig 2). Regardless, it's likely helpful to point to this display item to support claims made about soil C pools and stoichiometry made here.

A: Thanks for pointing out the problem. It is the soil stoichiometry we are discussed here, and the C:N ratio in the O-A horizon is indeed overestimated by the model. We will include it in the discussion when we resubmit.

C: Page13 Line25-27: "Slight overestimation of the modelled soil C:N ratio in the first layer (Fig.3) is probably due to the higher C:N ratio (52) of leaf litter inputs than the observed one (41.7)."

Page13 Line16: "The observed SOM C:N ratio (19.5)and C:P ratio (348) in the first model layer …"

R: Discussion: I have to admit I haven't thought much about the dynamics driving declines in soil C:P ratios with depth, nor am I very familiar with this literature. For everything the model is doing here, this text strikes me as an odd choice to highlight at the beginning of the discussion. That said, it. Is interesting. One detail I don't really follow is that to capture observations it seems like the P recycling term in the model has to be greatly reduced in model. It doesn't seem to logically follow that the community somehow shifts to 'nutrient rich' community that's also has lower nutrient use efficiency? Instead I think the findings of Rousk and Frey suggest that substrate quality determines the microbial communities in forest soils, but doesn't speak much to vertical distribution of microbes (or their stoichiometry) being. Discussed here?

A: Thanks for the comment. We think this finding is interesting and new, and should be stated early in the discussion. First of all, the soil stoichiometry is a rarely discussed topic in the modeling community, and the fact that C:P ratio decreases much faster than C:N ratio with depth is also very interesting for us. Besides, we only have observations for the soil stocks but not flux, so it is natural for us to start with the finding that we saw in the soil stocks. However, as all the reviewers are concerning about the model spin-up, stability/equilibrium state, we will also include this topic in the first part of the discussion.

For the second part of the question, we found that the model has to be tuned in a way that the microbial residue becomes P-poor in the surface layer to reproduce the C:P depth profile. To us it means the microbes need to be more dominated by fungi in the surface soil, and it agrees with what Rousk and Frey (2015) presented in their results (Table 2) that organic layer has higher fungi:bacterial ratio than mineral soil. It also agrees with one of their conclusions that more litter input will lead to higher fungi:bacterial ratio. Although they did not mention soil depth specifically, it is an obvious fact that litter input to soil decreases with soil depth.

C: No specific changes are made.

R: Table 1 should include soil C, N, & P pools of the model after spin up, as it's hard to assess total pool sizes from figures.

A: We only looked at the last 10 years' pool size change of the simulation. We will also include a new figure to demonstrate how the total pool size changes over 10000 years.

C: see the new figure, Fig.2, and relevant discussions about it. Readers can easily see the change of pool size within 10000 years' time in the new figure.

R: Fig 8 can colors of processes in the legend match the order they are displayed on the figure. As currently presented it's not easy for readers to interpret the figure. Introduction of the microbial stoichiometry part of the discussion seems like a nice sensitivity test of the model, but I don't like this being squeezed into the discussion and SI. Why not at least justify this experiment in the methods and describe findings in the results before discussing the findings? (It also likely makes sense to keep the figures in SI).

A: Thanks for the suggestion. We will include the microbial stoichiometry scenario in the methods section.

C: we improved the figure to better convey the information, and also include a short paragraph in Results section to help readers.

Page11 Line5-7: "The sources and sinks of soluble inorganic N and P also show very different patterns (Fig.7). The main source and sink for inorganic N in solution are gross mineralisation and plant uptake ofNH4, respectively; whereas for P, microbial uptake is the main sink and biomineralisation is a larger source than gross mineralisation in each scenario."

R: Page 12, line 25. What observations are the model able to reproduce? Can they be illustrated on the display items (* that also should be referenced here)?

A: We will rephrase the sentence to be more precise and relate to the display items.

C: Page17 Line9-11: "JSM demonstrated a capacity to reproduce the vertical patterns of soil stocks (Fig.3) and to satisfactorily produce both vertical and seasonal patterns of biogeochemical fluxes (Fig.5 and 6)."

R: Page 12, line 28, why not cite a commission paper that's already published

A: We have taken the carbon cycling framework of the most recent version of COMISSION (Ahrens et al. 2019, in review), which is already different from the published version (Ahrens et al. 2015). We will update the reference once it is accepted.

C: No specific changes are made.

Jena Soil Model (JSM v1.0; revision 1934): ~~a~~ A microbial soil organic carbon model integrated with nitrogen and phosphorus processes

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Abstract. ~~The plant-soil interactionsin a changing environment~~Plant–soil interactions, such as the ~~response of~~ coupling of plants' below-ground biomass allocation with soil organic matter (SOM) decomposition, nutrient release ~~,~~ and plant uptake~~to elevated concentration, is~~ , are essential to understand the ~~global~~ response of carbon (C) cycling ~~and predict potential future climate feedbacks. These~~ to global changes. However, these processes are poorly represented in the current terrestrial biosphere models ~~(TBMs) due~~ owing to the simple ~~linear~~ first-order approach of SOM cycling and the ignorance of ~~variation within the~~ variations within a soil profile. While the emerging ~~microbially-explicit soil organic carbon~~ microbially explicit soil organic C models can better describe C formation and turnover~~processes~~, at present, they lack ~~so far a coupling to nutrient cycles~~ a full coupling to the nitrogen (N) and phosphorus (P) cycles with the soil profile. Here we present a new SOM ~~model, JSM (~~model—the Jena Soil Model ~~), which is microbially-explicit~~(JSM)—which is microbially explicit, vertically resolved ~~,~~ and integrated with ~~nitrogen (N) and phosphorus (P) cycle processes. JSM includes a~~ the N and P cycles. To account for the effects of nutrient availability and litter quality on decomposition, JSM includes the representation of enzyme allocation to different depolymerisation sources based on the microbial adaptation approach ~~, and a representation~~ as well as of nutrient acquisition competition based on the equilibrium chemistry approximation ~~(ECA) approach. We~~ approach. Herein, we present the model structure and basic features of ~~the model performance against a German beech forest site~~model performance in a beech forest in Germany. The model ~~is capable of reproducing~~ reproduced the main SOM stocks ~~, microbial biomass , and~~ and microbial biomass as well as their vertical patterns ~~of~~ in the soil profile. We further ~~test the model sensitivity to its parameterisation and show~~ tested the sensitivity of the model to parameterisation and showed that JSM is generally sensitive to ~~the change of~~ changes in microbial stoichiometry and ~~microbial~~ processes.

1 Introduction

There is ample ~~of experimental~~ evidence from both ecosystem monitoring data (Bond-Lamberty et al., 2018; Hou et al., 2018; Jonard et al., 2015) and ecosystem manipulation experiments (Ellsworth et al., 2017; Iversen et al., 2012; McCarthy et al., 2010; Warren et al., 2011) that the ~~effect~~ effects of environmental changes, such as atmospheric CO_2 concentrations, global warming ~~,~~ and continued air pollution, on terrestrial ecosystems ~~depends on~~ are driven by the constraints imposed by ~~major nutrients~~

macronutrients such as nitrogen (N) and phosphorus (P). It is~~therefore fundamental~~ , therefore, of great relevance to identify and understand these constraints on ~~the~~ global carbon (C) cycling and storage ~~to predict potential future climate feedbacks~~ for predicting potential future carbon climate feedback (Ciais et al., 2013). There ~~has been a continuous effort to include the N cycle (Thornton et al., 2007; Zaehle and Friend, 2010; Smith et al., 2014) and the P cycle (Wang et al., 2010; Yang et al., 2014b; Goll et al., 201~~ ~~to improve the model representation of carbon-nutrient interactions~~ have been continuous efforts to integrate the N (Thornton et al., 2007; Z and P cycles (Wang et al., 2010; Yang et al., 2014b; Goll et al., 2017; Thum et al., 2019) in terrestrial biosphere models (TBMs) ~~over the past decades~~for improving the representation of C-nutrient interactions. However, despite major advances in simulating terrestrial biogeochemistry, these nutrient-enabled TBMs largely fail to reproduce the ~~response~~ responses of ecosystems to elevated atmospheric CO_2 ~~concentrations~~ concentration, as observed in the free air CO_2 enrichment ~~(FACE) experiments (Zaehle et al., 2014; Medlyn et al., 2015, 2016). One~~ experiments (Zaehle et al., 2014; Medlyn et al., 2015, 2016; Fleischer et al., 2019) . An important shortcoming of the current generation of models ~~, is their representation of plant-soil~~ is their poor representation of plant–soil interactions, in particular the ~~response~~ responses of soil organic matter (SOM) decomposition and nutrient release to altered plant inputs ~~, and therefore plant uptake~~ and ultimately plant uptake of mineral nutrients (Hinsinger et al., 2011; Drake et al., 2011; Zaehle et al., 2014).

Current TBMs largely adopt the CENTURY model (Parton et al., 1988) or comparable model approaches, ~~where soil organic matter~~ in which SOM is divided into two or three pools with different first-order decomposition rates. In these models, ~~the~~ nutrient mineralisation and ~~immobilization fluxes are dependent~~ immobilisation fluxes depend on the C transfer efficiency between SOM pools and their prescribed C:N:P stoichiometry. Recent insights ~~of~~ in soil science have questioned the ~~CENTURY approach of SOM cycling and pointed out~~ adequacy of the CENTURY approach to SOM cycling for simulating the effects of global changes, particularly in response to altered plant inputs. Researchers underscored the need and ~~directions~~ offered a direction for a more mechanistic ~~model representation~~ representation of soil processes in models, such as the ~~representation of~~ substrate limitation of soil microbial growth ~~and nutrient immobilisation~~ as well as the ~~physical stabilization of OM~~ nutrient immobilisation and physical stabilisation of organic matter through organo-mineral association ~~(Schmidt et al., 2011). One other important limitation is that most of the~~ (Schmidt et al., 2011; Lehmann and Kleber, 2015). Another limitation of many current SOM models in TBMs ~~represent the soil as one~~ is that they represent soil as a ‘bucket’, thus ignoring the strong variance of SOM cycling within ~~the soil profile (Koven et al., 2013)~~a soil profile (Koven et al., 2013; Arora et al., 2013; McGuire et al., 2018) . Such a highly empirical representation of SOM cycling, ~~where~~ in which important processes such as microbial ~~immobilization~~ immobilisation or rhizosphere deposition are not well represented, brings large uncertainties in future projections of terrestrial C sequestration (Bradford et al., 2016). ~~The inclusions of~~ There have been increasing efforts in taking into account microbial (enzymatic) dynamics and mineral association in ~~the soil organic carbon~~ soil organic C (SOC) models~~has shown the~~ , such as CORPSE (Sulman et al., 2014), MIMICS (Wieder et al., 2014), MEND (Wang et al., 2014) and RESOM (Tang and Riley, 2014) . Inclusion of these processes in SOC models has demonstrated possibilities to represent ~~the~~ SOC responses to global warming (Sulman et al., 2018). Moreover, ~~the~~ further inclusion of the explicit vertical resolution of biogeochemical processes and transport allows ~~reconciling~~ for the reconciliation of the SOC depth ~~profile and its~~ and ^{14}C profile (Ahrens et al., 2015). Although these new microbial SOC models ~~proved to~~ better describe C formation and turnover processes ~~better than the traditional ones, they lack so far a coupling to nutrient~~ than the conventional models, they still lack full coupling with the N and P cycles.

The main challenge in coupling ~~carbon~~ C and nutrient cycles in ~~microbially-explicit models resides in~~ microbially explicit models is to account for the large stoichiometric imbalances between the microbial ~~decomposer communities, soil micro-organisms,~~ decomposers (i.e. soil microorganisms) and their resources ~~,~~ (i.e. plant litter and SOM~~(Xu et al., 2013; Mooshammer et al., 2014). The microbial community~~) (Xu et al., 2013; Mooshammer et al., 2014). Soil microbial communities can adapt to these imbalances by adjusting ~~its~~ their C:N:P ratios, ~~usually through shifts of community structure such as changes in~~ typically through shifting community structure (e.g. fungal:bacterial ratios~~(Rousk and Frey, 2015); or by excreting elements that are in excess through adjusting their elements use efficiencies such as the carbon use efficiency~~) (Rousk and Frey, 2015) or through eliminating excess elements by altering their use efficiencies (e.g. C use efficiency) (Manzoni et al., 2012). A ~~more~~ well-known ~~mechanism to adapt to~~ adaptive mechanism to these imbalances is the exudation of extracellular enzymes to release nutrients through hydrolysis (Olander and Vitousek, 2000; Allison and Vitousek, 2005) ~~, or to release nutrients by enhancing~~ or enhanced SOM oxidation, ~~which is known as~~ known as the "rhizosphere priming effect" ~~(Craine et al., 2007; ?)~~ (Craine et al., 2007). Recent evidence has also shown that soil P availability ~~could regulate the~~ regulates phosphatase synthesis (Fujita et al., 2017) and ~~influence~~ influences SOM turnover (Lang et al., 2017). ~~Another emerging challenge of representing the nutrient processes in microbially-explicit models is the competition of nutrient uptake between plants and microbes (Dannenmann et al., 2016; Zhu et al., 2017). Particularly for phosphorus, this competition also involves mineral adsorption (Bünemann et al., 2016; Spohn et al., 2018).~~

~~Although~~ As the above-mentioned processes/phenomena are ~~not yet included neither in current TBMs due to their simple SOM module, nor in current microbial SOC models due to their lack of nutrient cycles, some novel approacheshave been proposed in pilot/prototypal models for representing them. One such approach is~~ receiving more attentions, an increasing number of emerging microbially explicit models have started to tackle these challenges by accounting for the N cycle, enzymatic biosynthesis and rhizosphere priming (Abramoff et al., 2017; Sulman et al., 2017; Huang et al., 2018; Sulman et al., 2019) using certain novel approaches. For instance, the microbial adaptation concept ~~, which is~~ has been applied to represent the adaptation of ~~microbial enzyme allocation to maximize their growth by~~ enzyme allocation by microorganisms to maximise their growth through altering the preferential source of decomposition between plant litter and SOM, as demonstrated ~~by~~ using the SEAM model (Wutzler et al., 2017). ~~Another approach named~~

Another emerging challenge of representing nutrient processes in microbially explicit models is the competition for nutrient uptake between plants and microbes (Dannenmann et al., 2016; Zhu et al., 2017). Regarding P, in particular, the soil mineral surface adsorbs inorganic P to compete with plants and microbes (Bünemann et al., 2016; Spohn et al., 2018). The equilibrium chemistry approximation (ECA) ~~, is~~ approach has been proposed to simulate the competition of substrate uptake kinetics in complex networks ~~by taking account the impact of one uptake kinetic on other substrates (Tang and Riley, 2013), and has~~ where the uptake kinetics of one substrate affects the others (Tang and Riley, 2013). ECA has also been applied to resolve mineral nutrient ~~sinks (plant-microbe~~ sink (plant–microbe uptake or mineral adsorption) ~~competition in prototype model~~ competitions in other modelling studies (Zhu et al., 2016, 2017).

In this study, we present the structure and basic features of a ~~new microbially-explicit,~~ novel microbially explicit and vertically resolved SOM model ~~integrated with~~ that integrates with the N and P ~~cycle processes, the~~ cycles—the Jena Soil Model (JSM). ~~We test and evaluate alternative hypotheses on the competition of~~ JSM combines the representations of the vertical structure, microbially explicit decomposition and stabilisation (Ahrens et al., 2015) with the microbial adaptation concept from the SEAM model (Wutzler et al., 2017) and the ECA approach (Tang and Riley, 2013). We tested alternative hypotheses regarding the competition among microbial, plant ~~,~~ and mineral nutrient sinks (uptake or mineral sorption) ~~, and the effect~~ and evaluated the effects of nutrient availability on the preferential decomposition of either ~~nutrient poor or rich~~ nutrient-poor or nutrient-rich organic matter using observed ~~profiles of soil carbon, nitrogen and phosphorus~~ soil C, N and P profiles in a temperate beech forest stand. Additionally, we ~~provide an assessment of~~ evaluated the model's sensitivity to ~~its parameterisation and the~~ parameterisation and associated uncertainty to help ~~understanding~~ understand these effects.

2 Material and methods

2.1 Model description

~~The Jena Soil Model (JSM)~~ JSM is a soil biogeochemical model ~~and was~~ built on the backbone of the vertically explicit ~~carbon-only soil organic carbon~~ C-only SOC model COMISSION (Ahrens et al., 2015). The COMISSION model was further developed ~~compared to Ahrens et al. (2015)~~ from the conventional one by introducing a scalable maximum sorption capacity based on soil texture for ~~DOC~~ dissolved organic C and microbial residues (Sect.~~1) and by introducing~~ S1.4) as well as temperature and moisture rate modifiers for ~~the microbially mediated~~ microbe-mediated processes and sorption (Sect.S1). We will investigate in a separate study~~how a~~ , how the maximum sorption capacity for mineral-associated organic ~~carbon contributes to~~ C contributes to the observed patterns of SOC ~~radiocarbon ages~~content and radiocarbon age. A schematic overview of ~~the JSM model is shown~~ JSM is presented in Fig. 1, and the mathematical description of the processes is ~~given~~ provided in Appendix A. The model is integrated into the ~~modelling framework of the QUINCY TBM (Thum et al., 2019) and can~~ QUINCY (Thum et al., 2019) TBM modelling framework and can either be applied as a stand-alone soil ~~module~~ model or coupled to the representation of the vegetation and surface processes. In this study, we ~~apply~~ applied JSM as stand-alone model. JSM ~~does not describe~~ neither describes the energy and water processes at the ~~atmosphere-soil~~ atmosphere–soil interface or in the soil profile, nor ~~does JSM simulate~~ simulates the production of litter~~fall~~. Model inputs (soil temperature, moisture and water fluxes ~~,~~ as well as ~~the litter fall dataas the model inputs) are~~ plant litter data) were derived from the QUINCY model.

JSM describes the formation and turnover of SOM along a vertical soil profile, which is explicitly represented ~~with~~ as exponentially increasing layer thickness ~~as soil depth increases~~ with increasing soil depth (Fig. 1). The biogeochemical processes and pools of C, N ~~,~~ and P are represented in each layer. Vertical transport of biogeochemical pools between the adjacent layers due to percolation and bioturbation is also modelled. To reflect the development of an organic layer, the model also includes an extra advective transport term which accounts for the ~~upward~~upwards/~~downward~~ downwards shift of the soil surface when the surface SOM accumulates/diminishes.

SOM is represented as pools of ~~soluable, polymeric , and woody litter ,~~ soluble, polymeric or woody litter as well as of dissolved organic matter (DOM), mineral-associated DOM, living microbial biomass, microbial residue (necromass) ~~,~~ and mineral-associated microbial residue, each of which contains organic forms of C, N and P. The ~~flow~~ flows of organic N and P ~~follows~~ follow the pathways of C, with ~~extra~~ additional nutrient-specific processes, such as mineralisation and plant uptake, to link organic matter turnover with inorganic nutrient cycles. Microbial biomass is assumed to maintain a fixed stoichiometry in the model~~, requiring the microbial synthesis~~. It assimilates organic forms of C, N and P ~~to fulfill the C:N :P ratio of the microbial biomass pool~~from DOM with fixed element use efficiencies and inorganic forms of N and P from soluble mineral pools. Microbes are assumed to aim to maximise their growth by maintaining high C use efficiency; however, when growth is limited by nutrients, microbes reduce their C use efficiency and increase nutrient mineralisation accordingly (See Sect.S1.5). The stoichiometry of all other SOM pools depends on the C:N:P ratios of influx and efflux, and these fluxes ~~all~~ retain the stoichiometry of their ~~sourcing pools ,~~ source pools unless the formation processes involve respiration. In addition, when microbes decay, nutrients are ~~preferably recycled to~~ preferentially recycled to the DOM pool due to the low C-to-nutrient ratio in the cyctoplasma, as proposed by Schimel and Weintraub (2003). The inorganic pools of N and P include soluble inorganic ammonium (referred to as $\mathrm{NH_4}$), nitrate (refered to as $\mathrm{NO_3}$), soluble inorganic phosphate (referred ~~as PO_4~~to as $\mathrm{PO_4}$), as well as adsorbed ~~PO_4, absorbed PO_4, occluded PO_4 and primary PO_4~~$\mathrm{PO_4}$, absorbed $\mathrm{PO_4}$, occluded $\mathrm{PO_4}$ and primary $\mathrm{PO_4}$. The inorganic P cycle follows the QUINCY model (Thum et al., 2019) ~~, with modifications due to~~ and accounts for microbial interactions. JSM explicitly traces $^{13}\mathrm{C}$, $^{14}\mathrm{C}$ and $^{15}\mathrm{N}$ following Ahrens et al. (2015) and Thum et al. (2019).

Enzymes are not explicitly modelled in JSM, ~~but~~ although these are described implicitly to regulate processes such as depolymerisation and nutrient acquisition. For enzyme allocation within depolymerisation ~~process~~processes, we extended the microbial adaptation approach of the SEAM model (Wutzler et al., 2017) by including P ~~and vertical explicitness and assuming~~ dependence of enzyme allocation and the assumption of a steady state of enzyme production, ~~which means~~ leading to the prediction that the total enzyme level is always proportional to the microbial biomass. The fractions of ~~enzyme~~ enzymes allocated to different depolymerisation sources (litter and microbial residue) are dynamically modelled to ~~maximize~~ maximise the release of the most limiting ~~elements of microbes~~ microbial elements. JSM tracks three potential fractions of enzyme allocation, which represent cases in which microbes only maximise depolymerisation release of C, N or P, respectively, and then updates the microbial enzyme allocation fraction by acclimating gradually to the potential fraction of most limiting element (See Sect.~~1~~S1.5.2). For nutrient ~~acquisition of~~ competition between plant, microbes and soil adsorption sites (only for phosphate), the potential rates are calculated ~~based on the respective enzyme richness ,~~ on the basis of the respective richness and half-saturation level of enzymes ~~,~~ and the impacts ~~from other competitors~~of other competitors, following the ECA approach (See Sect.~~2~~S2.2).

The impacts of soil conditions on biogeochemical processes are also represented in JSM. The temperature response of different processes (e.g. microbial growth, decay, and nutrient uptake in Sect.S1.4) are represented by Arrhenius equation with different activation energies. Moisture responses are described by two rate modifiers—one representing the effects of oxygen limitation (e.g. litter turnover in Sect.S1.2) and the other representing the effects of diffusion limitation (e.g. depolymerisation in Sect.S1.3). JSM also considers the effects of SOM content to correct bulk density (Sect.S3), which in turn affects other processes such as organic matter (Eq.S7) and phosphate (Eq.S25) sorption.

2.2 Site description and data for model analysis

The Vessertal (VES) site is a mature beech (*Fagus sylvatica*) forest stand ~~and~~ with an average tree age of ~~more than~~ >120 years, located in the ~~German central uplands~~ central uplands of Germany (Thuringian Forest mountain range). The ~~site has an intermediate elevation of~~ intermediate elevation is 810 m a.s.l~~with ,~~, with a high annual precipitation of 1200 mm and a mean annual temperature of 5.5 °C (Lang et al., 2017). It is one of the Level II intensive monitoring plots ~~of~~ in the Pan-European International Co-operative Program ~~on~~ for the assessment and monitoring of air pollution effects on forests (ICP Forests). ~~The~~ Since 2013, the VES site has also been ~~selected as~~ one of the main study sites in the ~~DFG funded~~ German Research Foundation (DFG) funded the priority programme 1685 ~~’~~‘Ecosystem Nutrition: Forest Strategies for ~~limited~~ Limited Phosphorus Resources’~~since 2013. .~~.

~~The soil was~~ Soil at the VES site is classified as Hyperdystric ~~skeletic chromic cambisol (WRB, 2015)with a loam~~ Skeletic Chromic Cambisol (WRB, 2015), with loamy topsoil and sandy ~~loam subsoiland is overlain by~~ loamy subsoil, overlain by a Moder organic layer. The current soil ~~was developed on Trachyandesite~~developed on trachyandesite, and the development started at the end of the last ice age, 10–12,000 years ago (Lang et al., 2017). The soil was sampled up to 1 m, with layer depths of 5–10 cm, for the measurements of total C, N and organic and inorganic P and basic physical properties such as bulk density and soil texture. Soil from the A horizon alone was extracted for the estimation of microbial C, N and P pools. Detailed sampling and measurement approaches are described in Lang et al. (2017).

The soil contains 19 $\mathrm{kg/m^2}$ C, 1.1 $\mathrm{kg/m^2}$ N ~~,~~and 464 $\mathrm{g/m^2}$ P up to ~~1 m soil depth~~1-m soil depth, including the forest floor (Lang et al., 2017). The ~~C content of SOM~~ soil C content decreases from 510 g C/kg soil in the forest floor to 126 g C/kg soil in the A horizon ~~and~~ to 5.9 ~~at 1 m~~ g C/kg soil at 1-m depth. The C:N ratio of SOM slightly decreases from ~~ca. 30~~ 19.5 in the forest floor to ~~ca. 20 at 1 m depth, while the decrease of~~ 14.75 at 1-m depth, whereas the C:P ratio ~~is stronger—from ca. 2500~~ decreases more steeply from 348.7 in the forest floor to ~~ca. 300 at 1 m~~ 46.6 at 1-m depth. The organic P fraction of total P also decreases from ~~two thirds~~ 67 % in the organic layer to ~~ca. 10 % at 1 m~~ 13 % at 1-m depth. The microbial C content decreases from ~~more than~~ >2000 µg C/g soil C in the forest floor (Zederer et al., 2017) to 764 µg C/g soil C in the top mineral soil (Bergkemper et al., 2016). The ~~microbes have~~ microbial biomass shows a C:N ratio of 13 and a very low C:P ratio of 10.3 (Lang et al., 2017).

2.3 Model protocol, model experiments ~~,~~and sensitivity analysis

Model protocol~~and calibration~~

The soil texture ~~profile~~ profiles for both QUINCY (for the generation of soil temperature, moisture and litterfall) and JSM simulations ~~was taken from the~~ were obtained from observations at the VES site. The mineral-associated DOM and residue pools were initialised ~~based on~~ on the basis of Eq.S7 ~~, using~~ using the observed soil texture and mineral soil density, and assuming that the soil surface sorption sites are less occupied as soil depth increases. The vertical profile of the other SOM pools was initialised with a default C content for each pool in the first layer and assumed to decrease with soil depth in proportion to the fine root profile (Jackson et al., 1996), except in the woody litter, which is only initialised in the first layer. The initialisation C ~~content in~~ contents in the first layer for ~~soluable~~ soluble litter, polymeric litter, woody litter, DOM, microbes and microbial residue ~~are~~ were 291, 2914, 1000, 2.4, 73.2 ~~,~~ and 203 $\mathrm{g/m^3}$ C, respectively. The N and P ~~content~~ contents of the SOM pools were initialised ~~with~~ using the stoichiometry of different pools~~: for~~. For litter pools, we adapted the litter stoichiometry from the QUINCY model (Thum et al., 2019); for microbes and microbial residues, we used the measured microbial stoichiometry (Bergkemper et al., 2016) ~~;~~ and for other SOM pools, we used the measured average SOM stoichiometry of the ~~1 m~~ 1-m soil profile (Lang et al., 2017). All SOC profiles were initialised with a pre-industrial $\Delta^{14}C$ values for all C pools, from which the ^{14}C values were developed. The soil inorganic P pools were initialised using the soil P ~~data-set by Yang et al. (2013)~~ dataset from Yang et al. (2014a), corrected with the current total inorganic P from field measurements and extrapolated to the whole soil profile following the approach used in the QUINCY model (Thum et al., 2019). ~~The organic matter material density~~ Organic matter material and mineral soil ~~density~~ densities were solved using the Federer equation (Federer et al., 1993) with ~~the~~ field data of the SOM content and bulk density. [1]

We first ran the QUINCY model for 500 years to generate soil forcing and then simulated the VES site for 200 years using JSM, repeating 30 years of soil forcing (half-hourly soil temperature, soil moisture, vertical water fluxes ~~,~~ and vertically resolved ~~litter fall~~litterfall that includes ^{14}C values) simulated by the QUINCY model for the VES site. To mimic the history of ^{14}C input, we ~~assumed~~ increased litter ^{14}C content for the final 60 years before the end of the simulation, ~~matching~~ assuming that the $\Delta^{14}C$ in gross primary productivity in response to the observed $^{14}\mathrm{CO_2}$ atmospheric pulse propagates directly into litterfall without any delay. We tested different simulation lengths (50, 200, 1000, 5000 ~~,~~ and 10000 years) and ~~found out that simulated SOM profile changes~~ observed that the simulated SOM profiles changed slowly after 200 years but the soil inorganic P pools ~~changes~~ changed gradually as the simulation time ~~increases (data not shown). Therefore, we chose~~ increased (Fig.2B). In the view of computational efficiency, we sought to compare the present-day soil profile observations with the simulated profiles ~~from the 200-year simulations, which~~ for 200 years, which also best fit the ~~time of the~~ date of soil inorganic P pool initialisation (1850, as indicated in ~~Yang et al. (2013)~~Yang et al. (2014a)). All the other presented results (including sensitivity analysis) are also based on the 200-year simulations, and the results of long-term simulations (~~1000y and 5000y) can be found in the supplementary materials~~1000, 5000 and 10000 years) are specified with their simulation times.

~~The calibration processes consisted of two main steps: in the first step we match the model results with the measured SOC profile, mainly by calibrating the depolymerisation, OM sorption, and litter turnover processes; in the second step, we match the model results with the measured soil organic P profile by calibrating the microbial growth & decay, nutrient acquisition, and soil inorganic P cycling. Other observed soil profiles were used as extra criteria to select parameterisation but not particularly used to calibrate the model.~~

Model experiments

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[1] ~~Solved by Microsoft Excel, using the Generalized Reduced Gradient nonlinear optimization method with algorithm developed by Leon Lasdon, University of Texas at Austin, and Alan Waren, Cleveland State University, and enhanced by Frontline Systems, Inc.~~

To further test the effects of different model features, we implemented several model experiments, including ~~:~~ a *SEAM-off* scenario ~~where~~ in which the enzyme allocation to polymeric litter and microbial residue are both fixed to 50% (Eq.1b), and ~~a~~ an *ECA-off* scenario ~~where~~ in which the ECA-based plant and microbial ~~uptake~~ uptakes of inorganic N & P and soil adsorption of phosphate ~~was switched off ,~~ were switched off and replaced by a demand-based microbial uptake of inorganic N & P ~~and ignored phosphorus~~ that ignored P adsorption flux (Eq.1c). All ~~the model experiments use~~ model experiments used the same parameterisation from the calibrated model with full model features, which is denoted as the *Base Scenario* in this study.

The differences between *Base Scenario* and *SEAM-off* & *ECA-off* are listed below~~,~~ :

$$\begin{aligned}
&Base\ Scenario:\\
&\qquad Enz^{poly}_{frac} \,\&\, Enz^{res}_{frac} \text{ calculated as Eq.S15}\\
&\qquad U^{*}_{X,y} \text{ for microbes, plant and adsorption calculated as Eq.S23} && \text{(1a)}\\
&SEAM-off\ Scenario:\\
&\qquad Enz^{poly}_{frac} = Enz^{res}_{frac} = 0.5 && \text{(1b)}\\
&ECA-off\ Scenario:\\
&\qquad U^{*}_{X,plant} = f(T_{soil},\Theta)v^{X}_{max,plant}C_{fine\_root}[X](K^{upt}_{m1} + \frac{1}{K^{upt}_{m2}+[X]})\\
&\qquad U^{*}_{X,mic} = F^{demand}_{mic,X}\\
&\qquad U^{*}_{P,adsorp} = 0 && \text{(1c)}
\end{aligned}$$

The plant uptake of inorganic N or P ($U^{*}_{X,plant}$) in the ECA-off scenario (Eq.1c) uses the ~~same equation~~ equations and parameters from the QUINCY model (Thum et al., 2019). ~~Other model experiments to demonstrate the effects of microbial stoichiometry and simulation time can be found in the supplementary material.~~

~~**Model sensitivity**~~ **Calibration and model sensitivity**

~~We~~ We calibrated the *Base Scenario* in two main steps. In the first step, we matched the model results with the measured SOC profile, mainly by calibrating the depolymerisation, organic matter sorption and litter turnover processes; in the second step, we matched the model results with the measured soil organic P profiles by calibrating the microbial growth & decay, nutrient acquisition and soil inorganic P cycling. The two steps were not performed iteratively; however, during the second step, we revised the parameters from the first step as necessary. Other observed soil profiles, such as the soil organic N and the bulk density, were used as additional criteria to select parameterisation, although not specifically used to calibrate the model. During the calibration processes, parameter values were gradually changed and the goodness of model fit was visually evaluated on the basis of observations.

To test the effects of different microbial stoichiometry, we ran a *Glob Mic Stoi* scenario in which the global average microbial stoichiometry (42:6:1, Xu et al., 2013) was used to parameterise the model instead of the observed microbial C:N:P ratio (10.3:0.8:1, Lang et al., 2017). To further test the model responses to different initial conditions, we ran the model with different initial SOM contents (50%, 75%, 150%, and 200% of the default initial content) for 1000 years to ensure that the soil reached a more stable state.

We also tested the sensitivity of JSM to ~~its~~ parameterisation using a hierarchical ~~latin~~ Latin hypercube design (LHS, Saltelli et al., 2000; Zaehle et al., 2005). We ~~select~~ selected 28 parameters from ~~the~~ calibration (Tab~~S2~~. S1) and varied each parameter between 80% and 120% of the ~~Base Scenario~~ base scenario values given in ~~the Tab. S1, drawn with~~ Tab. S2, which were obtained through LHS sampling from a uniform distribution to form a set of 1000 LHS samples ~~, which are used for the~~ and used in model sensitivity and uncertainty ~~analysis~~ analyses presented in this paper. We ~~evaluate~~ evaluated the model output from these simulations in terms of main biogeochemical fluxes ~~, such as~~ (e.g. respiration, net N & P mineralisation, microbial uptake of inorganic N & P, N & P losses ~~,~~ and P biomineralisation~~,~~) and main SOM pools (up to ~~1 m depth) , such as~~ 1-m depth) (e.g. total C, N ~~,~~ and P in SOM~~,~~ ; total soil inorganic P ~~,~~ and microbial C, N ~~, and P. We measure~~ and P). We measured parameter importance as the rank-transformed partial correlation ~~coefficient (RPCC~~coefficients (RPCCs) to account for potential non-linearities in the ~~relationship between parameters and model~~ association between model parameters and output (Saltelli et al., 2000; Zaehle et al., 2005).

3 Results

3.1 ~~Simulated SOM stocks~~ Model stability and ~~fluxes at the study site~~quasi-equilibrium state

~~In this study, we tested different simulation lengths of JSM and found out that the~~ We tested JSM with different initial SOM contents and different microbial stoichiometry. The simulated SOM profiles, including ~~the SOC,~~ SOC; C:N and C:P ratios of ~~SOM,~~ SO; microbial C, N ~~, and P content,~~ and P contents and bulk density, ~~don't change much with time~~ did not respond strongly to changes in initial SOM contents (Fig.S2) but were notably affected by the assumed microbial stoichiometry (Fig.S1). We further examined the effects of simulation time on soil profile development (Fig.2 and Fig.S1). SOC in the topsoil (30 cm) reached a stable state (ca. 70 $\mathrm{kg\ C/m^3}$) after approximately 150 years and the subsoil (30–100 cm) reached a stable state (ca. 30 $\mathrm{kg\ C/m^3}$), after approximately 1000 years. The accumulation rate of SOM decreased with time, but the complete soil profile had not yet reached a steady state (Tab.1) because C continues to accumulate slowly, particularly in deeper soil layers (>1 m). Although the organic P dynamics follow the soil C dynamics, the inorganic P pools inevitably deplete in the long-term simulation (Fig.2) due to high uncertainties in initialisation and P cycling processes. Therefore in this study, we ~~focus~~ focussed on the stable state of topsoil (30 cm) at the end of the 200-year simulations and ~~refer~~ referred to it as a ~~"~~‘quasi-equilibrium state~~"~~’ since slow changes are still occurring, ~~especially with~~ particularly in soil inorganic P pools and ~~with~~ SOM in deeper ~~soils~~ soil layers (Fig.S3, Fig.S4 and S5).

~~We first compare~~

3.2 Simulated SOM stocks and fluxes at the study site

We first compared the simulated profiles with the *in situ* ~~observations~~ observed ones (Fig.3). The modelled results ~~agree well with the~~ agreed well with observed stock sizes and vertical patterns, ~~and indicate~~ indicating that the stocks [here we define the term ‘stock’ as the total amount of all (model) pools within a larger set] of C, N ~~, and P in SOM have~~ and P pools in SOM show smaller temporal variations than the ~~stocks in microbes~~ microbial pools at the quasi-equilibrium state (Fig.3a to 3c) ~~, due to the~~ due to strong seasonal variations in ~~the~~ microbial biomass. We also ~~find a stronger~~ found a greater variation in the simulated organic ~~P to inorganic~~ P-to-inorganic P (Po-to-Pi) ratio (Fig.3d) than for ~~organic P~~ the individual organic and inorganic P stocks ~~separately~~ (data not shown), inferring that the seasonal dynamics of microbes also impose a seasonal pattern ~~to~~ of P immobilisation (from Pi to Po) and mineralisation (from Po to Pi).

The distribution ~~of total OM at each depth across OM-pools and their radiocarbon content~~ and radiocarbon profile of total organic matter in the simulations ~~are displayed in~~ varied across soil depths (Fig.4). The first layer (~~0cm, O-A~~ 0 cm, O–A horizon) is dominated by the plant litter and microbial component (living/dead microbes), and while the microbial component decreases strongly from ca. 40% at ~~0cm to almost none at 50cm~~ 0 cm to almost zero at 50 cm soil depth, the litter component still ~~consists~~ constitutes ca. 10% of the total SOC at ~~1m~~ 1-m soil depth. The mineral-associated ~~carbon~~ C (MOC) component switches from a minor component in the ~~O-A~~ O–A horizon (ca. 20%) to the dominant component (ca. 90% at ~~1m) in the deeper soil~~ 1 m) in deeper soil layers.

The simulated radiocarbon ($\Delta^{14}C$) profile ~~agrees with the observations in so far that~~ agreed with observed one (Fig.S1e); the $\Delta^{14}C$ ~~values increases~~ content increased within the O horizon and ~~starts decreasing with~~ started decreasing with increasing soil depth from mineral soil, i.e. ~~A horizon (Fig.S1e)~~the A horizon. This pattern indicates ~~the ’~~that the ‘bomb pulse’ ~~of~~ $\Delta^{14}C$ signal significantly ~~affect~~ affects the apparent ^{14}C age in the organic layer ~~due to the strong litter interactions and the impacts decrease~~ and its impact decreases with soil depth due to the slow turnover in deeper soil. Our simulations further ~~indicate~~ indicated that such a vertical pattern is caused by ~~the~~ MOC and microbial components, while the litter component ~~shows a general increase of radiocarbon percentage with increasing soil depth~~ stays modern throughout the profile (Fig.4). ~~Although the Base Scenario does~~ Increases in litter ^{14}C with depth suggest that more bomb-derived SOC is still found in subsoils due to slower litter turnover, while it is already replaced by more recent, ^{14}C-poorer SOC in the topsoil. Although the base scenario did not reproduce the measured radiocarbon profile~~but only the~~, albeit only its vertical pattern, ~~we do see~~ a much better fit with the measured radiocarbon profile and ~~an increase of~~ increase in soil ^{14}C age, ~~which are~~ driven by MOC~~as the simulation length increases~~, were indeed observed as simulation time increased (Fig.S1e and Fig.S4).

The simulated biogeochemical fluxes show ~~a~~ strong seasonal and vertical ~~pattern~~ patterns (Fig.5 and Fig.6), in which the flux rates in summer and in the ~~top layer~~ topsoil are generally higher than those in winter and in the subsoil, respectively. ~~However, the microbial uptake of inorganic N~~ Meanwhile, microbial inorganic N uptake shows a different seasonal pattern~~where the rate is lowest~~, with the lowest rates observed in August and September (Fig.6c). ~~This pattern is actually~~ In fact, this pattern is supported by the seasonal pattern of net N mineralisation flux~~where~~, in which the peak is ~~found~~ observed in August and September (Fig.5b). This ~~indicates that the~~ result indicates that organic N in DOM is the most abundant for microbial growth during August and September, ~~which leads to a strong~~ leading to a large reduction in the microbial inorganic N uptake and increase in ~~the~~ net N mineralisation. ~~To the contrast, the organic P~~ In contrast, organic P content in DOM is ~~most scarce~~

the lowest during August and September, ~~and it leads to a negative net P mineralisation and an increase of~~ leading to net P immobilisation and microbial inorganic P uptake elevation (Fig.5d and Fig.6a). While the vertical pattern of plant N uptake ~~follows that of the~~ parallels root distribution (Jackson et al., 1996), ~~the~~ plant P uptake is lower in the organic layer than in the topsoil due to ~~the~~ strong competition from microbes in the organic layer (Fig.6 and Fig.8).

The sources and sinks of soluble inorganic N and P also show very different patterns (Fig.7). The main source and sink for inorganic N in solution are gross mineralisation and plant uptake of NH_4, respectively; whereas for P, microbial uptake is the main sink and biomineralisation is a larger source than gross mineralisation in each scenario.

3.3 Model features: nutrient acquisition competition and enzyme allocation

In general, the ~~SEAM-Off scenario does~~ SEAM-off scenario did not differ much from the ~~Base Scenario with regard to~~ base scenario in terms of the main soil stocks and biogeochemical fluxes (Fig.3 and Fig.5)~~, but the ECA-Off scenario produces~~ ; however, the ECA-off scenario produced a lower microbial biomass and ~~a lower~~ Po-to-Pi ratio in the organic layer and ~~top soils. The total SOC seems not to~~ topsoil. Total SOC may not be influenced in ~~both scenarios, but the composition of SOC and the radiocarbon profile are all~~ either scenario, although its composition and radiocarbon profile were both altered (Fig.4).

3.4 ~~Model features: nutrient acquisition competition and enzyme allocation~~

We ~~present the microbial and plant uptake rates~~ presented the uptake of inorganic PO_4 and ~~the~~ competition between phosphate adsorption, ~~microbial and plant~~ uptake of inorganic P at three different depths (Fig.8) ~~, as well as the~~ and seasonal and vertical uptakes of inorganic N ~~and~~ & P for both microbes and ~~plant~~ plants (Fig.6). The simulations ~~show that microbes outcompete~~ showed that microbes outcompeted roots for inorganic P ~~(TW: in JSM) in all the chosen depths, but~~ uptake in JSM at all depths. However, the relative competitiveness of roots ~~to take up phosphate increases with soil depth. In other word,~~ for phosphate uptake increased with increasing soil depth because the plant P uptake rate decreases less strongly than the microbial P uptake with increasing soil depth. ~~The~~ In contrast, the phosphate adsorption rate ~~, in contrast, increases~~ increased strongly with increasing soil depth and ~~outcompetes~~ outcompeted biological processes (plant and microbial uptake) in ~~the deeper soil~~ deeper soil layers. The relative competitiveness of phosphate adsorption ~~also shows a strong decrease~~ against microbial and plant uptake also strongly decreased in summer in the ~~top soil, due to the high biological activities~~ topsoil due to high biological activity in warm months (Fig.8B). ~~For the competition of~~ With respect to competition for inorganic N, plants ~~outcompete~~ outcompeted microbes along the ~~whole~~ entire soil profile and ~~through the whole seasons, especially~~ throughout the year, particularly in summer when microbes assimilate N mainly from DOM (Fig.6c and d).

Turning off the model~~feature of the~~'s feature for nutrient acquisition competition, i.e. ~~ECA-Off scenario, leads to a noticeably~~ ECA-off scenario, led to a notably lower microbial biomass and Po-to-Pi ratio in the ~~top soil~~ topsoil (Fig.3). This is caused by ~~the~~ concurrent changes in ~~the inorganic P uptake of~~ microbes and plant ~~, especially in the top~~ inorganic P uptake, particularly in the topsoil layer where plants take up more inorganic P than ~~the Base Scenario~~ in the base scenario (Fig.6) due to ~~less competition from microbes. We also observe different~~ reduced competition with microbes. Moreover, there were differences in spatial and temporal ~~variation of fluxes in the ECA-Off scenario from~~ variations in uptake and mineralisation fluxes between the ECA-off scenario and the other two scenarios. For ~~example~~instance, the seasonal variation ~~of fluxes is~~ in fluxes was notably lower in the ~~ECA-Off scenario. The decrease of P flux rates~~ ECA-off scenario. Decrease in P flux rate with soil depth ~~seems less strong in the ECA-Off~~ may be weaker in the ECA-off scenario, but ~~the decrease of~~ decrease in net N mineralisation with ~~depth is more significant~~ soil depth is marginally stronger (Fig.5). This difference is ~~due to the fact that the~~ because that geophysical processes, such as adsorption and absorption, play ~~a much more important role~~ more crucial roles in the soil P cycle than in the N cycle and ~~they have a quite~~ that these show rather different seasonal and vertical ~~pattern~~ patterns from the biochemical processes, such as mineralisation.

The modelled enzyme allocation for depolymerisation ~~process~~ is presented in Fig.5. ~~In the figure, we compare the actual~~ We compared the enzyme allocation curve of polymeric litter (Enz^{poly}_{frac} in Eq.S17) with three potential allocation curves (α^{X}_{poly} where X stands for C, N, and P, in Eq.S15), which represent ~~the cases when microbes only want to maximize~~ cases in which microbes only maximise C, N ~~,~~ or P release from depolymerisation. ~~The~~ All modelled fractions of ~~actual~~ enzyme allocation to polymeric litter ~~are all~~ were well below 50% for the whole soil profile, indicating that polymeric litter is ~~the~~ less preferred than microbial residues for depolymerisation in the soil, particularly in ~~the~~ very deep soil layers where no roots are ~~presented~~ present and microbes would thus only produce enzyme to depolymerise microbial residues because the content of residue is much higher than that of polymeric litter. The simulated curve of ~~actual~~ allocation overlaps with the curve of potential allocation to ~~maximize~~ maximise P release, indicating that ~~the depolymerisation process~~ depolymerisation is solely driven by ~~the~~ P demand. This ~~indication~~ explains why microbial residues are preferred over polymeric litter ~~,~~ since the C:P ratio of microbial residues is much ~~higher~~ lower than that of ~~the~~ polymeric litter (data not shown). Despite ~~the very~~ rather different enzyme allocation fractions shown in Fig.5, ~~most~~ majority of the modelled stocks and fluxes ~~are~~ were not significantly influenced when ~~the enzyme allocation is~~ enzyme allocation was turned off (Fig.3 and 5). More profound differences ~~are seen in the SOC composition and the radiocarbon profile that there are~~ were observed in the composition and radiocarbon profile of SOC; there was less litter and more SOC in the ~~SEAM-Off~~ SEAM-off scenario than in the ~~Base Scenario~~base scenario, resulting a systematic difference in the radiocarbon ~~profile~~profiles between the two scenarios (Fig.4).

3.4 Model sensitivity and uncertainties

The ~~inner-quartile range of the~~ interquartile range of outputs (Fig.10) from ~~the model sensitivity study reveals that all the outputs are well centered~~ model sensitivity analysis revealed that all outputs were well centred around the results of the parameterisation of the ~~Base Scenario~~ base scenario (Tab.S2), except microbial inorganic N uptake and N losses. In general, the soil stocks ~~are~~ were more stable than the microbial pools and biogeochemical fluxes~~, whereas the mineralisation of N is surprisingly resistant and the microbial uptake of inorganic N is~~ . N mineralisation was surprisingly insensitive while microbial inorganic N uptake was very sensitive to ~~the parameter changes. The mineralisation of N in JSM is~~ parameterisation. N mineralisation in JSM was mainly driven by the C:N ratio of ~~the~~ DOM, which ~~is quite~~ remains rather stable due to the similar C:N ratios of plant litter, microbes, and microbial residues. The very sensitive response of microbial ~~uptake of inorganic N is because microbes have~~ inorganic N uptake was attributed to the high affinity (low $K_{m,mic}$ value) ~~transporters for N uptake (Kuzyakov and Xu, 2013) and is sensitive to the concentration change of~~ N uptake transporters of microbes

(Kuzyakov and Xu, 2013) and their sensitivity to changes in NH$_4$ ~~. The relative partial correlation coefficient (RPCC)~~ concentration. The RPCC of parameters with outputs (Tab.2) also ~~demonstrates~~ demonstrated that the C and N ~~content in SOM and the C , N fluxes respond more to the changes of~~ contents of SOM as well as the C and N fluxes were more sensitive to changes in C processes, ~~i.e. depolymerisation, OM sorption ,~~ such as depolymerisation, organic matter sorption and litter partitioning, while the microbial dynamics and the P fluxes ~~are more prone to the changes of~~ were more sensitive to changes in microbial and nutrient processes, such as maximum biomineralisation rate ($v_{max,biomin}$) and ~~recycling of P~~ P recycling during microbial decay ($\eta^{P}_{res\rightarrow dom}$). Overall, most of the selected outputs ~~are~~ were strongly influenced by ~~the~~ microbial stoichiometry. The five most influencing parameters in JSM ~~are~~ were microbial C:N ratio ($\chi^{C:N}_{mic}$), microbial N:P ratio ($\chi^{N:P}_{mic}$), microbial mortality rate (τ_{mic}), ~~fraction of~~ soluble litter C fraction transformed into DOM ($\eta_{C,sol\rightarrow dom}$), and ~~fraction of P~~ P fraction recycled from res to dom during microbial decay ($\eta^{P}_{res\rightarrow dom}$).

4 ~~Discussions~~Discussion

4.1 Features of nutrient cycling

Soil stoichiometry

~~The JSM is able to~~ Following calibration, JSM could reproduce the main soil stocks of C, N ~~, and P, microbial biomass ,~~ and P; microbial biomass and soil bulk density ~~,~~ as well as their vertical patterns along the soil profile in a ~~German beech forest site~~beech forest stand in Germany. The observed SOM C:N ratio (19.5) and C:P ratio (348) in the first model ~~layer, O-A horizon, fit~~ layer—the O–A horizon—fit well within the ranges of ~~the~~ reported soil stoichiometry of temperate broadleaf ~~forest~~ forests (Xu et al., 2013), and there ~~is~~ was a much stronger decreasing trend of C:P ratio than C:N ratio ~~as soil depthincreases~~with increase in soil depth, indicating that ~~the~~ organic P in SOM is ~~"decoupled" from the CN~~ ‘decoupled’ from the C and N cycles (Yang and Post, 2011; Tipping et al., 2016).

This decoupling ~~effect of~~ of the soil P cycle is represented by ~~the biomineralisation process in TBMs, but~~ biomineralisation in TBMs; however, the vertical decoupling of C:N:P stoichiometry ~~was~~ is poorly reproduced (Fig.S6) even when ~~the~~ microbial biomass is explicitly represented (Yu et al., 2018). Our study ~~indicates~~ indicated that the decrease ~~of~~ in C:N ratio is mainly due to ~~the SOC composition shift~~ a shift in SOC composition with soil depth (Fig.4), ~~that said the fraction of~~ whereby fraction of the nutrient-poor litter component decreases and ~~the fraction of~~ that the nutrient-rich MOC component increases. Slight overestimation of the modelled soil C:N ratio in the first layer (Fig.3) is probably due to the higher C:N ratio (52) of leaf litter inputs than the observed one (41.7).

However, ~~for the decrease of~~ with respect to the decrease in C:P ratio, the model simulations ~~indicate~~ indicated that the change ~~of~~ in microbial nutrient recycling scheme with depth might ~~play a bigger role than~~ be associated with shift in the SOC component~~shift~~. To account for ~~the~~ different stoichiometry of cell walls and plasma of microbes in JSM, we ~~introduce~~ introduced the microbial nutrient recycling parameter ($\eta^{X}_{res\rightarrow dom}$, X for N or P) that ~~assigns~~ partitions microbial residues with ~~a higher~~ lower C:N:P ratio ~~than DOM when microbes decay. Due to the fact that~~ according to P stoichiometry, that is, a higher nutrient content is allocated to DOM, while the residual pool receives the remaining part with a lower nutrient content. Since

JSM currently does not distinguish among microbial guilds, the microbial nutrient recycling ~~parameter also mimics~~ parameters also mimic different stoichiometry of microbial guilds, such as bacteria and fungi. ~~We find that the~~ The model only adequately ~~reproduces~~ reproduced the vertical SOM C:P ratio profile when ~~we decrease~~ the microbial P recycling parameter ~~with depth, which results in a decreasing~~ decrease with increasing depth, resulting in a decreased C:P ratio with increasing soil depth. Such a shift in the microbial P recycling ~~parameter indicates the microbial community changes from a~~ parameters indicates changes in microbial communities from nutrient-poor ~~fungi dominance~~ fungi-dominated to a nutrient-rich ~~bacteria dominance with~~ bacteria-dominated one with increasing depth, which ~~is~~ has also been evidenced by Rousk and Frey (2015)~~, and our model suggests~~ . Our model suggests that this community shift mainly regulates ~~the~~ decrease in SOM C:P ratio ~~decrease in~~ at the study site.

N cycle vs. P cycle

~~The JSM has~~ JSM had already reached a quasi-equilibrium state at the end of the 200-year ~~simulations, where~~ simulation, when the respiration of C and plant uptake of N and P ~~are~~ were very close to the C, N, and P from ~~litter fall~~ litterfall and SOM accumulates slowly in the soil (Tab.1~~). The reason for not reaching real equilibrium might firstly be~~ , Fig.2). As the simulation time increased, the C and N cycles approached true equilibrium but the P cycle did not (Tab.1); this could be due to the lack of vegetation feedback, ~~and secondly the constant~~ or the constantly increasing occluded P pool and decreasing primary P pool that do not allow ~~a real~~ to reach true equilibrium in JSM~~, which is also the case for all the TBMs because the same~~ . Similar trend have been observed with all TBMs because they employ the structure of inorganic P cycle ~~from~~ described in Wang et al. (2010) is used. This ~~will lead to a stability problem especially~~ leads to a boundary issue, particularly in long-term simulations, and ~~needs proper investigationin future~~ warrants further investigation, particularly for the development of ~~soils~~soil profiles.

In JSM, ~~the~~ plant nutrient uptake is driven by ~~the root biomass , which is prescribed with~~ root biomass (prescribed by the QUINCY outputs~~,~~) and its uptake capacity ~~, which is taken from the published literature (Kuzyakov and Xu, 2013; Kavka and Polle, 2016) . The plant~~ (as reported in (Kuzyakov and Xu, 2013; Kavka and Polle, 2016)). Plant uptake is further influenced by ~~the microbial (and adsorption for P) competition but~~ microbial (P adsorption) competition, but it is not regulated by ~~the~~ plant demand due to the absence of vegetation ~~process. The fact that the~~ processes. The simulated plant N and P ~~uptake at~~ uptakes at the quasi-equilibrium state ~~are~~ were very close to the N and P inputs from the litterfall (Tab.1)~~indicates~~ , indicating that realistic root biomass and uptake capacity enable ~~simulating the~~ the simulation of nutrient uptake for plant~~growth. This conclusion~~ . This finding supports the recent change ~~of~~ in plant uptake simulation in TBMs from plant demand driven (Yang et al., 2014b) to trait (root biomass, uptake capacity, and inorganic nutrient pool) driven (Zaehle and Friend, 2010; Goll et al., 2017; Thum et al., 2019), which strengthens the interactions between soil nutrient availability and plant growth.

The simulated microbial uptake of inorganic P (238.0 $\mathrm{kgP/ha/yr}$) ~~is not only~~ was much higher than the plant inorganic P uptake (8.5 $\mathrm{kgP/ha/yr}$) ~~, but also much higher than the microbial uptake of inorganic N~~ and microbial inorganic N uptake (Fig.7). This difference ~~is~~ was strongly driven by the difference between ~~litter stoichiometry~~ litterfall and microbial stoichiometry. In JSM, ~~the~~ nutrient assimilation for microbial growth occurs at two steps~~,~~ . In the first one~~is the microbial DOM uptake in which~~ , a certain fraction of N ~~and~~ & P (mic_{nue} and mic_{pue}) ~~in the DOM are~~ from microbial DOM uptake is assimilated directly by microbes~~, and~~ ; in the second step~~microbes further take up the~~ , dissolved inorganic N ~~and P through microbial~~

~~N and~~ & P are further taken up by microbes through microbial inorganic N & P uptake to ~~fulfill~~ fulfil their stoichiometry. In the ~~Base Scenario~~base scenario, we used the measured microbial C:N:P ratio ~~of~~ at the study site (10.3:0.8:1), which largely differs from the litterfall C:N:P ratio (800:14.8:1), particularly in terms of the P content. Therefore, although the demand ~~of~~ for N and P for microbial growth ~~do~~ does not differ much, the assimilation of dissolved organic N is much higher than that of dissolved organic P, resulting in a much higher demand ~~of~~ for microbial P uptake than for N uptake from the inorganic pool and ~~a~~ very different seasonal ~~pattern of microbial uptake of~~ patterns of microbial inorganic N and P uptakes (Fig.6). This is well demonstrated in Fig.5 and Fig.7~~that the~~ ; net mineralisation, ~~which equals gross mineralisation minus microbial uptake of inorganic nutrients~~calculated by subtracting microbial inorganic nutrient uptake from gross mineralisation, is always positive for N and mostly negative for P, ~~especially~~ particularly in the warm season when microbial biomass is high. While ~~the mainity of the gross N mineralisation~~ majority of the mineralised N is taken up by ~~plant~~plants, only a minor fraction of ~~the gross P minerlisation is for plant uptake~~ mineralised P is taken up by them, and most of it, together with the ~~extra biomineralsation flux, are~~ additional biomineralised P, is taken up by microbes in the form of dissolved inorganic ~~phosphate~~P. This pattern implies that the ~~mobilization~~ mobilisation of soil N is driven by ~~the~~ plant demand and ~~the mobilization~~ that of soil P is driven by ~~the~~ microbial demand.

Microbial stoichiometry

Since ~~we use a very different~~ the microbial C:N:P ratio ~~(10.3:0.8:1, Lang et al., 2017) than~~ we used (10.3:0.8:1, Lang et al., 2017) was very different from the global average value (42:6:1, Xu et al., 2013), ~~extra model~~ additional modelling experiments were conducted with the global microbial stoichiometry to ~~see~~ examine the effects of ~~microbial C:N:P~~ this ratio (Fig.S1-4). The SOC ~~profile~~ and microbial C ~~profile are not significantly different~~ profiles did not differ significantly in the new scenarios, ~~but~~ although the N & P stocks and fluxes ~~are~~ were greatly influenced. ~~One~~ As a direct consequence of a change in microbial stoichiometry change~~is the resulted~~ , the resultant SOM C:N ~~ratio~~ and C:P ~~ratio become~~ ratios became lower and higher~~than the~~ , respectively, than values in the ~~Base Scenario~~base scenario. Moreover, the total demand for microbial N ~~is much higher than the Base Scenario~~ was much higher and the demand for microbial P ~~is much lower~~ was much lower than that in the base scenario, leading to a higher microbial ~~uptake of inorganic N~~ inorganic N uptake and lower microbial ~~uptake of inorganic P , which further imposes changes in the plant-microbe competition of inorganic N and P and~~ inorganic P uptake, which in turn alter the plant–microbe competition for inorganic N & P as well as the vertical and seasonal patterns of plant and microbial uptake of inorganic nutrients. Although the microbial P demand ~~is~~ was lower in the scenario with the global microbial stoichiometry than ~~the Base Scenario, it is still driving~~ in the base scenario, it still drove the soil P ~~mobilization~~mobilisation. However, ~~the N mobilization~~ N mobilisation in the new scenario ~~is no longer only plant-driven but driven by both microbes and plants~~was no longer exclusively plant driven and became both microbe and plant driven. This indicates that the microbial stoichiometry is ~~one~~ a key factor for soil nutrient processes and ~~plant-soil~~ plant–soil interactions in JSM.

In JSM, the choice of nutrient ~~mineralisation–immobilization~~ mineralisation–immobilisation pathways (Manzoni and Porporato, 2009) during microbial DOM uptake, i.e. the microbial nutrient use efficiencies in Eq.S13, ~~does~~ did not greatly change the total microbial nutrient assimilation but ~~impose a significant impact on~~ significantly impacted the partitioning between organic (microbial DOM uptake) and inorganic (microbial inorganic nutrient uptake) nutrient assimilation (Tab.2). This partitioning

~~will greatly alter~~ greatly alters the isotopic signals of ~~the~~ soil pools and is essential to understand ~~the~~ soil nutrient cycling and thus to ~~disentangle the soil effects from the~~ unravel soil effects based on vegetation signals (Craine et al., 2018)~~,~~ — something which is not possible ~~in~~ with the current TBMs due to ~~the~~ poorly defined and parameterised microbial nutrient use efficiencies (Manzoni and Porporato, 2009). It is possible to use JSM to predict realistic microbial nutrient use efficiencies with ~~constrains~~ constraints of tracer experiments ~~data, but needs to be properly investigated in future~~ by labelling different forms of dissolved nutrients. However, future detailed investigation is needed due to complications arising from other involved processes such as adsorption/desorption and nitrification/denitrification.

4.2 Key features and model limitations

We ~~apply~~ applied the ECA approach described by Tang and Riley (2013) to simulate ~~the competition for inorganic nutrients. Our model simulations generally indicate~~ inorganic nutrient competition. In general, our model simulations indicated that microbes take up ~~moreinorganic~~ more inorganic P than plants, which ~~agrees with the finding from~~ supports the findings of ^{33}P ~~addition~~ tracer experiments at two other beech forests in Germany (Spohn et al., 2018). However~~for N~~, our study ~~shows~~ showed that plants take up more inorganic N than microbes (Fig.7A and Fig.S1). This pattern seems to disagree with the findings of field studies of ^{15}N addition (e.g. Bloor et al., 2009; Dannenmann et al., 2016) ~~,~~ and a modelling study using the same approach to simulate competition (Zhu et al., 2017). The reason for this disagreement is that in JSM, we assumed ~~a~~ high microbial N use efficiency ~~of DOM and the main part~~ from DOM and majority of microbial N assimilation ~~is~~ was actually fulfilled by DOM uptake. ~~Plants therefore take up less~~ Therefore, plants take up more inorganic N than microbes. However, in ^{15}N ~~addition experiments and the~~ tracer experiments and a model study by Zhu et al. (2017), there ~~is~~ was no distinction between ~~the assimilation from the organic source and inorganic source, thusthe~~ assimilation from organic and inorganic sources; thus, microbes outcompete plants in the sense that the total N assimilated by microbes exceeds the total N taken up by ~~the~~ plant roots, which ~~is also ture in this study. One other uncertainty of the plant-microbe~~ was also true in our study. Another uncertainty related to the plant–microbe competition for inorganic N is the microbial stoichiometry we used in ~~the~~ parameterisation. As discussed in the previous section, ~~the change of~~ a change in microbial stoichiometry from the ~~field observed~~ observed field value to the global average value ~~can switch the system~~ resulted in a switch from microbes outcompeting ~~plant~~ plants for inorganic N to the opposite trend. Additionally, the choice of microbial nutrient use efficiencies ~~will not only affect~~ not only affected the microbial demand for inorganic nutrients ~~, but also affect~~ and the concentrations of inorganic N & P~~and thus~~, thereby influencing the potential uptake rates of microbes and roots.

We extended the enzyme allocation approach of the SEAM model (Wutzler et al., 2017) by including P dependence and vertical explicitness and by assuming a steady state of enzyme production. Due to the very small microbial C:P ratio used in ~~the~~ model parameterisation, our results ~~indicate that the depolymerisation process~~ indicated that depolymerisation is solely driven by P demand~~and thus~~; thus, microbial residues are the preferred substrate because they have a much lower C:P ratio than polymeric litter. ~~It~~ This is also supported by the ~~huge~~ massive P biomineralisation flux (Fig.7) ~~, which is~~ independent of depolymerisation and gross mineralisation, ~~and shows that the~~ indicating that microbial growth is strongly P limited. Even in the scenario using the global microbial stoichiometry, ~~the depolymerisation is~~ depolymerisation was still solely P driven, and P biomineralisation ~~supplies more than~~ fulfilled over half of the microbial P demand (Fig.S5). This result is partly supported by the global enzymatic activity data ~~that the~~ in which global ratios of specific C, N and P acquisition activities converged on 1:1:1 (Sinsabaugh et al., 2008), while the global microbial stoichiometry ~~is~~ was much higher, indicating that relatively more resources are allocated to acquire P than to acquire N and C. This result actually reveals a caveat in the current implementation of enzyme allocation in JSM ~~,~~ that the main process ~~to hydrolyze organic P , biomineralisation, is~~ via which organic P is hydrolysed, biomineralisation and the mobilisation of sorbed inorganic P due to root exudation are not included in the enzyme allocation calculation. It also explains ~~why the difference between Base Scenario and the enzyme allocation turned-off (SEAM-Off) scenariois very small~~the very small difference between the base scenario and the SEAM-off scenario.

~~The JSM shows the capacity to (re) produce the~~ JSM demonstrated a capacity to reproduce the vertical patterns of soil stocks (Fig.3) and to satisfactorily produce both vertical and seasonal patterns of ~~the soil stocks and biogeochemical fluxes~~ biogeochemical fluxes (Fig.5 and 6). While the seasonal patterns are primarily driven by the temperature response of the represented processes, the vertical patterns are shaped by the combined ~~effect of biochemical factors~~ effects of biochemical and geophysical factors represented in the model. As seen in Fig.3 and Fig.4, although ~~the total SOC decreases~~ total SOC decreased with soil depth, the microbial, litter ~~,~~ and MOC components showed very different patterns. Following the COMISSION model(Ahrens et al., In prep.), ~~in JSM we constrain~~ we constrained the capacity of organo-mineral association with ~~the~~ silt and clay ~~content~~ contents and soil bulk density ~~(BD)~~in JSM. In the organic layer and ~~top soil~~topsoil, the continuous litter input sustains a large microbial biomass and microbial residue pool~~, but~~ ; however, due to the very low ~~BD and its~~ bulk density and relatively low silt ~~and clay content, the~~ & clay contents, sorption is weak and ~~the~~ MOC content is very low. As ~~the~~ soil depth increases, ~~the BD and the~~ bulk density and silt & clay ~~content both increases so~~ contents increase such that microbial residues and DOM ~~are more strongly stabilized~~stabilised to a greater extent. This hinders ~~the microbial assimilation of DOM and the immobilization of nutrients, and leads~~ microbial DOM assimilation and nutrient immobilisation, leading to a strong decline in microbial biomass and an increase in MOC. As a consequence of the decreasing microbial biomass and ~~decreasing~~ litter inputs, ~~there is~~ much less microbial residue and DOM ~~to be sorbed~~ are available for sorption to the mineral soil, which ~~causes~~ explains the observed decrease ~~of~~ in total SOC in deep soil layers.

~~However, there are some caveats need to be mentioned about~~

Nonetheless, certain caveats of this study and ~~the JSM model. First, the effects of initial condition and the simulation length on the inorganic P cycle.As~~ JSM should be discussed. A main challenge is the different simulation times for different purposes. Our results indicated that in the upmost 30 cm of soil, SOM content stabilises after 150 years while in the upmost 1 m SOM stabilises after 1000 years of simulation (Fig.2), regardless of the initial SOM content (Fig.S2). However, with respect to the radiocarbon profile, as indicated by Ahrens et al. (2015), a very long simulation time (~~13,500 years) is required to reconcile~~ 13500 years) was required to match both the measured $\Delta^{14}C$ ~~profile and SOC profile~~ and SOC profiles at a nearby Norway spruce forest site. ~~But such~~ In our study, a 10000-year simulation time was still not sufficient to match the measured $\Delta^{14}C$ profile, indicating that an even longer simulation time is required. Although JSM is very stable in the long term in term of SOM development and storage, long-term simulation of soil P balance as a result of continuous weathering and occlusion remains a significant challenge (Fig.2, Tab.1). Such a long simulation time is unrealistic for ~~JSM~~ the P cycle due to the unknown ~~condition~~

~~of soil inorganic~~ conditions of the initial soil P pools and the un-equilibrated soil ~~inroganic~~ inorganic P cycling processes (Yang et al., 2014b). Although we ~~use~~ used a much shorter simulation length in this study, ~~there are still noticeable uncertainties due to the~~ noticeable uncertainties remain due to inorganic P cycling parameters ~~. Second, the model~~ (Tab.2). Additionally, the long simulation time required to match the radiocarbon profiles is also problematic for future coupling to TBMs because these models typically examine centennial time scales. A possible solution is to spin-up radiocarbon (>10000 years) independent of the plant–soil spin-up (1000 years), although this approach needs to be properly tested in the future.

Another caveat involves the model's representation of microbial adaptation schemes. In JSM~~we describe~~ , we describe enzyme allocation, which is one of the schemes of microbial adaptation proposed by Mooshammer et al. (2014)~~, enzyme allocation, but as mentioned above, the allocation to phosphatase~~ ; however, as discussed above, enzyme allocation to phosphatases might be essential and ~~needs~~ might thus need to be included. Additionally~~we also find that one other~~ , we found out that another adaptation scheme, the microbial community shift between ~~fungal~~ fungi and bacteria, is ~~very important to reproduce~~ crucial for reproducing the vertical pattern of soil stoichiometry. Although we ~~mimic such~~ mimicked such a shift in this study by calibration and parameterisation, a more mechanistic representation is necessary in the future for representing the acclimation of ~~SOM~~ microbial functional properties to climate and environmental changes. ~~Last but not least~~

Concerning the model's description of N dynamics, in the current version, N processes such as nitrification/denitrification and abiotic ammonium adsorption are not yet implemented. Although the simplified N dynamics will probably not alter the main findings of this study, it is important to investigate these in the future since plants often have a preference for ammonium uptake (Masclaux-Daubresse et al., 2010). Finally, given the good quality of the input data, ~~the JSM can~~ JSM could adequately reproduce the soil stocks and flux rates at the ~~chosen study site, but the capacity of extrapolation~~ selected study site; however, its capacity to extrapolate to other climate and soil conditions ~~need~~ needs to be further investigated in the future.

~~The JSM is overall~~ JSM is highly non-linear and sensitive to the parameters controlling microbial growth and decay (Tab.2). The C and N stocks in SOM ~~,~~ as well as ~~the~~ respiration and net N mineralisation ~~, are more~~ are highly sensitive to the parameter changes of depolymerisation and organo-mineral association, whereas the ~~stocks of~~ organic/inorganic P stocks and P mineralisation ~~respond more strongly~~ are highly sensitive to the microbial processes. ~~This supports~~These trends support, and also ~~explains~~explain, the finding of Yang and Post (2011) and Tipping et al. (2016) that the P cycle is decoupled from the C and N cycles in the soil. A more in-depth explanation for this difference, ~~as seen from~~ based on our results, is that the gross mineralisation associated with microbial DOM uptake ~~could~~ can supply microbes and ~~plant~~ plants with sufficient N but not P~~, thusa huge~~ ; thus, a large amount of P needs to be ~~mobilized, especially from SOM but also~~ mobilised, particularly from SOM as well as from mineral pools, to sustain microbial growth. Therefore, the microbial pools and soil P stocks/fluxes ~~show high sensitivities~~ are highly sensitive to microbial processes.

5 Summary and future directions

We presented the mathematical formulation ~~of~~ for a new SOC ~~model, JSM, which extends~~ model—JSM—which is an extension of the vertically explicit, ~~microbial based~~microbial-based, and organo-mineral ~~association enabled~~ association-enabled SOC model, COMISSION, ~~with~~ developed by introducing the N and P processes ~~using~~ via novel approaches such as ~~optimized~~ optimised enzyme allocation, nutrient acquisition competition, and ~~processes~~ process acclimation. The model was evaluated with the observed C, N ~~,~~ and P stocks of SOM~~,~~; soil inorganic P stock~~,~~; microbial C, N ~~,~~ and P contents ~~,~~ and soil bulk density ~~of the topmost 1m soil from a German beech forest and demonstrated that it is capable of capturing the sizes~~ in the topmost 1-m soil in a beech forest stand in Germany. JSM captured the extents and vertical patterns of ~~the~~ these observations. We further presented the main features of nutrient cycling under the new model structure and the sensitivities of model outputs to parameter changes~~. Both of them indicate~~; both indicated that the P cycle is largely decoupled from the ~~C-N cycle and has very strong interactions~~ C and N cycles and shows very close associations with microbial dynamics. ~~The evaluation~~ Evaluation of model experiments ~~points to the need of better representing interactions between P cycle and~~ underscores the need for improved representation of microbial dynamics in JSM, particularly their interactions with the P cycle.

~~The next step of the model evaluation is~~ To better represent microbial dynamics, we would need detailed and advanced understanding of microbial processes from experiments for implementation and testing in the model. For example, how will microbial C use efficiency change in response to changes in C sources (e.g. DOM or litter addition) and nutrient availability (e.g. N & P addition)? How starkly does the microbial community adjust its stoichiometry, change its element use efficiency or alter extracellular enzyme synthesis under dynamic external conditions?

Next steps for evaluation of JSM are to investigate the effects of P cycling on microbial dynamics and SOM cycling ~~more in depth~~ in greater detail by subjecting it to other beech forest sites in Germany along a soil P availability gradient ~~,~~ and to evaluate if the contrasting P cycling patterns proposed by Lang et al. (2017)~~as "acquiring system" and "recycling system" can be reproducedby the model. Such~~ —‘acquiring system’ and ‘recycling system’—can be reproduced. Such a model evaluation is expected to identify the key/missing processes of the model to reproduce the contrasting P cycling schemes ~~, and how these processes influence the~~ and to assess their effects on the SOM turnover/stability~~of SOM~~.

JSM ~~is~~ was developed under the framework of the new biosphere model ~~,~~QUINCY, and the future plan is to apply this model coupled with the vegetation component of the QUINCY model described by Thum et al. (2019), which will ~~allow us to have~~ offer an alternative to better represent the interactions between root growth/activity and SOM turnover and stabilisation in ~~terrestrial biosphere models~~TBMs.

Code availability. JSM is developed using the framework of the QUINCY model and is licensed under GNU GPL version 3. The scientific code of JSM requires software from the MPI-ESM environment, which is subject to the MPI-M-Software-License-Agreement in its most recent form (http://www.mpimet.mpg.de/en/science/models/license). The source code is available online (https://git.bgc-jena.mpg.de/quincy/quincy-model-release, branch "jsm/release01"; doi:10.17871/quincy-model-2019), but access is restricted to registered users. Readers interested in running the model should request a username and password from the corresponding authors or via the git-repository. Model users are strongly encouraged to follow the fair-use policy stated at https://www.bgc-jena.mpg.de/bgi/index.php/Projects/QUINCYModel.

Author contributions. SZ and MS conceived the model. LY and SZ developed the model. MS measured the ^{14}C data. All authors contributed to the interpretation of the results and writing of the manuscript.

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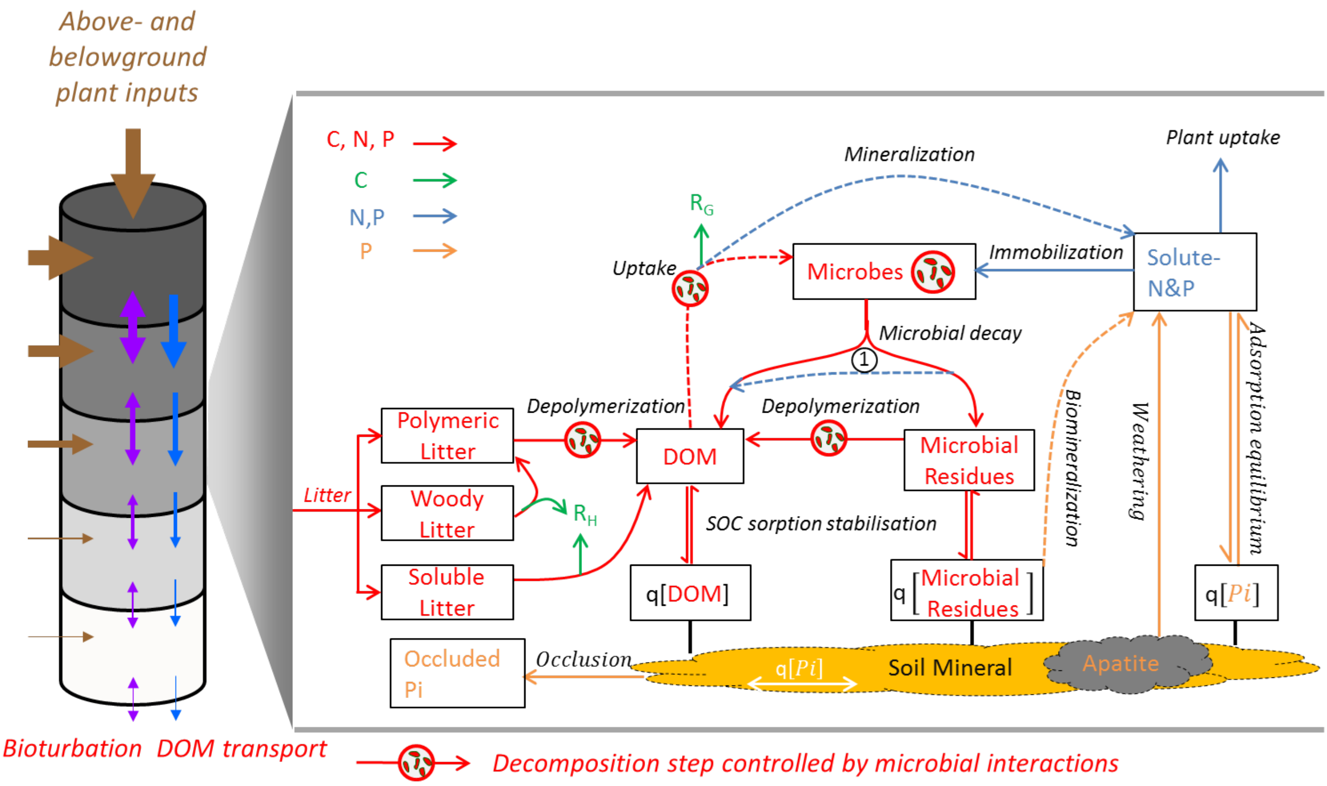


Figure 1. Theoretical representation of Jena Soil Model (JSM) structure. The vertical soil profile (~~10m~~9.5 m) is split into 15 soil layers~~,~~; above-ground litter is added on top of the soil profile~~,~~; root litter enters into each soil layer according to the root distribution. Bioturbation and DOM transport translocate SOM between soil layers. In each soil layer, boxes refer to pools and lines refer to processes, in which red lines: biogeochemical fluxes ~~with~~ of C, N and P; green lines: respiration fluxes, R_H for heterotrophic respiration and R_G for microbial growth respiration; blue lines: fluxes ~~with~~ of N and P; orange lines: fluxes ~~with~~ of only P; dashed lines: biogeochemical processes that involves stoichiometry change between the sourcing and sinking pools. ①: microbial nutrient recycle from residue to DOM during decay; $q[X]$: mineral-associated form (adsorbed to soil mineral surface ~~,~~ or absorbed into soil mineral matrix) of X, which can be DOM, microbial residues ~~,~~ or inorganic phosphate (Pi).

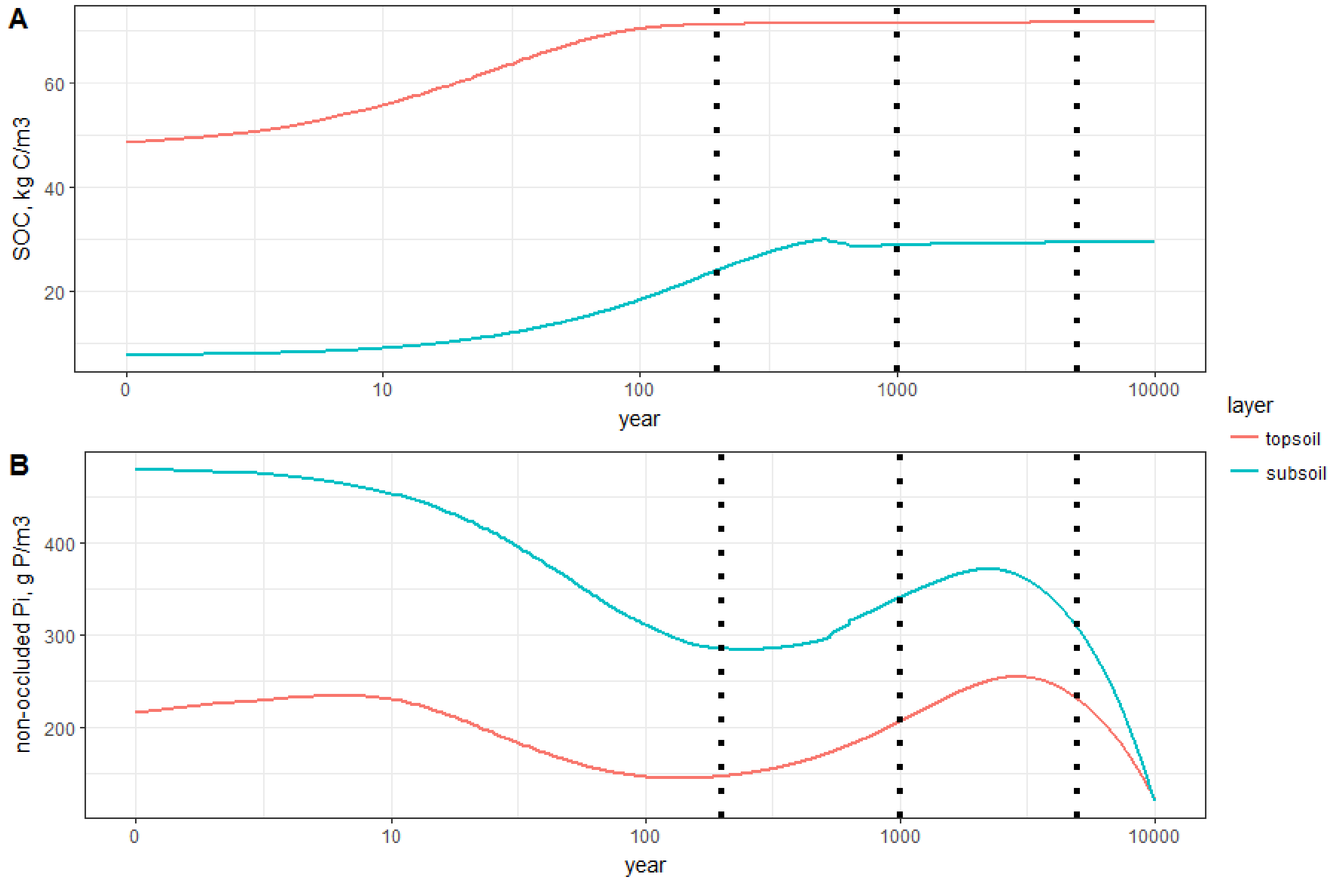


Figure 2. Simulated dynamics of (A) SOC and (B) non-occluded inorganic P contents in topsoil (30 cm) and subsoil (30–100 cm) for 10000 years. The three vertical dashed lines represent 200, 1000 and 5000 years, respectively.

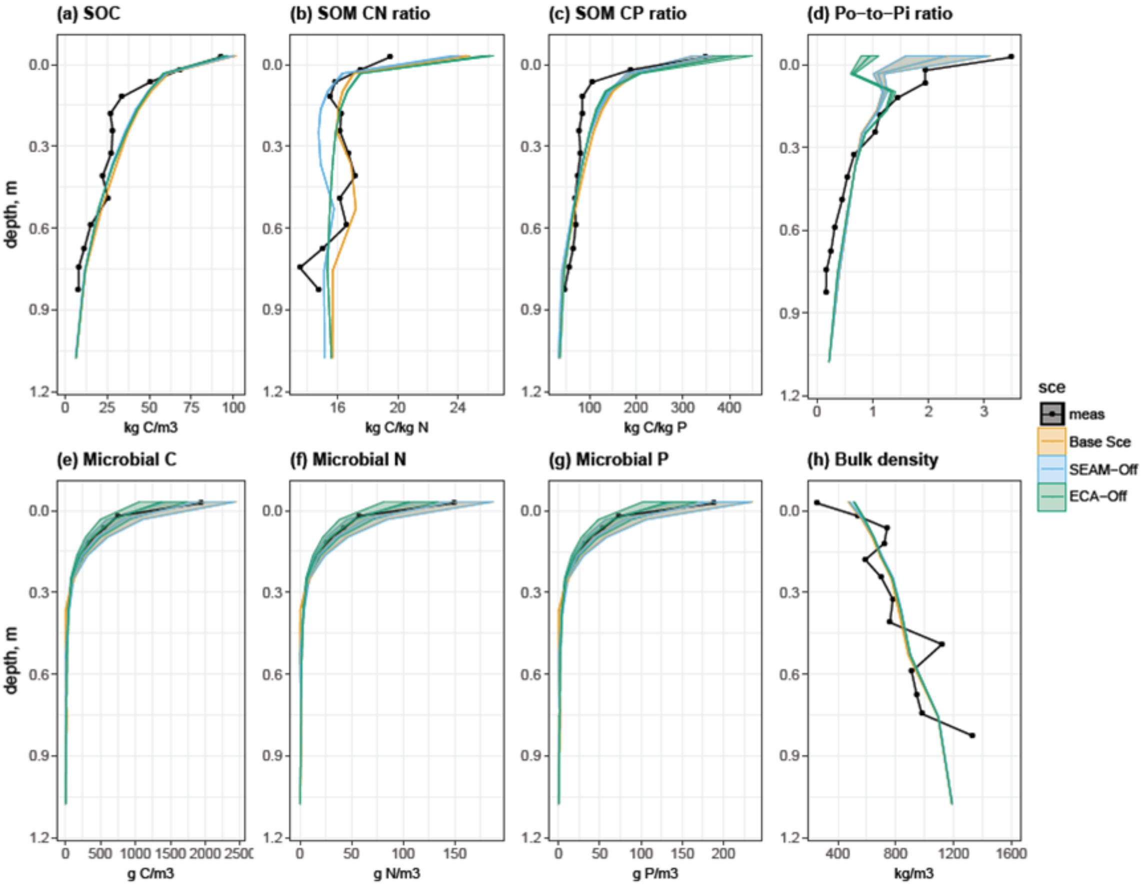


Figure 3. Simulated and observed (a) SOC content, (b) C:N ~~ration~~ ratio in SOM, (c) C:P ratio in SOM, (d) organic ~~P to inorganic~~ P-to-inorganic P ratio in soil, (e) microbial C ~~, N, and P~~ content, (~~(e~~f) ~~to~~ microbial N content, (g) ~~),~~ microbial P content and (h) soil bulk density at the study site up to ~~1m~~ 1-m soil depth. Black lines and dots: observations; ~~Color~~ Coloured lines and shades: simulated mean values and ranges of standard deviation by different model experiments in Sect.2.3. ~~The microbial~~ Microbial C, N ~~,~~ and P ~~are~~ values were only measured in the top ~~30cm~~ 30 cm of soil. Simulated means and standard deviations ~~are~~ were calculated using data ~~of~~ from the last 10 years of model experiments.

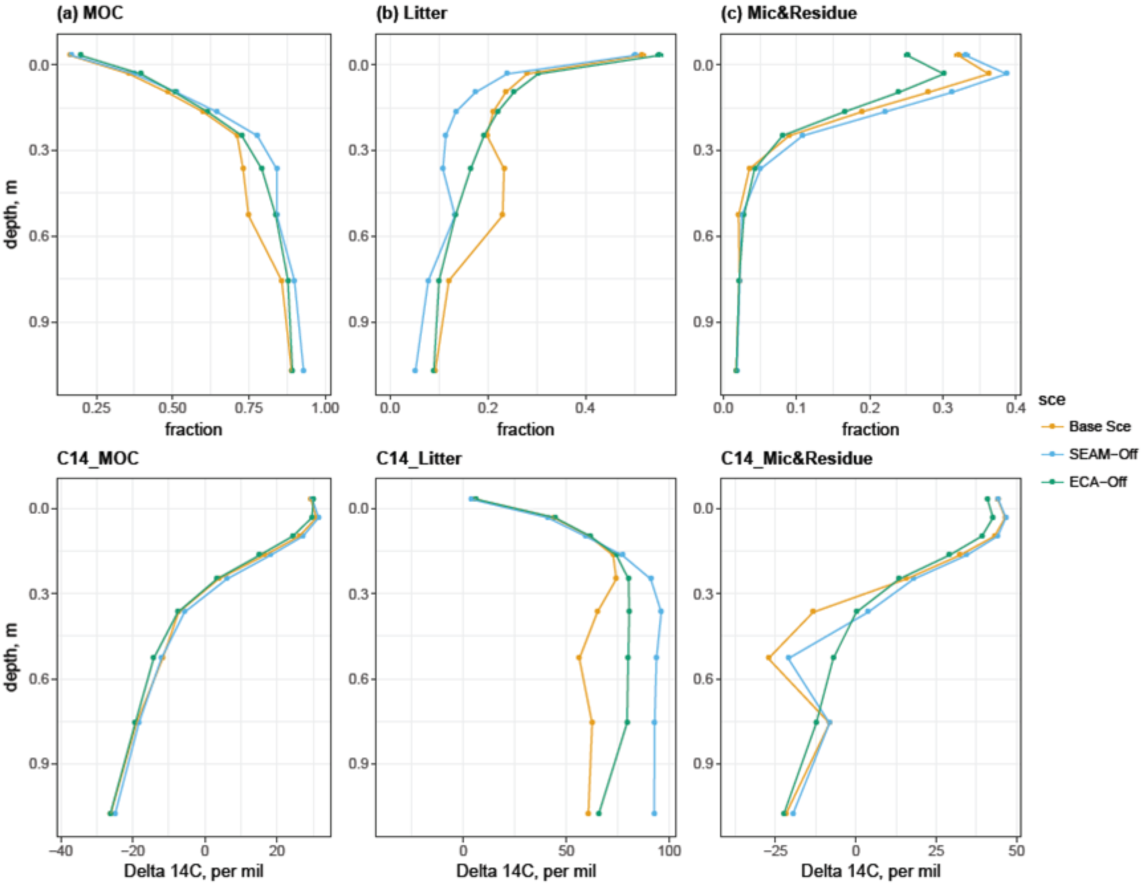


Figure 4. Simulated SOC fractions (upper panels) and their respective radiocarbon profiles (bottom panels) at 1-m soil depth. Column (a): mineral-associated C (MOC), including adsorbed DOM and adsorbed microbial residue; Column (b): litter, including woody, polymeric and soluble litter; Column (c): live and dead microbes. Data points are derived using data from the last 10 years of the model experiments. All model experiments used 200-year simulations and were not validated against the measured $\Delta^{14}C$.

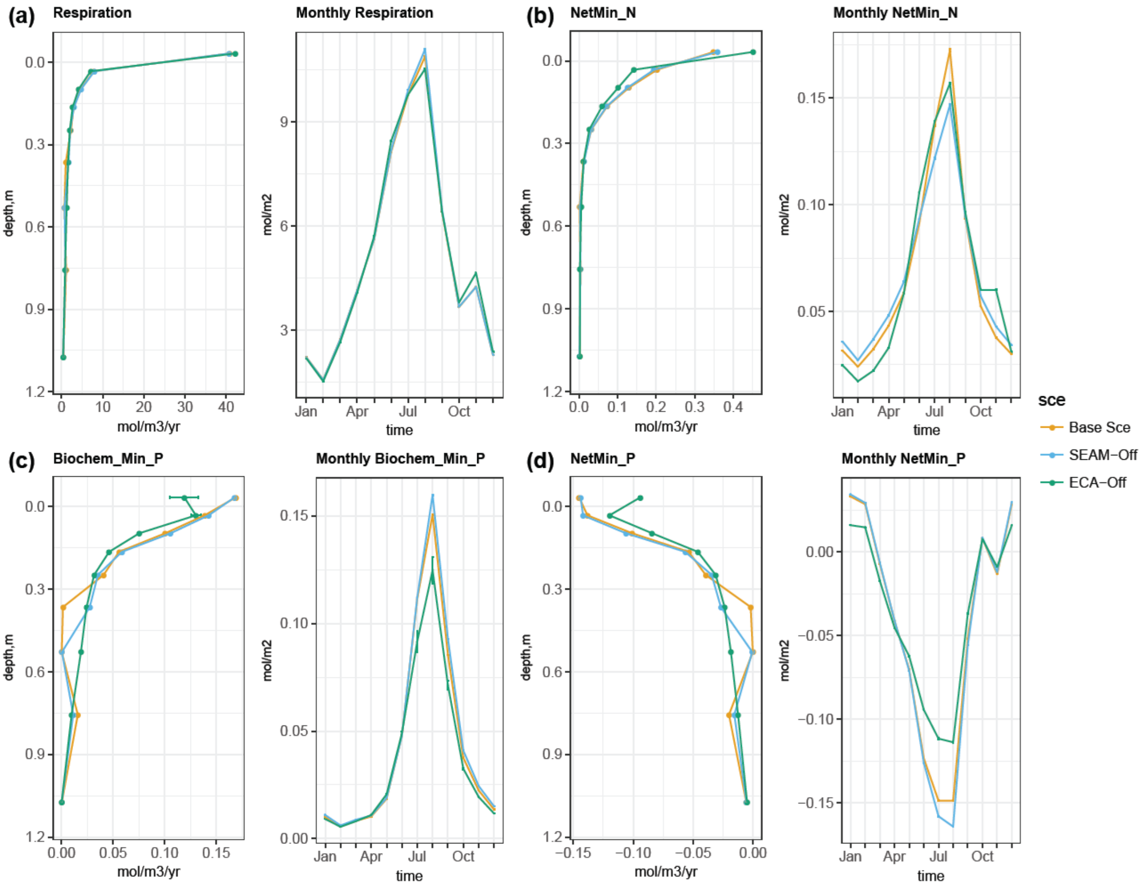


Figure 5. Simulated seasonal and vertical distribution of (a) respiration, (b) net N mineralisation, (c) biochemical P mineralisation ~~,~~ and (d) net P mineralisation at the study site ~~for the whole~~ at 1-m soil ~~profile~~depth. Points represent the mean values and error bars represent the standard deviations, both calculated using data ~~of~~ from the last 10 years ~~from the~~ of model experiments.

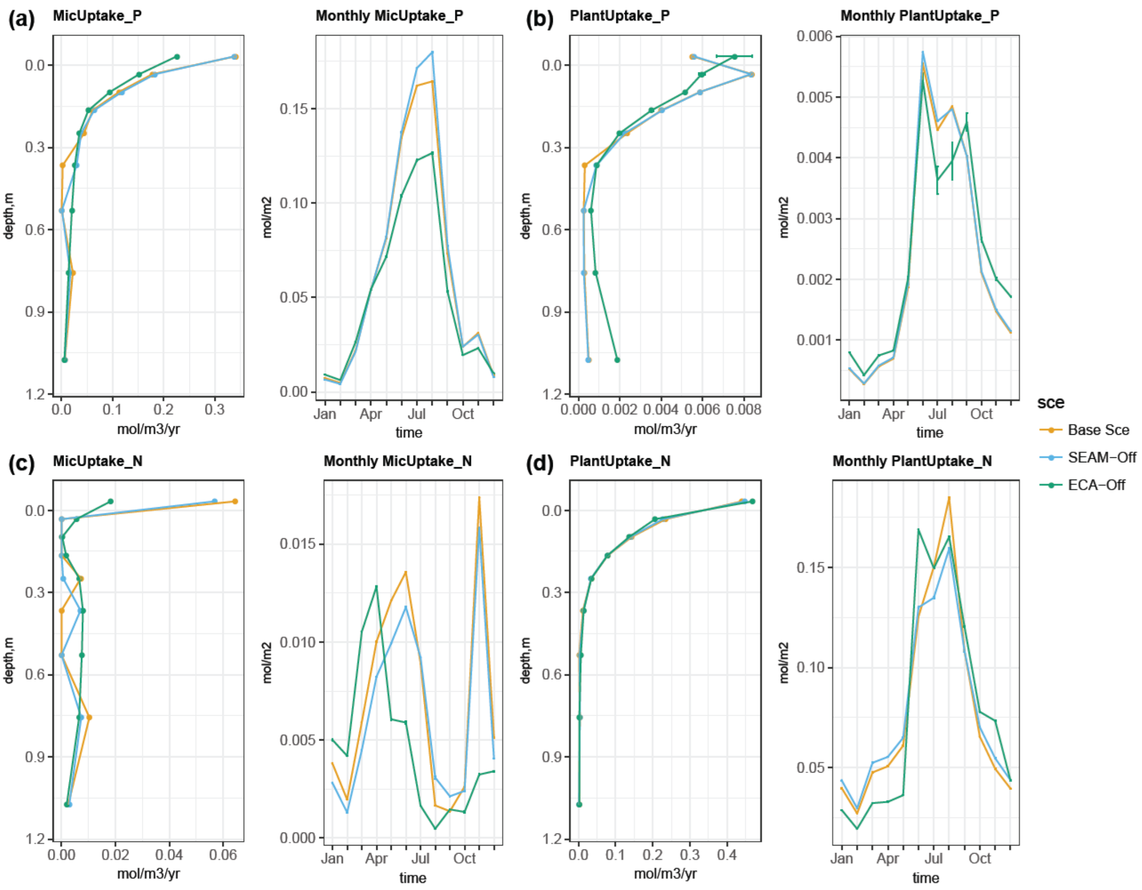


Figure 6. Simulated seasonal and vertical distribution of (a) microbial inorganic P uptake, (b) plant P uptake, (c) microbial inorganic N uptake, and (d) plant N uptake at the study site ~~for the whole~~ at 1-m soil ~~profile~~depth. Points represent the mean values and error bars represent the standard deviations, both calculated using data ~~of~~ from the last 10 years of model experiments.

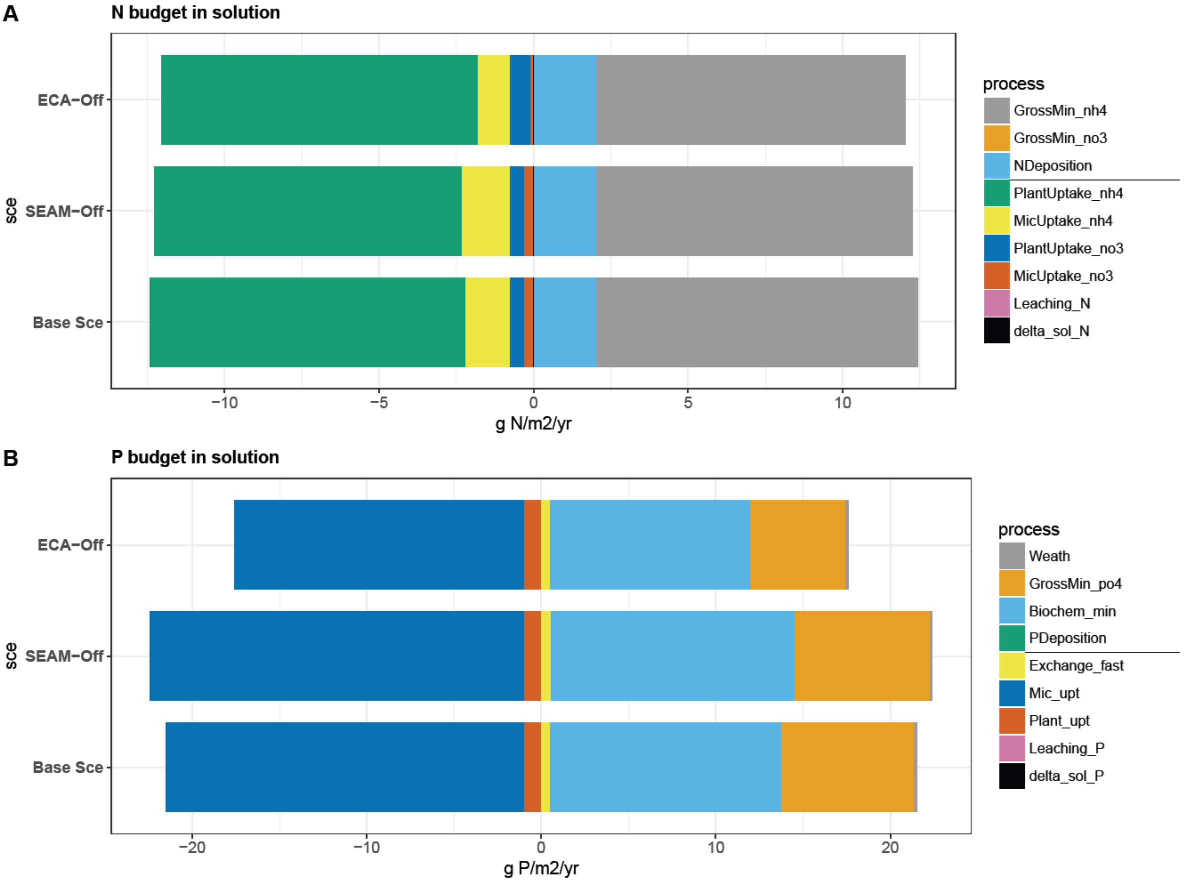


Figure 7. Simulated yearly budget of (A) N and (B) P in soil solutions. In panel A, sourcing fluxes of N are presented in the order of gross mineralisation of $\mathrm{NH_4}$ and $\mathrm{NO_3}$, N deposition (In the bar plot: from right to the zero point; in the legend: from the top to the separation line); sinking fluxes of N are presented in the order of plant and microbial uptakes of $\mathrm{NH_4}$, plant and microbial uptakes of $\mathrm{NO_3}$, N leaching (both inorganic and organic) and changes in soluble N content ($delta\_sol\_N$) (In the bar plot: from left to the zero point; in the legend: from the separation line to the bottom). In panel B, sourcing fluxes of P include weathering, gross mineralisation of $\mathrm{PO_4}$, biochemical mineralisation of $\mathrm{PO_4}$ and P deposition; sinking fluxes of P includes adsorption ($Exchange\_fast$), microbial and plant uptakes, P leaching (both inorganic and organic) and changes in soluble P content ($delta\_sol\_P$) (The order of presented processes follows the same rule as N). The budgets are calculated using data from the full simulation (200 years) of the model experiments.

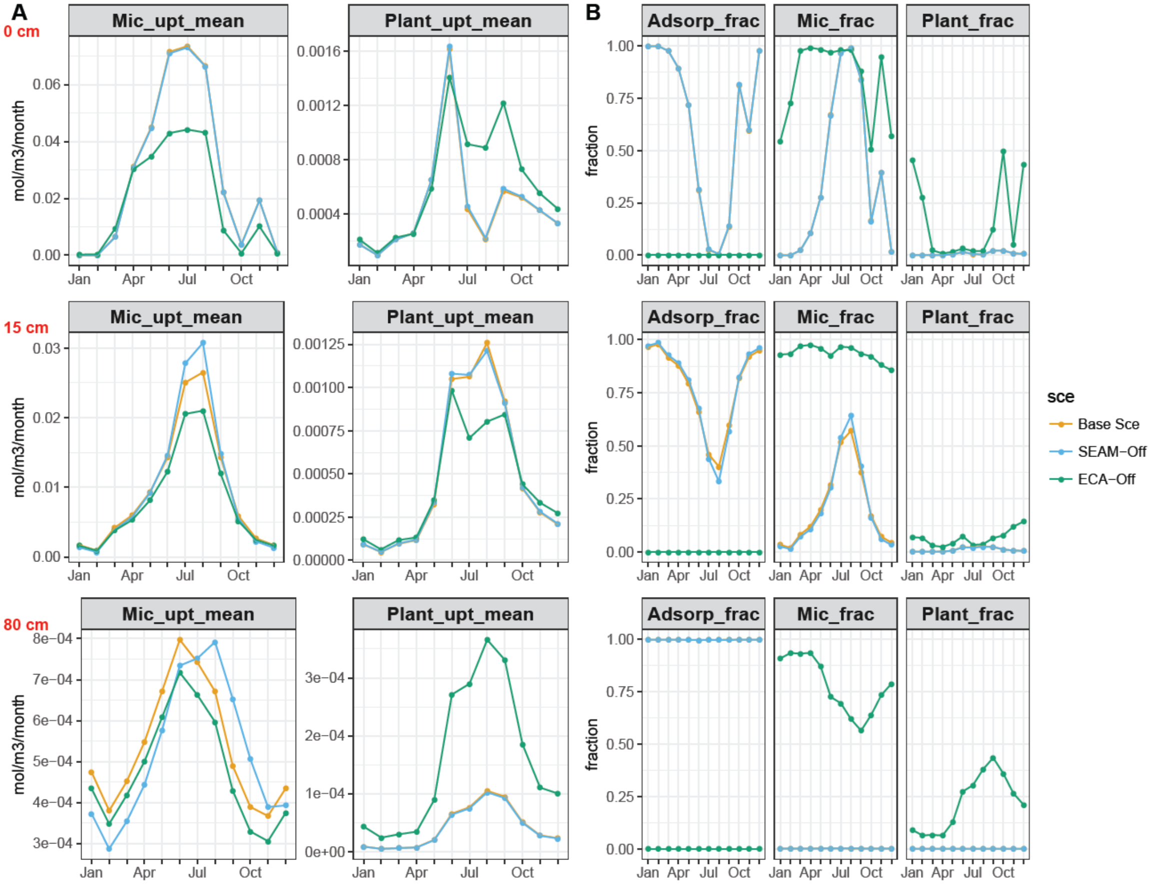
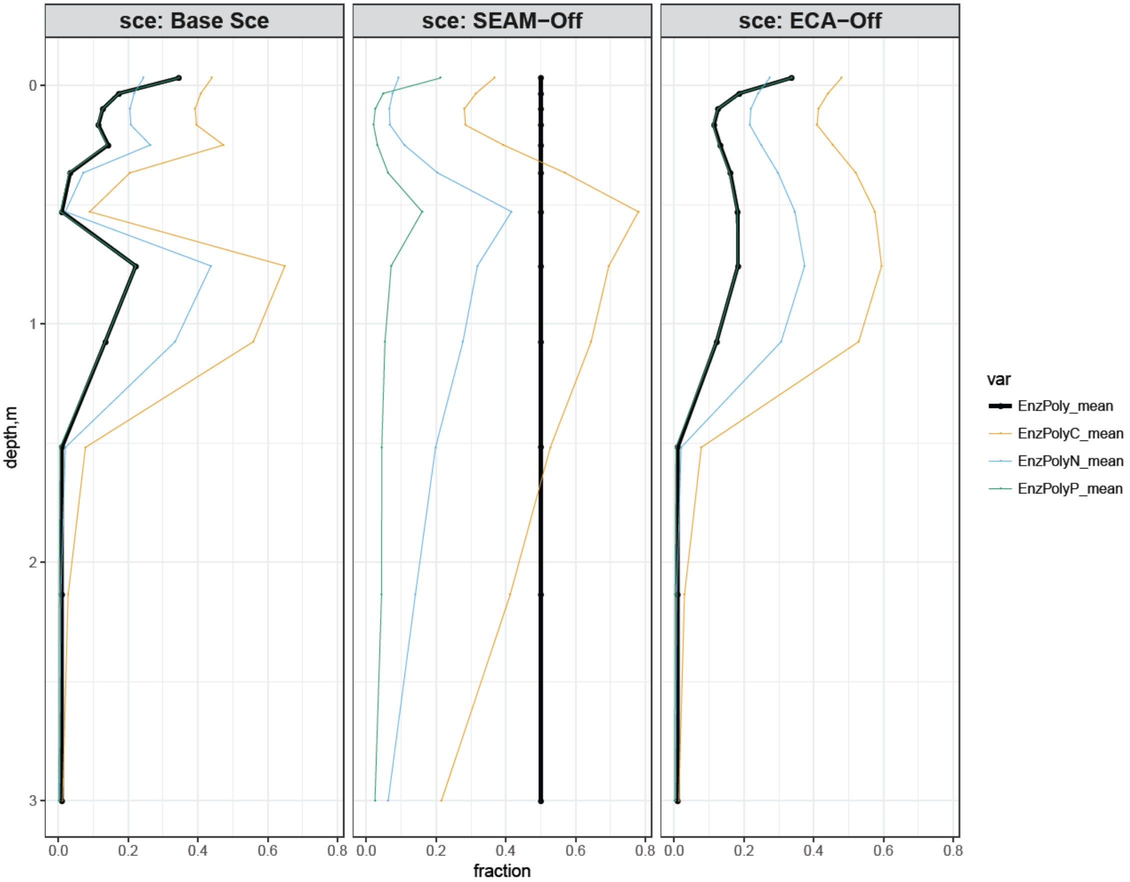


Figure 8. Simulated (A) microbial ~~P uptake~~ and plant P uptake rates and (B) relative competitiveness (in fractions) of P adsorption, microbial P uptake ~~,~~ and plant P uptake at ~~0cm depth~~ depths of 0 (~~O-A~~ O–A horizon, upper ~~panel~~panels), ~~15cm depth~~ 15 (~~A-B~~ A–B horizon, middle ~~panel~~panels), and ~~80cm depth~~ 80 cm (~~B-C~~ B–C horizon, bottom ~~panel~~panels). In panel (A), monthly mean values at different depths are presented ~~through the~~ throughout whole year; in panel (B), relative competitiveness is calculated as the fraction of the individual rate to the sum of all three rates (P adsorption rate, microbial P uptake ~~,~~ and plant P uptake). All data points are derived from data from the last 10 years ~~' data~~ of ~~the~~ model experiments.



~~Simulated SOC fractions (upper panel) and their respective radiocarbon profiles (bottom panel) for up to 1m soil depth. Column (a): mineral-associated carbon (MOC), including adsorbed DOM and adsorbed microbial residue; Column (b): litter, including woody, polymeric and soluble litter; Column (c): live and dead microbes. Data points are derived~~ from the last 10 years ~~' data of the model experiments. All model experiments are only 200 years and not validated against the measured $\Delta^{14}C$.~~

~~Simulated yearly budget of (A) nitrogen and (B) phosphorus in soil solution. In panel A, sourcing fluxes of N includes gross mineralisation of and , N deposition; sinking fluxes of N includes plant and microbial uptake of , plant and microbial uptake of , N leaching (both inorganic and organic), and size change of soluble N (*delta_sol_N*). In panel B, sourcing fluxes of P includes weathering, gross mineralisation of , biochemical mineralisation~~ of ~~, P deposition; sinking fluxes of P includes adsorption (*Exchange_fast*), microbial and plant uptake, P leaching (both inorganic and organic), and size change of soluble P (*delta_sol_P*). The budget are calculated using data of the full simulation (200 years) from the~~ model experiments.

~~Simulated SOC fractions (upper panel) and their respective radiocarbon profiles (bottom panel) for up to 1m soil depth. Column (a): mineral-associated carbon (MOC), including adsorbed DOM and adsorbed microbial residue; Column (b): litter, including woody, polymeric and soluble litter; Column (c): live and dead microbes. Data points are derived~~ from the last 10 years ~~' data of the model experiments. All model experiments are only 200 years and not validated against the measured $\Delta^{14}C$.~~

~~Simulated yearly budget of (A) nitrogen and (B) phosphorus in soil solution. In panel A, sourcing fluxes of N includes gross mineralisation of and , N deposition; sinking fluxes of~~ ~~includes plant and microbial uptake of , plant and microbial uptake of , N leaching (both inorganic and organic), and size change of soluble N (*delta_sol_N*). In panel B, sourcing fluxes of P includes weathering, gross mineralisation of , biochemical mineralisation~~ of ~~, P deposition; sinking fluxes of P includes~~

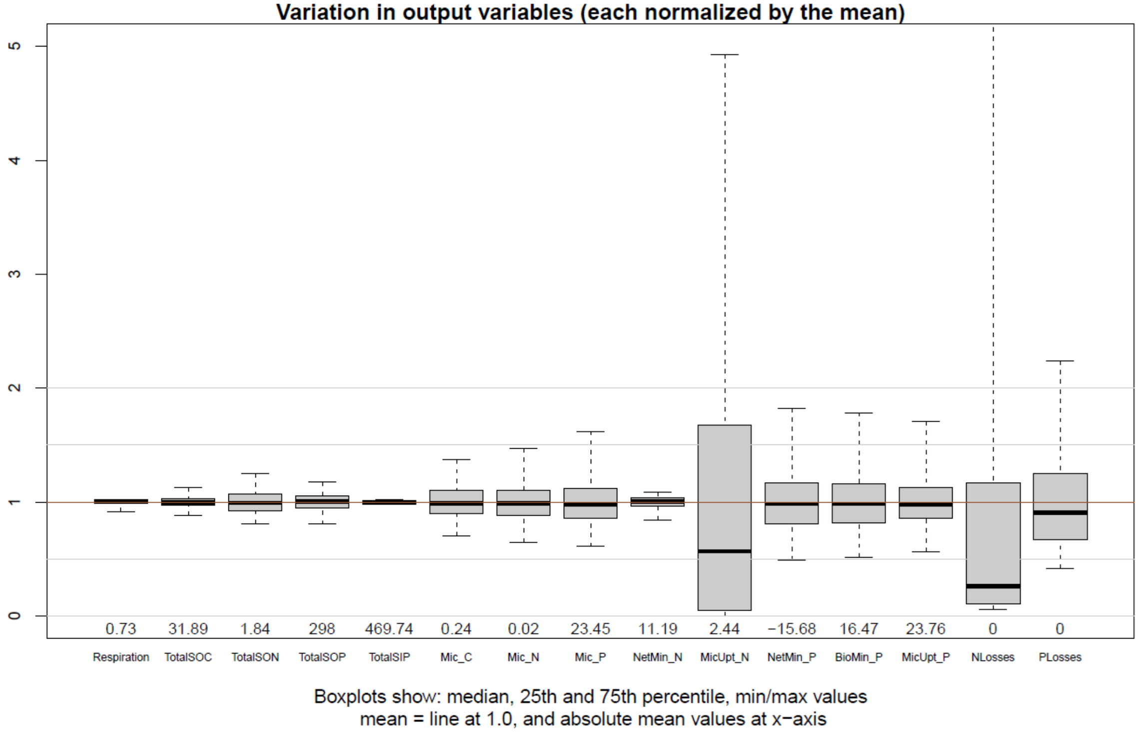


Figure 10. ~~Normalized~~ Normalised output variations in the LHS sensitivity analysis. The selected output variables include respiration~~,~~; total soil organic C, N ~~,~~and P~~,~~; microbial C, N ~~,~~and P~~,~~; net N mineralisation~~,~~; microbial N uptake~~,~~; net P mineralisation~~,~~; biomineralisation of P~~,~~; microbial P uptake ~~, the losses of~~ and N and P losses. All the calculations are ~~done~~ performed for the topmost ~~one meter~~ 1 m of soil based on ~~the~~ data from the last 10 years of ~~the~~ 1000 LHS simulations.

Table 1. The annual soil C, N and P fluxes of model experiments at the study site. Positive values infer accumulation in the soil, and negative values infer loss from the soil. The values are the accumulated sum of the whole soil profile, calculated based on ~~the~~ data from the last 10 years of ~~the~~ model experiments.

Variable	Unit	Base Scenario	SEAM-Off	ECA-Off	1000y	5000y	10000y
Biogeochemical fluxes							
C litterfall	gC m^{-2} yr	788.0	788.0	788.0	788.0	788.0	788.0
Respiration	gC m^{-2} yr	-741.0	-746.2	-746.2	-778.0	-787.4	-788.0
ΔSOC	gC m^{-2} yr	47.0	41.8	41.8	10.1	0.7	0.04
N litterfall	gN m^{-2} yr	14.52	14.52	14.52	14.52	14.52	14.52
N deposition	gN m^{-2} yr	2.04	2.04	2.04	2.04	2.04	2.04
Plant N uptake	gN m^{-2} yr	-13.29	-13.26	-13.28	15.67	16.01	16.01
N leaching	gN m^{-2} yr	-0.01	-0.01	-0.01	0.08	0.49	0.54
ΔSON	gN m^{-2} yr	3.25	3.29	3.26	0.80	0.06	0.002
P litterfall	mgP m^{-2} yr	980.4	980.4	980.4	980.4	980.4	980.4
P deposition	mgP m^{-2} yr	4.2	4.2	4.2	4.2	4.2	4.2
P weathering	mgP m^{-2} yr	155.6	155.6	142.6	277.8	197.0	522.8
Plant P uptake	mgP m^{-2} yr	-852.0	-866.8	-886.9	-920.9	-959.5	-1134.6
P leaching	mgP m^{-2} yr	-0.3	-0.3	-1.7	-0.5	-1.7	-8.4
P desorption	mgP m^{-2} yr	-233.0	-243.8	-185.6	-58.3	157.4	345.7
ΔSOP	mgP m^{-2} yr	520.9	516.9	424.1	399.3	63.0	18.7

Table 2. The five most important parameters (Par) and their respective ~~RPCC~~ RPCCs for each output variable and the overall model importance (OVI). ~~The RPCC is~~ RPCCs were calculated for each output variable, and the overall importance of parameters ~~is~~ was measured by calculating the mean of the absolute ~~RPCC values~~ RPCCs across all output variables, weighted by the uncertainty contribution of these model outputs. The parameters are listed in Tab.S2 and explained in Tab.S1.

	Rank 1		**Rank 2**		**Rank 3**		**Rank 4**		
Variable	Par	RPCC	Par	RPCC	Par	RPCC	Par	RPCC	Pa
Total SOC	$v_{max,depoly}^{poly}$	-0.84	$v_{max,depoly}^{res}$	-0.80	$\frac{1}{\tau_{mic}}$	0.83	$\eta_{C,wl\rightarrow poly}$	0.71	$\eta_{C,sol}$
Total SON	$\chi_{mic}^{C:N}$	-0.99	$v_{max,depoly}^{res}$	-0.94	$\eta_{C,sol\rightarrow dom}$	0.84	$\chi_{mic}^{N:P}$	0.40	$\eta_{C,wl}$
Total SOP	$\chi_{mic}^{C:N}$	-0.97	$\chi_{mic}^{N:P}$	-0.97	$v_{max,biomin}$	-0.84	$\eta_{res\rightarrow dom}^{P}$	-0.78	$\frac{1}{\tau_m}$
Total SIP	k_{weath}	-0.58	$\eta_{res\rightarrow dom}^{P}$	0.57	$v_{max,biomin}$	0.47	$\chi_{mic}^{N:P}$	0.45	η_{res-}^{P}
Microbial C	$\frac{1}{\tau_{mic}}$	-0.98	$\eta_{C,sol\rightarrow dom}$	0.86	$\chi_{mic}^{C:N}$	0.68	$\chi_{mic}^{N:P}$	0.67	$\eta_{C,wl}$
Microbial N	$\frac{1}{\tau_{mic}}$	-0.97	$\chi_{mic}^{C:N}$	-0.95	$\eta_{C,sol\rightarrow dom}$	0.83	$\chi_{mic}^{N:P}$	0.63	$\eta_{C,wl}$
Microbial P	$\frac{1}{\tau_{mic}}$	-0.96	$\chi_{mic}^{N:P}$	-0.94	$\chi_{mic}^{C:N}$	-0.93	$\eta_{C,sol\rightarrow dom}$	0.79	$\eta_{C,wl}$
Respiration	$\frac{1}{\tau_{mic}}$	-0.71	$\chi_{mic}^{N:P}$	0.69	$\chi_{mic}^{C:N}$	0.65	$v_{max,depoly}^{res}$	0.45	mic
Net N mineralisation	$\chi_{mic}^{C:N}$	0.97	$v_{max,depoly}^{res}$	0.65	mic_{cue}^{min}	-0.40	$\eta_{C,sol\rightarrow dom}$	-0.32	$\frac{1}{\tau_m}$
Microbial N uptake	mic_{nue}	-0.98	$\chi_{mic}^{C:N}$	-0.90	$\eta_{C,sol\rightarrow dom}$	0.75	$\eta_{C,wl\rightarrow poly}$	0.38	χ_{m}^{N}
Net P mineralisation	$\eta_{res\rightarrow dom}^{P}$	0.94	$\chi_{mic}^{N:P}$	0.84	$\chi_{mic}^{C:N}$	0.84	$\eta_{C,sol\rightarrow dom}$	-0.67	$\eta_{C,wl}$
P ~~Bio-mineralisation~~ Biomineralisation	$\eta_{res\rightarrow dom}^{P}$	-0.94	$\chi_{mic}^{N:P}$	-0.85	$\chi_{mic}^{C:N}$	-0.84	$\eta_{C,sol\rightarrow dom}$	0.67	$\eta_{C,wl}$
Microbial P uptake	mic_{pue}	-0.91	$\chi_{mic}^{N:P}$	-0.90	$\chi_{mic}^{C:N}$	-0.89	$\eta_{res\rightarrow dom}^{P}$	-0.85	$\eta_{C,sol}$
N Losses	$\chi_{mic}^{N:P}$	0.72	$\frac{1}{\tau_{mic}}$	-0.72	$\chi_{mic}^{C:N}$	0.67	$v_{max,upt}^{dom}$	0.41	$v_{max,}$
P Losses	$v_{max,upt}^{dom}$	0.22	mic_{pue}	0.15	mic_{cue}^{min}	-0.14	$\eta_{res\rightarrow dom}^{P}$	-0.11	k_{enz}^{P}
OVI	$\chi_{mic}^{C:N}$	0.73	$\chi_{mic}^{N:P}$	0.57	$\frac{1}{\tau_{mic}}$	0.47	$\eta_{C,sol\rightarrow dom}$	0.42	η_{res-}^{P}