

Many thanks to the reviewers for their comments. We have revised the paper and feel it is now a much better contribution. There have been many interacting changes which are clearly highlighted in the attached document.

Interactive comment on “JULES-CN: a coupled terrestrial Carbon-Nitrogen Scheme (JULES vn5.1)” by Andrew J. Wiltshire et al.

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### General comments

Introducing a prognostic nutrient cycle, here the nitrogen cycle, into a land surface model (LSM) is a challenging task. As the importance of nutrient limitation on productivity has been clear for a while and we have gone from one LSM with a prognostic N cycle in CMIP5 to several in CMIP6 this is a step all LSM are taking. So for undertaking this task and finishing an LSM that have included all the major N related processes I congratulate the authors. Some processes have been left quite simplistic (e.g. N<sub>2</sub> gas with its additional turnover) but this is a natural step in the process of developing a modelling framework. The paper goes through the steps they have taken to incorporate the key terrestrial N cycle processes and show how different model setups behaves over historical simulations. These simulations have then been analysed on a global and biome scale and have shown that the model simulates the carbon and nitrogen pools and fluxes comparable to the limited available observations.

The main reason to include a prognostic nutrient cycle is to represent a limitation on plant productivity. The authors have shown that their N limitation is within observation on the biome level, but the global spatial distribution still puzzles me (see general comments). It would also be interesting to see how N limitation affect PFT distributions or at least some mention of it even if N limitation doesn't have any direct influence. In general, it would have been nice to see some perturbation experiments to see how the N cycle would react. Especially BNF and N limitation on productivity. But as this is covered in another paper (Davies-Barnard et al. 2020) it could have been good to refer to those results more than in just a short note in the introduction.

We have added a figure showing the fractional distribution of the vegetation and how it changes with the different configurations. We have also extended the discussion section to include next steps and a description of the results in the Davies-Barnard paper.

I think this is an excellent model description paper. All the relevant equations and model structures are well documented and described. I would like to congratulate the author to a job well done! Hope my comments will be to some help.

Thank you for your helpful review comments. As you note we have endeavoured to develop a parsimonious scheme for application in the UK Earth System Model. This is a first step in enabling further representation of the role of nutrients including fully coupling with gas phase chemistry.

In revision we will include reference to the Davies-Barnard paper and other relevant results from CMIP experiments.

Section 3.1.1 – Biological Nitrogen Fixation feels misplaced in Section 3.1 Vegetation Carbon and Nitrogen. Would fit better in section 3.2 Soil Biogeochemistry together with other N sources and losses that are described here.

This has been moved to the soil inorganic nitrogen section and sign posted earlier on in the text.

Section 3.1.3 – With eqn 12 and that  $z$  is the fraction of canopy above current layer, the canopy will always have the same C:N ratio and it will not depend on LAI as it was in Mercado et al. (2007). In Davies-Barnard et al. (2020) it is stated that leaves have flexible C:N ratio. How have I misunderstood this? Yes, leaves have flexible C:N ratios, but the canopy as a whole have a fixed C:N ratio. If the canopy C:N ratio is fixed then there will be a mismatch between canopy N and irradiance compared to Mercado et al. (2007) as irradiance will decrease exponentially through the canopy depending on LAI but leaf N will not. Will this affect the photosynthesis?

Thank you pointing out the issue. Agreed, there is a mismatch between canopy N and irradiance in the current formulation. This is being investigated and will be documented separately and addressed in subsequent configuration updates.

L245-248: “If not enough inorganic nitrogen is available, the system is nitrogen limited and an additional term is required in the carbon balance representing excess carbon which cannot be assimilated into the plant due to lack of available nitrogen ( $\Psi_c$ ). A positive  $\Psi_c$  results in a reduction of carbon use efficiency.” – N limitation only affects NPP and not GPP with an additional respiration term decreasing the CUE. As GPP isn’t affected by N limitation then the water demand will stay the same. So the water “cost” for NPP will be higher in JULES compare to models that let N limitation directly affect GPP. Is this something that has been considered during the development?

You are correct that N limitation doesn’t directly impact water demand. However, there is an indirect affect via the coupling between N limitation and LAI. This is something we are aware of and will be taking into account in analysis of CMIP experiments and future model developments. .

L271: “The nitrogen available for growth is the total available nitrogen multiplied through by  $(1 - \lambda)$ .” – I assume that the “nitrogen available for growth” is  $N_{avail}$  and is used in L283.  $N_{avail}$  isn’t defined until L378. Please clarify this in the text.

Corrected

Section 3.2.1 – Does litter and diffused SOM enter frozen soil layers? Could be the reason we see a higher soil C for CNlayer at higher latitudes (Figure 7).

This has been added to the model description:  $D(z)$  is the diffusivity in  $m^2 s^{-1}$  and varies both spatially and with depth \citep{burke2016gmd}:

$\begin{equation} \label{diff}$

$D(z) = \begin{Bmatrix}$

$D_0 \quad ; \quad z \leq 1 \text{ m} \quad \backslash \backslash$

$\frac{D_0}{2}(3 - z) \quad ; \quad 1 \text{ m} < z < 3 \text{ m} \quad \backslash \backslash$

$0.0 \quad ; \quad z \geq 3 \text{ m}$

$\end{Bmatrix}$

\end{equation}

Without permafrost,  $D_o$  ( $m^2 s^{-1}$ ) is given by a bioturbation mixing rate equivalent to  $1 \text{ cm}^2 \text{ year}^{-1}$ . When permafrost is present, the mixing represents cryoturbation and  $D_o$  increases to a value equivalent to  $5 \text{ cm}^2 \text{ year}^{-1}$ . This parameterisation of  $D(z)$  means that the soil organic pools can transfer between permafrost and non-permafrost soils albeit at a relatively slow rate.

We have expanded the discussion around Figure 7 and the vertically resolved soil biogeochemistry to include the “The soil in JULES-CN<sub>{layer}</sub> has more organic carbon (Figure \ref{fig:zonal\_stocks}), organic and inorganic nitrogen (Figure \ref{fig:fluxes\_stocks}). The parameterisation of the vertically resolved soil biogeochemistry means that once JULES-CN<sub>{layer}</sub> is spun-up the soil carbon and nitrogen within the frozen soil is relatively stable because of the low temperatures.”

L430-436: – The additional turnover of inorganic nitrogen is a great solution to a well-known issue when soil N starts building up uncontrollable due to N deposition or BNF.

Agreed. It is something we plan to investigate in greater depth in the future.

Section 3.2 and 3.3 – A table with constants from sections 3.2 and 3.3 similar to Table 1 for section 3.1 would be a nice addition to the manuscript.

This has been added as Table 2.

L532-534: – N leach is very small. Any idea why it is so small? Have you considered some adjustments to get the number to increase? Change the value of  $\beta$ ?

We have changed the value of the effective solubility of nitrogen in water and can get an increase in the leaching by doing this. However, it is still fairly small compared with the estimates in Figure 4. One of these reasons is that, in reality, some component of the leaching is from the fertilizer which is not yet included in JULES-CN. We have added a comment to this effect in the document.

L538-539 and Figure 4. – Net N mineralisation and N uptake seem to be very small. Are the units for them really  $\text{Tg N yr}^{-1}$ ?

These were in the wrong units and have now been updated

L564-565: “This is a consequence of the higher nitrogen limitation on JULES-CN leading to less litter fall and subsequently less soil carbon.” – I guess N limitation on SOM decomposition isn’t strong enough to make the SOM pools increase in size? Could it be that the fixed plant C:N ratios prevent feedback of poorer litter quality under higher N limitation that would result in a slowdown of SOM decomposition?

Yes, it is feasible a shift to a lower C:N plant ratio would decrease litter quality in turn slowing decomposition. The impact will be dependent on the balance of processes and any change in total litterfall.

Figure 1. – Fixation seems to enter the vegetation in the figure, but section 3.1.1 says it enters inorganic N pool. Update figure.

Figure 1 has been eliminated because it is very similar to Figure 4 and supplies no additional information over Figure 4.

Figure 6. – Is the increased soil C at high latitudes for CNlayer mainly due to the additional decay rate modifier per depth or is it due to N limitation on decomposition? Because with a lot less vegetation C the input of litter must also be less. So something else needs to dictate the build-up of soil C as this is opposite to what is stated in L564- 565.

In the Nhat when JULES-C is compared with JULES-Clayers there is a large increase in organic carbon (see Figure 6 in <https://gmd.copernicus.org/articles/10/959/2017/gmd-10-959-2017.pdf>). In both JULES-CN and JULES-CNlayered the N limitation on decomposition is relatively small. The vertical profile of soil temperature has a big impact on the decomposition in the layered models and allows soil carbon to build up in the deeper soils. The layered model is expanded upon further in the text.

Figure 6, 7 and 9. – Figure 6 is the result we are after when introducing an N cycle, N limitation on productivity. The N limitation spatial distribution puzzles me to some extent. That you haven't investigated the reason for the strong N limitation in tropical savannah (L550-551 "Further work is required to understand why tropical savannah is so limited.") is something I think should have been done. And also that Northern Europe doesn't see any N limitation, but Western Europe does is also strange. I would have liked to have maps for figure 7 and 9 to try and understand this better, now a lot of information is hidden within the latitudinal bands. Also, a figure with annual net mineralisation would be of interest to understand what is happening.

Interestingly, I have changed how to extract the biome specific information out of the model results (medians instead of means) and now we get the savannah and tundra forest being OK limitation-wise but the tropical forests not being limited enough. (it's a bit scary how different the use of a slightly different metric can make the results appear!). We do think, however, that the new Figure 5 and 6 are a more appropriate reflection of each other. This means that we are now interested in why tropical forests aren't limited enough - Phosphorus?. This has been added to the discussion.

We have also added an additional figure which includes of the more relevant N stocks and fluxes and a discussion about this impact of this figure.

Figure 6, 7 and 9. – How can it be that CNlayer has stronger N limitation at higher latitudes than CN (less Veg C in figure 7 and more yellow in figure 6) when there is more inorganic N in the soil (figure 9)? This needs to be explained better. Is it due to the root profile and that all N isn't available?

Indeed, there are two inorganic nitrogen pools in the layered model - the total pool and the inorganic N that is available to the plants. This depends on the root distribution and on whether the soil is frozen. There may well be less available inorganic nitrogen in JULES-CNlayered than total inorganic nitrogen in JULES-CN meaning that the plants could be more nitrogen limited in some regions. This discussion is expanded in the discussion about JULES-CNlayered.

Technical corrections

L9: "Biological fixation and nitrogen deposition are external inputs. . ." – From section 3.1.1 it is clear that BNF isn't an external input. Please revise this sentence

Corrected

L204-205: "We therefore a new parameterisation of retranslocation and labile nitrogen that is dependent on the phenological state" – please revise this sentence

Done

L278: “. . . is is . . .” – remove one is.

Done

L474: “. . . Equation51 . . .” – change to “. . . Equation 51 . . .”

Done

L646: “. . .5 residence tome of carbon . . .” – change tome to time.

Done

L675: “. . . model model . . .” – remove one model.

Done

Figure 4. “. . . period 19960-2005 . . .” – correct to 1960.

Done

## References

Davies-Barnard, T., Meyerholt, J., Zaehle, S., Friedlingstein, P., Brovkin, V., Fan, Y., Fisher, R. A., Jones, C. D., Lee, H., Peano, D., Smith, B., Wårlind, D., and Wiltshire, A.: Nitrogen Cycling in CMIP6 Land Surface Models: Progress and Limitations, Biogeo- sciences Discuss., <https://doi.org/10.5194/bg-2019-513>, in review, 2020.

Mercado, L. M., Huntingford, C., Gash, J. H., Cox, P. M., and Jogireddy, V.: Improving the representation of radiation interception and photosynthesis for cli- mate model applications, *Tellus B*, 59, 553–565, 2007, <https://doi.org/10.1111/j.1600-0889.2007.00256.x>.

Interactive comment on “JULES-CN: a coupled terrestrial Carbon-Nitrogen Scheme (JULES vn5.1)” by Andrew J. Wiltshire et al.

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Wiltshire and co-authors nicely document their additions of a nitrogen cycle and vertically resolved soil biogeochemical model to the JULES model for use in UKESM1. The offline simulations include documentation of simulated vegetation and soil carbon and N pools and fluxes and their change over the historical period. A comparison with some observations is provided for model evaluation

### Major concerns

My major concerns aren't that substantial, but stem from contradictions in what's expected from the paper and what's actually delivered.

The paper sets off comparing the C only, CN and CN\_Layered implementation of the model, but a number of display items omit results from the CN\_Layered configuration. Specifically, Fig. 10-12 &

Table 2 do not show results from the layered model, why? Should these effects of vertical soils also be discussed in 5.3? Because these results are not presented, I think major revisions are warranted.

These were not all included so as to simplify the story. However, we will re-examine and add the CN\_layered simulations where it is most appropriate in the revised version. This has involved a significant re-write of the Results section which is more comprehensive.

Are there meaningful differences in plant distributions simulated with the new N enabled or CN\_layered models?

We have added a Figure showing the pft distribution of the different types of vegetation. This configuration of the model has not yet been brought together with the new height competition which is included in UKESM1 so the exact PFT distributions will change with extra vegetation types and a height-based competition. Therefore, the results are just an indication of the effects of changing the model configuration.

The multi-layered canopy model is introduced in section 3, but never really discussed in section 5. Should it be? Are there any interesting insights enabled by this new feature of the model?

The section has now been extended. The idea behind this section was to document the link between leaf level photosynthesis and respiration and the interactive N scheme. The section has been restructured and updated.

Minor and technical concerns: These are more numerous but intended to clarify and improve the paper.

I like the high-level overview of the main findings summarized in the abstract, but I wondered if more quantitative results should also be provided (pending length requirements for the journal)? We have added a couple of sentences discussing the values of the nitrogen limitation and the carbon use efficiency to the abstract.

Paragraph starting on line 70. I appreciate how clearly model assumptions are laid out. For example, the approach here looks at the "large-scale role of nitrogen limitation on carbon use efficiency", but I wonder if there's evidence to support this common assumption made in models in real ecosystems? What is the assumed impact of N limitation on NEP? The net results it that is dampens

The introduction has been changed significantly to include these additional bits of information, plus the additional text suggested by the other reviewers.

Can paragraphs around lines 60 & 90 effectively be combined? Both paragraphs seem to have a common purpose of documenting the model connections and history. It's also not really clear how JULES fits into UKESM (also called UKESM1) vs. HadGEM2

We agree this is unclear. We have reworded this so as to make it clearer. We have combined line 90 on into the beginning of the model description section when more details are required.

Is section 2 subheading really warranted? Maybe just combine subheadings for 2 & 3 into one longer section?

Done

There are some redundancies in the text (section 3) where sentences are repeated at different points.

Section 3 has been altered so it is now a general introduction to JULES and the model description below.

Line 162. I'm confused why "These stoichiometric functions already exist in the model" for MR fluxes. This suggests the new work here is just to explicitly represent the Npools that were being implicitly assumed in the carbon only model? Separately, is it worth documenting the source for vegetation stoichiometry (presumably used in Cox et al. 2011)?

This section has been revised to make clarify what is existing and what has had to be extended to have a fully interactive N scheme. The vegetation stoichiometry is also referenced - Enquist, B. J., Brown, J. H., and West, G. B.: Allometric scaling of plant energetics and population density, *Nature*, 395, 163–165, 1998

Fig 1: The assumption that 'roots' in the model have a lower (or equal) C:N than leaves seems surprising to me, but this but seems contradicted by 'Ratio of root to top leaf nitrogen' (Table 1), please clarify. Roots have wide variation in C:N (Iversen et al. 2017), but if anything I'd assume they should have a higher C:N ratio than leaves (Kattge et al. 2011).

Roots have the same C:N ratio as the top leaf, but as N concentration decreases through the canopy the current formulation means that the C:N ratio is lower. Future work will explore parameterising root C:N ratios directly. We note this in the discussion.

Table 1: "Top leaf nitrogen concentration": listed twice

Removed

Line 175, this statement doesn't seem to be true for grasses, which have declining C:N with height (Fig 2).

Corrected.

Section 3.1.1, oh no, why define N fixation (which should limit NPP) as a function of NPP in the model?! This isn't the first modeling group to make this assumption, but a brief discussion and literature review seems warranted (see Vitousek et al. 2013; Thomas et al. 2015; Wieder et al. 2015; Meyerholt et al 2016)

We have inserted further discussion, including the references suggested.

Section 3.1.1- I think inputs from N fix lead off these details of the CN model because that's where the N cycle 'starts', which seems logical, but putting it under a "Vegetation carbon and nitrogen" (subheading 3.1) seems odd, especially since Nfix contributes to the soil N pool (not plants). Maybe different names for the higher level subheadings (3.1 and 3.2) would be warranted? Alternatively, use Fig 1 to group these fluxes together.

We have tried to sign post the different components of the nitrogen cycle better. The fixation is now included in the inorganic nitrogen section.

Line 182 What is potential NPP? (eq. 9). How does this differ than the 'actual' NPP? If not discussed here, please reference where this is described (3.1.4).

This section been moved to the Inorganic nitrogen section. NPP\_pot is defined very clearly in the vegetation growth and allocation section..

Line 225 where is the multi-layer canopy approach included in these simulations? I'm assuming with with CNlayered, but this isn't clear in section 4 (line 495)

This has been changed to - "JULES-CN\_{layer} is a version of JULES-CN which has identical above ground processes to JULES-CN but additionally includes vertically discretised soil biochemistry."

What is 'spreading' in the model (section 3.1.4)? Is this prescribed by some land use time series dataset or prognostic (more like a DGVM)? Text on page 11 makes me think it's the later.

This has been added: "Biomass can also increase by spreading through an increase in covered area" where the term spreading has been introduced.

The assumptions made in the phenology and allocation section are thoroughly defined, but it's hard to understand for readers not familiar with TRIFFID how N limitation is implemented in the model. It seems like it's an instantaneous down regulation of NPP, with extra carbon respired by plants that are N limited? With that N limitation calculated by the tissue and pft specific stoichiometry defined in the model?

Yes, this is correct. The model description has been updated to make it clearer.

Eq. 25-28. I don't really understand how the soil model is wired based on these equations. If R\_DPM and R\_RPM are the respiration terms from litter pools, how do some of these fluxes go back into the BIO and HUM pools, which themselves are respired (and also simultaneously included as inputs to BIO and HUM)? It seems that soil respiration fluxes to the atmosphere are actually  $R_{tot} * B_R$ , if so, the  $R_{*}$  fluxes should be some kind of soil turnover term (not respiration).

This has been changed to make the respiration/turnover clearer. New text -",  $R_{tot} = R_{DPM} + R_{RPM} + R_{BIO} + R_{HUM}$  where  $R_{tot}$  is the total turnover in  $kg\ C\ m^{-2}\ s^{-1}$ .  $(1 - \beta_R)$  is the fraction of the total turnover that is respired to the atmosphere.  $\beta_R$  depends on soil texture and ranges from 0.75 for a clay soil to 0.85 for a soil with no clay content. From this the respiration to the atmosphere can be defined as  $(1 - \beta_R) R_{tot}$ ."

It seems like  $B_R$  is a critical number here, as it controls the soil carbon use efficiency and the amount of N required during litter decomposition (eq. 35). Is this parameter value defined somewhere?

Beta R is now defined in a new equation:  $\beta_R = \frac{1}{4.09 + 2.67e^{(-0.079clay)}}$

Eq. 29-32 do the N fluxes need to include  $I_{DPM} + I_{RPM}$ ?

No - immobilisation is a microbial process in which inorganic nitrogen is made into new organic matter. Microbes don't make new plant litter (plants make that!), they only produce BIO/HUM. The  $I_{DPM}$  and  $I_{RPM}$  terms are there in  $I_{tot}$ . They're somewhat confusingly named.  $I_{DPM}$  is the immobilised nitrogen that *originated* from DPM.



Line 355, as above can this be called potential turnover, not "potential respiration"?

This has been changed

Eq. 33. I'm trying to wrap my head around the vegetation controls over decay rates and how that may feedback to a CN model that has vegetation with very different stoichiometry and N demand (woody vs. grass pfts; Fig 2) but that allows for plant competition (on a single soil column). I assumed the maps of nutrient limitation (Fig. 6) reflect differences in vegetation N demand (per unit of C), but are decay rates also slower for grasses (increasing the N limitation in these ecosystems)?

The interactions and feedbacks are potentially highly complicated given the ability for the PFTs to compete. The grasses produce a higher fraction of decomposable plant material relative to the tree PFTs (0.67 to 0.25, now in Table 1). In turn, decomposable plant material decays approximately 300 faster than resistant material. Grasses therefore have a faster turnover of nutrients. Our interpretation of Figure 6 (now Figure 4) is that it reflects the vegetation N demand. However, more work is required to understand the savannah grass response.

Eq. 36, Is this still a potential decomposition rate, as it's 'limited' by N availability?

This has been changed

Line 385, what are 'these two pools'? I think it should be DMP and RMP, but it's not clear in the text?

This has been clarified – indeed there are the two litter pools

What happens to wood in the soil CN model? How is it allocated to the pools described?

The ratio of dpm to rpm is a PFT dependent parameter so implicitly takes into account the proportion of wood in a PFT. It is lower for a woody pft and higher for a grass pft. This is discussed at the top of Section 2.2.

Eq. 39, is there anything that prevents this flux from being negative? Are there times when immobilization > mineralization?

Fluxes will have been limited by  $F_n$  to make sure this isn't negative. If it hits the minimum pool size, it calculates a correction term ( $neg_n$ ) and that correction term is then included as a negative gas flux. But that is applied just as an 'extra' gas flux and not applied to  $minI$  and  $immob$ . So Eq 39 is never negative, but gas flux can be, if that makes sense! This has been added: ".  $f_N$  limits the nitrogen fluxes so that  $(M_{tot} - I_{tot})$  is always positive. However, if pool sizes become too small  $N_{gas}$  could become negative to ensure nitrogen is conserved."

Eq. 39, Should the N loss description go into 3.3 (inorganic N) instead of the soils section (3.2)?

I think it is clearer to have this first component of gas loss here because it is defined using the mineralisation/immobilisation which is discussed here. I agree that it is on the boundary between inorganic and organic nitrogen.

Where does  $N_{turnover}$  flux (eq. 46) go in the model, the atmosphere? How large is this tuning flux relative to other loss terms?

N-turnover flux it has been renamed  $N_{gasI}$  and goes to the atmosphere. This is now discussed in Figure 4 and we state the proportion of loss via this process is about 90% of the total gas loss.

Eq. 46, where does  $N_{\text{gas}}$  (eq. 39) fit into the N budget summarized here? Section 4, How does the model handle agricultural fractions of grid cells?

This has been added: The total gas loss is the sum of  $N_{\text{gas}}$  and  $N_{\text{gas}}$  from Equation \ref{eq:ngas}. There are no agricultural fractions represented by this model. I've stated that there are two gas loss terms.

Section 501 I'm used to fluxes and pools being roughly proportional in models like this. If NPP is 11% lower in the CN model, why are the vegetation stocks roughly equal in the C and CN model? Similarly, if the vertically resolved model has a similar NPP to the CN model why are vegetation C pools so different?

This is because the turnover times change – the vegetation and soil turnover times are now plotted separately

Fig 4, 8 and others, Since the text is organized with C, CN, and CN\_layered should the display items be similarly organized?

We put JULES-CN first because that is the configuration we are describing as the main focus of the paper. JULES-C is only included in the paper for comparison purposes and JULES-CNlayered is included last because it is an extension of JULES-CN. We will check through the text and make sure it is that way in the text. This was particularly relevant when discussing the “historical simulations”.

Fig 4 what is the 'N-loss' flux supposed to represent? As drawn, I think this is a gaseous N loss, but as labelled it's not clear how this connects with  $N_{\text{gas}}$  and  $N_{\text{turnover}}$  fluxes (see above).

The N loss term has been changed to a N Gas term and it is the sum of the gas losses from the inorganic N pool and the organic N pool. This has been added to the caption N- gas is the sum of  $N_{\text{gas}}$  and  $N_{\text{gas}}$  with  $N_{\text{gas}}$  approximately 90 % of the total gas loss

Fig 4, how deep are the soils being represented, this is especially important to consider in the vertically resolved model and should likely be described in methods (3.2.1)

This has been added to section 3: These configurations of JULES adopt the standard 4 layer soils with a maximum depth of 3 m. However it should be noted that \cite{burke2016gmd,chadburn2015gmd} adopt a configuration which increases both the maximum soil depth and number of soil layers.

Line 535, doesn't this just mean the model is at equilibrium as it should be given your spinup procedure?

However, the model could still be in equilibrium with a slower recycling rate. The recycling rate through the system is a characteristic of the model.

Section 5.2 seems out of place, as the extent of N limitation should be preceded by a more thorough comparison of the model states and fluxes. One suggested organization could be comparing the 1) Spatial distribution of present day stocks / fluxes and residence times (e.g. Figs 4, 10, 7, 9, & 8 in that order) and 2) Temporal evolution of relevant stocks / fluxes over the historical period (e.g. Fig 11 & 12) 3) N limitation (Fig 6, 5) as diagnosed by  $NPP_{\text{Potential}} / NPP$  and its evolution over time (Fig 11b).

The results section has been re-worked to make a clearer flow through the figures. Stocks and fluxes followed by N limitation.

The title for Fig 5 (and associated text) implies that you conducted a N fertilization experiment (see Wieder et al. 2019), but I don't think this is accurate. Instead you're calculating a N limitation diagnostic ( $NPP_{pot}/NPP$ ) and comparing that to results from an observational synthesis.

Title changed to "Response ratio ( $NPP_{pot}/NPP$  achieved)" as in Figure 6. This is defined as "the response ratio, is the ratio of the potential amount of carbon that can be allocated to growth and spreading of the vegetation ( $NPP_{pot}$ ) compared with the actual amount achieved in the natural state (NPP)". Text about the observations is also changed to include: "which summarises a meta analysis of nitrogen addition experiments. The black bars showing the mean of the observations and the red lines the uncertainty."

I'd suggest flipping the order of Figs 5 & 6, as they both show the same information, but Fig 6 is less processed model output, with 5 serving to summarize biome-specific information and related it to observations.

We have switched the order of Figures 5 and 6 as suggested and changed the associated text.

Fig 6, Line 553. It seems like the model is more strongly limited in grasslands, which have much higher N requirements / unit of C (Fig 2). This doesn't really show up in results for 'tundra' or 'grasslands' (only for Savannah). I wonder why?

We have looked at this again. We have decided to use the median of each biome rather than the mean of each biome to calculate the results shown in Figure 6. This is because JULES does not necessarily simulate the correct vegetation for the whole of each biome and outliers will influence the mean. These will not influence the median in the same manner. Looking at Figure 6 the results are more comparable with what we might expect – JULES is not limited enough in the forest biomes but it is now more appropriately limited in the tundra and the savanna. We have also changed the scale of the y-axis in the figure to make the results clearer to see.

Should multi-paneled figures be labeled ('a', 'b', 'c') and accordingly described in the figure caption?

This has been done

Fig 7, can legends be smaller or moved into the figures (as in Fig. 9) so the data are easier to read?

This figure has been improved as suggested.

Fig 9, should the bottom panel be labeled soil C residence time and also include data from the C-only model?

This has been deleted and the soil residence times plotted instead in Figure 8.

Fig. 11b what is the time series of 'response ratio anomaly'? Is this the change in  $NPP_{Pot} / NPP_{act}$  that used to diagnose N limitation shown in Figs 5 & 6? If so, is this what you're calling 'progressive N limitation' (line 599), in which case this should be clarified on and expanded in the text.

We have moved this sub figure to sit alongside the other discussion of Nitrogen limitation and expanded upon it in the text.

Fig 12 & section 5.2.3 The low bias in NEE ( 0.5 Pg / y, roughly 25%). This would lead to an underestimation of the land carbon sink of about 25 Pg over the period from 1960-2010 (or about 12 ppm CO<sub>2</sub> in the atmosphere). Thus, while the IAV of NEE looks better here, that overall magnitude of the land sink may be too low with the CN version of the model. This isn't a deal breaker for the paper but time implications of the low bias with the CN (and CN\_layer) model should be discussed in

the text, especially since JULES\_CN is included in UKESM1.

A discussion has been added in the text. The relationship between JULES-CN and UKESM1 has been made clearer – they are related, but the configuration of JULES in UKESM1 (JULES-ES) has a whole bunch of other components which are not included here and will affect both the vegetation distribution and the NEE.

Section 5.3. Is it just frozen soils that are causing this? it seems the differences in Veg C pools extend down to 40 degrees north (Fig 7). Is this somehow connected to assumptions about the fraction of N that plants have access to in the vertically resolved model (e.g. 51)?

Indeed, the plants with the shallower roots preferentially take nitrogen from the shallower soils so this process will also contribute to the nitrogen limitation in JULES-CN layer. This has been added: “This additional limitation of nitrogen uptake caused by frozen soils and the dependence of plant N uptake on root distribution”

Line 611, as noted in Fig 12, the low biases in land C uptake seems notable if you’re trying to capture changes in the atmospheric CO2 growth rate.

This is stated here slightly further down: “. Due to nitrogen limitations on CO2 fertilization, mean NEE in JULES-CN (1.66 Pg C/yr) is lower than in JULES-C (2.06 Pg C/yr), and also lower than the estimate from GCP (2.11 Pg C/yr)”

Line 671 what is “climate-induced mineralization” I’m assuming this has something to do with accelerated decomposition from climate change increasing N mineralization rates?

Changed to “accelerated soil decomposition caused by climate change leading to increased mineralisation rates”

Is there a data availability statement required for the journal?

As a model description paper we provide access to the code as documented here and the rest of the JULES model subject to a freely available non-commercial licence agreement. In addition to further encourage and support the use and application of standard ‘configurations’ we provide access to the ‘suites’ used here.

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Interactive comment on "JULES-CN: a coupled terrestrial Carbon-Nitrogen Scheme (JULES vn5.1)" by Andrew J. Wiltshire et al.

Anonymous Referee #3

Received and published: 20 August 2020

This manuscript explains the N cycle in the JULES-CN model which forms the land component of the UKESM. Simulations from the UKESM have contributed to the CMIP6 effort. The N cycle component of JULES, as explained, here is very simple compared to existing models out there. This is completely acceptable as long as it is clarified that the model parameterizations are simple, their limitations acknowledged, and the implications discussed. I am afraid, however, that the manuscript doesn't appear to do so and in my mind requires substantial work to address this and other concerns I raise below.

1Major comments

I have several major concerns.

It is well known that leaf N content is related to its photosynthesis capacity (Field and Mooney, 1986). When CO<sub>2</sub> increases, photosynthesis increases but this rate of increase is slowed if enough N is not available. This process is referred to as photosynthesis downregulation (McGuire et al., 1995). So, it is clear then, that N limitation acts on photosynthesis and thus on the gross primary production (GPP) flux. However, the approach used in the manuscript, in contrast, reduces the NPP (without adjusting the GPP) which is equivalent to reducing carbon use efficiency ( $CUE = NPP/GPP$ ). Since there is no biological justification for this provided, I am struggling to understand the reasoning behind this. Also, if that framework is still used, TRIFFID models  $V_{cmax}$  as a function of leaf N content (eqn. 51 in Cox 2001) so it makes sense to adjust  $V_{cmax}$ .

Related to this concern, is the fact, that I am not able to find in the manuscript in detail how this reduction in NPP is implemented or how it results and because of the interaction of which processes. Unless I missed it, the only reference to this important process is made on line 78 as "... and then reducing plant net carbon gain to match available nutrients".

It is well known that current observation-based CUE is around 0.5. This is also seen in Figure 10. The CUE for the JULES-CN model is lower than that for the JULES-C model because that's how JULES-CN

is designed - to lower NPP and hence CUE as CO<sub>2</sub> increases and N supply can't keep up. I am wondering what happens in a future simulation for RCP 8.5 scenario. Will your CUE drop down to something like 0.25 by year 2100 which seems totally unrealistic? This will be one implication of your model design since you have chosen to reduce NPP and not GPP.

Agreed, it is well established that tissue level N concentrations correlate with photosynthetic capacity and metabolism. It is also established the first order effect of N fertilisation is enhanced growth. However, it is less clear on the mechanisms, for instance field experiments of enhanced N fertilisation have found increases in growth but no change in photosynthetic rate (e.g. Brix et al., 1969, Wang et al., 2012). Other analysis, looking at climatological gradients in N deposition found no dependency between foliar N and N deposition. It is, however, fair to say other analyses (e.g. Mao et al., 2020) do establish this link. In general, models to date make differing assumptions about these coupling mechanism between C and N cycles leading to substantial uncertainty in their projections (Zaehle and Dalmonech, 2011).

Our approach here is to capture the established first order emergent response of N addition on growth which translates into leaf area and biomass without the complex and uncertain impacts on leaf physiology. As we use a fully dynamic vegetation scheme Nitrogen availability can drive changes in plant level C:N ratios through competition. This is the first implementation of a coupled C-N scheme in the UK model and we fully expect to develop this aspect further including assessing flexible stoichiometry.

Further to the points raised above, not of all the CMIP6 models only UKESM and MPI-ESM 1.2 (Mauritsen et al., 2019) include a coupled fully dynamic vegetation model with nitrogen scheme. In both cases, the schemes assume fixed plant stoichiometry. In which case, if CUE dropped very low there would be a dynamic vegetation response leading to a dieback. In our CMIP6 experiments we do not see a strong reduction in CUE (over the course of ssp585 reduction from 0.53 to 0.48). Analysis of CMIP6 runs as part of C4MIP demonstrates we have a strong and robust representation of carbon feedbacks (Arora et al., 2020).

The second big assumption in the model is that of fixed C:N ratios of plant tissues. The implications of this assumption are not discussed. Since C:N ratio of plants varies in space (as indicated by different values of nIO in Table 1) this indicates their ability to adapt to different environmental conditions in space. Assuming, plants can do the same in time as CO<sub>2</sub> increases doesn't this imply that the assumption of fixed C:N is too strong and your model will limit NPP perhaps more excessively than it in the real world (with the caveat that in the real world GPP is constrained).

It is common for DGVMs to parameterise a top-leaf nitrogen content per PFT as part of the process of capturing diversity and functional traits. This is the case whether a full nitrogen cycle is included or not. This is common with the point raised in 1. It is likely that foliar N varies in space independent of nutrients as was found in the Aber study. This is not captured in the typical approach to dynamic vegetation modelling. It is entirely plausible that with increased nutrient limitation plants limit their foliar N and therefore GPP and NPP. In our approach, with fixed stoichiometry we may excessively constrain the model but through the dynamic vegetation response we might see a shift towards a plant with a lower C:N.

In context of model evaluation, it would have been extremely helpful to include a simulation in which N deposition is turned off. This simulation would have allowed to see if the effect of N deposition is indeed to increase NPP as would be intuitively expected.

This paper is just an initial description of the JULES-CN model which alongside other additional land surface processes has been implemented in UKESM. The JULES-C run implicitly gives an signal of the effect of N deposition. It has also been used within Davies Barnard et al. (2020, <https://bg.copernicus.org/articles/17/5129/2020/bg-17-5129-2020.pdf>) who explored the response of NPP to N and CO2 fertilization from perturbation experiments. More detail of results from the Davies Barnard paper have been added to a new discussion section.

In addition,<sup>15</sup> the TRENDY model simulation S2 doesn't take into account land use change and the fertilization of crops. Crop fertilization is a major source of leaching and gaseous emissions of N2O and NOx. I am wondering if this is the possible reason that the simulated leaching in Figure 4 is so low compared to other estimates.

Yes, it is quite likely although we haven't explicitly quantified that. We have added a discussion about N fertilization and leaching into the leaching section.

Also, does the model simulate the realistic sign of response when driven with climate forcing only. Typically, a model's response to various forcings allows to see at least if the sign of the response is consistent with expectations.

These biogeochemistry only/ radiative only/no N deposition runs are available in TRENDY and C4MIP and will be assessed as part of our future work. However, we think it is beyond the scope of this paper to include a comprehensive assessment of these results. We will refer to these studies as part of the new discussion.

4. I realize that there are very few observation-based estimates available for N related pools and fluxes. However, still there are plenty of quasi-observation and model based estimates against which model results could have been compared. For example, in Figure 4 there are no quasi-observed or model estimates for several quantities. Model estimates are, however, available for immobilization and mineralization (von Bloh et al. 2018), plant N uptake (Zaehle et al. 2010; Xu-Ri and Prentice, 2008; Wania et al., 2012), and inorganic N mass (von Bloh et al. 2018; Xu-Ri and Prentice, 2008; Wania et al., 2012). These estimates will allow to put your model results in some context.

These numbers have been added to figure 4 and it has been noted in the text that some of these comparisons are from other models rather than available observations.

5. Model parameterizations are not compared to other models, and the conceptual basis of parameterizations and their implications, are not discussed (as mentioned above for the choice to reduce NPP and use fixed C:N ratios).

We have significantly revised the model description section. We think our new description will address these concerns in sufficient detail.

For example, biological nitrogen fixation (BNF) is modelled as a straight-forward function of NPP. This is okay but the manuscript doesn't note that meta-analysis studies have found that BNF increases with increasing CO2 (Liang et al., 2016) but decreases with increasing N deposition and fertilizer application (Ochoa-Hueso et al., 2013) both of which apparently result in increase in NPP.

This has been added to the BNF section.

In addition, BNF is typically higher over agricultural areas.

BNF is, in effect, very high over agricultural areas in JULES, as nitrogen is not limiting for cropland areas and the source (fertilisation or BNF) does not affect the model outcome.

Similarly, all gaseous losses are expressed using Nturnover but in nature there are several pathways using which gaseous losses occur. N<sub>2</sub>O and NO<sub>x</sub> losses occur during nitrification (via nitrifier denitrification) and N<sub>2</sub>, N<sub>2</sub>O, and NO<sub>x</sub> losses occur during denitrification.

Not interested in losses to atmosphere but removing the appropriate amount of N

It would be scientifically beneficial for the manuscript, and for a reader, if simplifications made are clearly highlighted and their limitations discussed, because then it is possible to interpret the model results in light of these limitations.

We have significantly revised the model description section. We think our new description will address these concerns in sufficient detail.

6. The majority of the results shown in the manuscript focus on the ability of the new model to reproduce all the aspects of the C cycle as the previous model did. As a result, the N cycle module is not evaluated rigorously. The manuscript doesn't report N demand, how it changes over time, what part of the N demand is not met, what part of N demand due to increasing CO<sub>2</sub> is met by N deposition, time series of mineral N pool, time series of plant N uptake, time series of C:N ratio of whole plant and other plant components, and geographical distribution of simulated C:N ratios (even though I realize they are specified). Since this is the first time JULES' N cycle component is being published it is reasonable to expect that such a manuscript will rigorously assess the new N cycle module.

We have added a figure with time series of N demand for growth and spreading, N uptake for growth and spreading alongside the unmet N. Net N mineralisation, C to N ratio of litter,

7. There is no mention of phosphorus cycle at all. It is well known that in the tropics phosphorus limits photosynthesis and not nitrogen. How is this accounted for? My guess is this is somehow built into the V<sub>max</sub> rates which are function of leaf N content (eqn. 51 in Cox 2001). If the model can reproduce correct zonal distribution of GPP it must take phosphorus limitation in the tropics somehow into account.

The effect of Phosphorus has been discussed as part of a future direction and understanding paragraph.

8. Finally, the lack of units, the lack of rate change equations for several pools, and unclear statements make it difficult to understand the model parameterizations as noted below in minor comments. In its current form, there is no way a reader can fully understand and reproduce the parameterizations reported here in some other model.

Units have been added to the relevant variables, additional rate change equations have been added. This has involved quite a few changes which are apparent in the document but hard to read in the document here. I think we have significantly improved the readability of the document. We have also added a nomenclature section as an appendix.

2 Minor comments

9. Abstract, line 8, "It represents all the key terrestrial nitrogen processes in an efficient way.". The word "efficient" here is misleading.

Change to parsimonious



10. Abstract, line 9, I find it extremely confusing that BNF is mentioned as an external input. BNF is how N enters the coupled vegetation and soil system. Consider the case, if we were to refer GPP as an external input since that's how C enters the coupled vegetation and soil system. N deposition and fertilizer, on the other hand, can be called external because they are not natural just like fossil fuel emissions.

Changed to "Biological fixation is dependent on productivity, with nitrogen deposition as an external input"

On page 2, in addition to BNF, leaching is also referred to as an external (loss). This also seems strange since on the carbon cycle side we don't refer to heterotrophic respiration or dissolved inorganic C in runoff as external losses.

Changed to "Nitrogen leaves the vegetation and soil system via leaching and a bulk gas loss parameterisation"

11. Page 2, line 34, "Internally organic N is lost ...". Here "internally", perhaps is much better described as "cycling of N within the coupled vegetation and soil system".

Changed to: "Within the system organic nitrogen is transferred from the vegetation to the soil through the production of litter and disturbance"

12. Page 2, line 36, "Both inorganic and organic nitrogen may become available for plant uptake". Since organic N uptake is very small and therefore not even modelled (including in your model) perhaps it would be better if this is clarified.

Changed to: " , although the amount of inorganic N uptake by plants is small and typically not included in models"

13. Page 2, line 39. "In a changing climate, rising atmospheric CO<sub>2</sub> drives an increase in the terrestrial carbon cycle and Gross Primary Productivity (GPP)." This is a vague sentence. What does "an increase in the terrestrial carbon cycle" mean?

Changed to: "rising atmospheric CO<sub>2</sub> drives an increase in the land carbon uptake and hence an increase in the gross primary productivity. This results in an extra demand for nitrogen which could potentially limit the increase in future carbon stocks"

14. Page 2, line 56, " ... are between a reduction of 39 % and a slight increase of 1% ...". Please consider rewording this sentence/phrase. It is somewhat hard to follow.

Changed to: "For example, [cite{doi:10.1111/gcb.15114}](https://doi.org/10.1111/gcb.15114) used a perturbed model ensemble to show that N limitation reduces both the projected future increase in land carbon store due to CO<sub>2</sub> fertilisation and the projected loss in land carbon due to climate change"

15. Page 3, line 65. " ... and a new managed land module ...". Please consider rewording to "and a new module for land management ...".

Done

16. Page 3, lines 72-74. "This is achieved by extending the implicit representation of nitrogen in the existing dynamic vegetation and plant physiology modules TO EN- ABLE A MORE COMPREHENSIVE NITROGEN CYCLE WITHIN THE LAND SURFACE". Please consider deleting the text in capitals given N cycle framework used here is extremely simplified.

Done

17. Page 3, Lines 74-75. "Nutrient limitation operates through two mechanisms; the available carbon for growth and spreading is reduced and the decomposition of litter carbon into the soil carbon is slowed". The word spreading at this point in the manuscript is unclear. Only after reading the rest of the manuscript it is clear that "spreading" means changes in the spatial extent of vegetation. Please consider using another phrase/word to replace "spreading".

changed to "the available carbon for vegetation uptake is reduced"

Please also consider not using the phrase "decomposition of litter carbon into the soil carbon" here and elsewhere. Technically litter doesn't decompose into soil carbon. As litter decomposes it releases CO<sub>2</sub> and the dead organic matter is broken into smaller more recalcitrant materials, which the models consider as soil carbon. In reality, of course, there is a continuum.

changed to "the decomposition of litter carbon is slowed"

18. Page 4, lines 114-115. "As standard, JULES-C includes an implicit representation of nitrogen which has been extended to be fully interactive.". A sentence or two about how nutrient constraints on photosynthesis are implicitly modelled in JULES-C will be helpful.

Additional text to explain the implicit scheme added - "The philosophy behind the developments described here is to produce a parsimonious model to capture the established first order emergent response of N addition on growth which translates into leaf area and biomass without the complex and uncertain impacts on leaf physiology. Our approach is therefore to simulate the large-scale role of N limitation on vegetation carbon use efficiency (CUE - ratio of net to gross primary productivity) and soil carbon turnover. This is achieved by extending the implicit representation of N in the existing dynamic vegetation and plant physiology modules to be fully interactive. At the core of surface exchange in JULES is a coupled stomatal conductance photosynthesis scheme parameterised in terms of the maximum rate of Rubisco carboxylation,  $V_{cmax}$  (mol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>).  $V_{cmax}$  has a dependency on the leaf N concentration. Similarly, plant maintenance respiration has a dependency on leaf, root and stem N concentration \cite{cox1998canopy,cox1999impact,cox2001,clarketal2011}. Implicit within JULES, even in simulations excluding the carbon cycle is the parameterisation of plant tissue level N concentrations and associated allometry \cite{gmd-13-483-2020}. Simulations with an interactive carbon cycle therefore assume that enough N is available to meet vegetation growth and turnover. Here, we simply limit growth if not enough N is available. To do this requires a full representation of the N cycle in the land surface including a coupled soil carbon-nitrogen and inorganic N scheme."

19. Page 4, line 120. "The vegetation nitrogen component captures the nitrogen limitation on the C stock, and ...". As described here the N limitation acts on NPP which is a C flux and not on the C stock.

changed to "nitrogen limitation on the net primary productivity, and includes retranslocation"

20. Page 4, last sentence, line 126. "... it slows the rate of litter decomposition INTO SOIL ORGANIC MATTER." Please consider removing the phrase in capitals.

Done

21. Page 5, lines 129-135. I felt, it is little too early to introduce the seven JULES- CN parameters given that at this point in the manuscript, the parameterization themselves haven't been introduced.

Moved to the end of the model description section to summarise.

Also on line 130, Does " ... the effective solubility of nitrogen", refers to solubility in water.

Changed to "the effective solubility of nitrogen in water"

22. Section 3.1. It seems the model's roots are in fact fine roots (since  $R_c = L_c$  in eqn(3)), and coarse roots and stem are included in the  $W_c$  term. Please make this clear.

Done

23. For eqn (1) please specify the units of all terms. I suspect these are  $\text{KgC m}^{-2}$ .

Added

24. For eqn (2) what are the units of  $o_l$  and  $L_b$ .

Done

25. What are units of the individual terms in eqn (5) through (9) and the remaining equations.

Added

26. Page 6, lines 160-178. This entire section is based on Figures 2 and 3 which form the backbone of specified C:N ratios and their variation with canopy height. It would be extremely helpful to know the basis of these relationships.

Section 3.1 has been updated to make clear these are the existing relationships that are implicit in the JULES model. The basis for these is now given in the text. "TRIFFID employs fixed allometry such that the split between leaf, root and stem carbon are defined by a single state prognostic variable that defines the total biomass. Biomass density increases via growth and is reduced by litter production and competition. Biomass can also increase by spreading through an increase in covered area. Nitrogen is implemented to limit growth and spreading such that the change in vegetation nitrogen cannot exceed that available. This section documents the vegetation model starting with the vegetation carbon and nitrogen structure (\ref{sec:struc}) including the additional complexity of labile nitrogen (\ref{phen}). The following section describes how growth and spreading is limited by nutrient availability (\ref{sec:allocup}). The final section describes how vegetation carbon and nitrogen is turned over by disturbance and competition (\ref{sec:litter})."

27. Page 6, lines 180-181. "Biological nitrogen fixation (BNF) is ASSUMED TO BE THE largest natural supplier of nitrogen to the terrestrial ecosystem". Consider re- moving the words in capitals and including the word in bold. Fertilizer application is the largest anthropogenic N flux and BNF is largest natural flux.

Done

28. Page 6, line 181. "Following Cleveland et al. (1999), the nitrogen fixation is determined as a proportion of the net primary production before nitrogen limitation (NPPpot)". This is incorrect. Cleveland et al. (1999) parameterized BNF as a function of actual evapotranspiration (AET) not NPP.

While we concur that ET is the primary parameterization described by Cleveland et al. (1999), we refer the reviewer to page 637 of Cleveland et al. (1999): "NPP could also relate to N fixation; NPP may be a proxy for carbon potentially available to fixers. The relationships between N fixation and

modeled NPP are depicted in Figure 2...". It would be remiss to not cite Cleveland as this parameterisation is directly related to that work. We have clarified in the text that NPP is the secondary model from Cleveland et al. (1999).

Also, NPPpot is not defined anywhere close to this equation where it is introduced the first time. The first definition of NPPpot occurs on page 9, line 242, as "NPPpot supplied to TRIFFID represents the potential amount of carbon that can be allocated to growth". Then a somewhat different definition occurs on page 19 which defines NPPpot as the NPP when nitrogen is unlimited. Isn't NPPpot just the NPP from the original framework without any reduction. I don't think, you do a calculation with unlimited N applied, per se.

Changed-We have revised the definition of NPP\_pot to "potential amount of carbon that can be allocated to growth and spreading of the vegetation" and the response ratio to "the ratio of the potential amount of carbon that can be allocated to growth and spreading of the vegetation ( $NPP_{pot}$ ) compared with the actual amount achieved in the natural state (NPP)" We have also added a sentence saying "the NPP\_pot is defined in the same way as the net primary productivity in JULES before the explicit nitrogen cycle was included"

In context of BNF, and eqn (9), the parameter  $\zeta$  is not listed in Table 1.

$\zeta$  is not dependent on pft so I don't think it is necessary to add it to table 1.

29. Page 7, Table 1. It would be extremely help if nI0 is inverted and written as 1 in units of Kg C/Kg N so that the values are easily comparable to C:N ratios reported in literature.

Changed – this statement has been added to the caption: " $n_{I0}$  is the N concentration at the top of the canopy but is shown here as  $1/n_{I0}$  so that it is comparable to expected C:N ratios from the literature."

Also, nI0 is listed twice in Table 1 and please consider rewording "Top leaf N concentration" to "N concentration at the canopy top".

Changed

30. Page 7, lines 188-189. "However, in JULES-CNlayered the vertical distribution of the fixed nitrogen in the soil depends on the root distribution ...". What does "fixed" refers to in this context. Also, at this stage in the manuscript it is not clear what does "depends on root distribution" means?

Changed to "However, in JULES-CN $_{layered}$  the  $BNF$  is distributed vertically in the soil depending on the fraction of roots in each layer. If a soil layer is frozen there is no  $BNF$  into that layer."

31. Page 7, lines 201-203. "This distinction is inconsequential in the carbon only mode but is more critical when considering nitrogen interactions as the implication is that at all times the plant has enough nitrogen in reserve to maintain full leaf". From here on it becomes difficult to follow the logic used in the model. I am not able to understand what does "the plant has enough nitrogen in reserve to maintain full leaf" means?

This section has been restructured and clarified.

32. Page 8, eqn. (10). I am confused here. Lb is introduced as a variable called balanced leaf area index but not explained what actually it means. In eqn (2), leaf C, LC is a function of Lb. In equation

(9), leaf area index (LAI) ( $L$ ) is also related to  $L_b$  through  $p$ . Somewhere here, there is the split of  $LC$  into labile and non-labile (the one which determines the actual LAI). Did I get this correct? How are  $L$  in eqn. (9) and  $LC$  in eqn. (2) related? Are they related through specific leaf area (SLA)?

This section has been updated. Now  $L_b$  is clearly defined, and it has been made clear this variable is the main mechanism that changing vegetation structure affects surface exchange. Units are now explicit.

33. All through up to this point in the manuscript, the rate change equations for the vegetation N pool are not presented. At this point in the manuscript, I am still unclear what "retranslocation" means. Is this the transfer of resorbed N from leaves before they are shed. If yes, to which plant components?

The whole section has now been updated and clarified. Retranslocation is nitrogen being moved from leaves to the labile pool prior to leaf fall.

34. page 8, lines 251-216. "During leaf-off the labile component is the equivalent of the retranslocated leaf nitrogen plus an additional store of nitrogen in preparation for the following bud burst". This sentence introduces yet another pool. It would be really helpful if all the pools and their rate change equations are properly introduced.

The rate change equations are included. The structure has been updated to clarify the pools and the implementation of rate changes.

35. Page 8, line 29. "The mean canopy nitrogen content is described by ...". Please reword this to "The vertical distribution of leaf N content in the canopy is described by ...".

done

36. Page 9, line 235. "Canopy Leaf C:N ratios are resultingly 44% higher than top leaf ratios". I am unable to understand this. Does "canopy leaf C:N ratios" refers to mean canopy leaf C:N ratio or the vertical profile of C:N ratios along the canopy depth starting from the top.

The mean canopy C:N ratio. Text clarified.

If leaf N content in the leaves at the top of the canopy is higher and decreases exponentially, and if C content is uniform than it implies that C:N ratio of leaves is lower in the leaves at the top of the canopy and higher at the bottom. Integrating eqn (12) over LAI yields  $\int L n_0 \exp(-knz) dz = n_0 L (1 - \exp(-knL))$  which implies that the mean C:N will depend on the LAI,  $L$ . So I am unclear where does the number 44% comes from.

Agreed. However, in the Mercado implementation there is no dependence on total LAI.  $z$  is the fraction of the canopy above a point in the canopy and is therefore independent of LAI. The implication of this is being explored elsewhere.

37. Page 9. Section 3.1.4. The term  $\Lambda_{lc}$  in eqn. (13) is not defined and only when the reader reaches eqn. (21) it is clear what this term is. Similarly for  $\Lambda_{ln}$ .

Updated and clarified.

38. Page 10. Line 263.  $\Lambda_n$  is defined as the retranslocation of nitrogen from leaves and roots into the plant labile pool. I am not sure how does it relate to  $p$  in equation 10 which is also related to retranslocation.

Clarified in the text. Here, retranslocation is used to define the flux of carbon. In eq 10, the retranslocation coefficient is used to parameterise the labile store. Under the assumption that higher retranslocation corresponds to a greater store.

39. Where is  $\Psi_c$  from equation (13) defined? Is this what  $\Psi$  is in eqn. (17)?

Apologies, this was a typo and should be  $\Psi_g$ .

40. Page 10. Line 271. "The nitrogen available for growth is the total available nitrogen multiplied ...". Please reword this as "The nitrogen uptake used for plant growth is the total nitrogen uptake multiplied ...". I think, that's what is meant here. Available N sounds like the N available in the soil inorganic pool that can be potentially taken up by plants.

done

41. Page 10. Line 272. "Equations 13 and 15 are then solved by bisection such that the nitrogen uptake for growth ( $\Phi_g$ ) is less than or equal to the available nitrogen...". Do you mean the bisection method to find root of an equation? This and remaining part of this paragraph is difficult to understand since there is no  $\Phi_g$  term in either equation (13) or (15).

This section has been updated to explain more clearly the solution to the equations presented.

In addition, since units of the various terms are not provided it is difficult to follow the equations on page 10.

42. Page 10, line 282. "... and  $N_v/C_v$  defines the whole plant C:N ratio ...". You mean  $C_v/N_v$ ?

Now given as the inverse of the whole plant C:N ratio

43. In the absence of the competition module of the TRIFFID model properly described it is difficult for a reader to know what does "density-dependent litter production" and "density-dependent component for intra-PFT competition for space" means in Section 3.1.5. Please consider introducing this in a sentence or two.

Done

44. Page 11, please define  $\Lambda_c$  and  $\Lambda_n$  in words explicitly where they are first introduced.  $\Lambda_c$  was introduced in equation (22) but not defined until next page near eqn. (28).

Done

45. Page 11, lines 310-311. "The effect of nitrogen limitation on the litter carbon flux is captured in the excess carbon term  $\Psi_i$ ". Throughout the manuscript there is no expression for  $\Psi_i$  so it's difficult

to understand it. I do understand based on what is written in the manuscript that it the excess C that cannot be used. So it must be related to N uptake, allocation fractions for C, and specified C:N ratio of the three C pools.

Made it clearer in the text that the subscript,  $i$ , is used to indicate PFT levels and is defined in previous equations.

46. Page 12, line 339. " $\beta_R$  depends on soil texture". I don't think, this dependence can be too strong. Can you please mention the typical value of  $\beta_R$ .

This line has been added:  $(1-\beta_R)$  is the fraction of soil respiration that is emitted to the atmosphere - this depends on soil texture and ranges from 0.75 for a clay soil to 0.85 for a soil with no clay content

47. The rate change equations for litter and soil C pools are helpful. Similar equations for vegetation C and N pools would be so helpful.

The rate changes are in Eq 12 and 14. This section should be a lot clearer now.

48. Page 13, line 349-350. "Input into the BIO and HUM nitrogen pools comes from the total immobilisation of inorganic nitrogen into organic nitrogen where  $I_{tot} = I_{DPM} + I_{RPM} + I_{BIO} + I_{HUM}$ ".  $I_{tot}$  is divided into BIO and HUM pools. Since BIO is the microbial pool shouldn't all immobilization end up there.

In reality, carbon (and therefore also nitrogen) should go from litter pools -> microbe pool -> Humified pool (since HUM is made of microbial necromass). But in RothC, carbon can go straight from litter to HUM. Therefore the nitrogen fluxes must follow this as well. This sentence now says: "Following the framework of the RothC model, input into both the  $BIO$  and  $HUM$  nitrogen pools is from the total immobilisation of inorganic nitrogen into organic nitrogen where  $I_{tot} = I_{DPM} + I_{RPM} + I_{BIO} + I_{HUM}$  (in  $kg\ N\ m^{-2}\ s^{-1}$ )"

49. Page 13, eqn (33). Does the subscript  $i$  still refers to PFTs?

Changed  $i$  to  $p$  so soil carbon pools are represented by subscript  $p$  and vegetation pfts are always represented by subscript  $i$ .

50. Page 13, line 365. "... the respired fraction ( $\beta_R$ ) and the C to N ratio of the destination pool ...". This is confusing since on line 339  $(1-\beta_R)$  was referred to as "the fraction of soil respiration that is emitted to the atmosphere".

This was a mistake in line 365 - the fraction respired to the atmosphere is  $(1-\beta_{R,i})$

51. Page 14, line 371. "... where  $i$  is one of RPM or DPM." Please use a different subscript here since you have used  $i$  previously to represent PFTs.

Changed  $i$  to  $p$  so soil carbon pools are represented by subscript  $p$  and vegetation pfts are always represented by subscript  $i$ .

52. Pages 13 and 14. The FN terms in eqn (36) limits the respiration of the DPM and RPM litter pools. So it is unclear to me why FN would depend on  $I_{BIO}$  and  $I_{HUM}$  in eqn. (37).

Respiration is carried out by microbes so they won't decompose as much of the DPM/RPM pools if they haven't got enough nitrogen to convert that carbon into BIO/HUM. The total amount of

nitrogen they have available depends on  $I_{\text{BIO}}$  and  $I_{\text{HUM}}$  because  $M_{\text{BIO}} - I_{\text{BIO}}$  (and similarly  $M_{\text{HUM}} - I_{\text{HUM}}$ ) is the net mineralised nitrogen from the turnover of BIO and HUM. This has been added: "Respiration is carried out by microbes who require sufficient nitrogen to convert the  $\$RPM\$$  and  $\$DPM\$$  pools into  $\$BIO\$$  and  $\$HUM\$$  pools. This nitrogen is available from the net mineralised nitrogen from the turnover of  $\$BIO\$$  and  $\$HUM\$$  pools."

In this same equation, I am also unclear what is  $N_{\text{avail}}$  at this point in the manuscript. As with several other terms, the terms are introduced but their expressions are mentioned or the terms clarified much later which makes it very difficult to follow the logic. It is only further down in eqn. (51) that  $N_{\text{avail}}$  is clarified.

A pointer to  $N_{\text{avail}}$  which has been redefined as  $N_{\text{inorg}}$  for the bulk case has been added to help the document flow better.  $F_n$  has also been added to the vertically resolved case because it has a slightly different definition.

Also, in eqn. (37) what happens if  $DDP_M$  or  $DRP_M$  are negative? Is this possible, since mineralization can be more than immobilization?

They are always positive because the values for  $CN_{\text{soil}}$  are  $\ll CN_{\text{dpm/rpm}}$ . If they were negative,  $F_n$  should just be 1 because there would be more mineralisation than immobilisation from **all** pools. A sentence to address this has been added to the paper: "The demand is always positive because the C to N ratio of soil is very much less than the C to N ratio of the  $\$DPM\$$  and  $\$RPM\$$  pools"

53. Page 14. Similarly in eqn. (39) can  $I_{\text{tot}}$  be more than  $M_{\text{tot}}$  making  $N_{\text{gas}}$  negative.

Fluxes will have been limited by  $F_n$  to make sure this isn't negative. If it hits the minimum pool size, it calculates a correction term ( $neg_n$ ) and that correction term is then included as a negative gas flux. But that is applied just as an 'extra' gas flux and not applied to  $minI$  and  $immob$ . So Eq 39 is never negative, but gas flux can be, if that makes sense! This has been added: ".  $f_{\text{N}}$  limits the nitrogen fluxes so that  $(M_{\text{tot}} - I_{\text{tot}})$  is always positive. However, if pool sizes become too small  $N_{\text{gas}}$  could become negative to ensure nitrogen is conserved."

54. Page 15. Eqn. (41). Is  $fdpm$  used here different from  $fDPM$  used in eqn. (25).

Changed – they are the same.

55. Page 15. Lines 416-417. "The litter inputs are distributed so that they decline exponentially with depth, with an e-folding depth of 0.2 m". With this parameterization can litter enter a soil layer even if there are no roots in that layer.

This is correct and added "This means that litter can enter a soil layer even if there are no roots in that layer":

56. Page 15. Line 423. Please consider using "bulk" or "single layer" instead of "non-layered".

Changed

57. Please consider using another term for gaseous losses rather than turnover.

Changed "additional inorganic gas loss term"

58. Page 16, Lines 433-434. "Without this additional turnover available N may increase excessively, potentially due to excessive biological fixation in regions that are generally unlimited". What does "regions that are generally unlimited" mean?



Changed "Without this additional gas loss term available N may increase excessively, potentially due to excessive biological fixation in regions where the  $\$NPP\$$  is very close or equal to the  $\$NPP_{\text{pot}}\$$ "

59. Page 16. Line 434-435. "In the current model configuration this parameter is set to 1.0 (360 day<sup>-1</sup>) such that the whole pool turns over once every model year". Do you mean 1.0 year<sup>-1</sup> which would translate to (1/360) day<sup>-1</sup> and not 360 day<sup>-1</sup>? Also, since the time step of the biogeochemistry is the same as for TRIF- FID (i.e. 10 days) there has to be  $\Delta T$  somewhere. And, I suspect, <sup>25</sup>360 is used and not 365 since the calendar year in the UKESM model is 360 days. Correct?

Changed to "1/360 (day<sup>-1</sup>)". Indeed 360 days represents a year in UKESM.

60. Page 16, line 436. "This results in an effective saturation limit of 0.002 KgN m<sup>-2</sup>...". Not clear - saturation limit of what?

Turnover is limited by typical fluxes in and out of pool. In practise it never gets bigger. This line has been deleted.

61. What are the units of  $\beta$  in eqn. (47). Just above eqn. (47)  $\beta$  is said to be assigned "a value of 0.1 based on sorption buffer coefficient of Ammonia although here it represents the sorption of all inorganic nitrogen species". Note here that typically only NO<sub>3</sub><sup>-</sup> leaches into the runoff and not NH<sub>4</sub><sup>+</sup> so please consider modifying this sentence.

Beta is dimensionless (added) and the sentence is changed to: ' $\beta$  is assumed to have a value of 0.1 and in JULES-CN represents the combined sorption of all inorganic nitrogen species [\cite{wania2012carbon}](#).'

62. Page 16. Eqn. (48). Isn't  $f_1$  simply the fraction of roots in each soil layer. And again,  $f_2$  is not defined or described here but further down in eqn. (53).

We have reformatted this section in an attempt to make things clearer. It now includes the following straight after the equation to act as a better signpost. Each of the modified components of Equation [\ref{eq:ninorg}](#) are discussed in detail below. The additional parameters required are  $f_{R,i}(z)$  - the fraction of roots in each layer (Equation [\ref{eq:norm\\_root}](#));  $f_{l,i}(z)$  - the fraction of available inorganic nitrogen in each layer (Equation [\ref{eq:frac\\_avail}](#)) and  $\$N_{\text{flux}}\$$  - the transport of inorganic nitrogen from the layer by the soil water fluxes (Equation [\ref{eq:layer\\_leach}](#)).

63. Page 16. Line 453. "where  $f_{\text{root}}(z)$  is the volumetric root fraction at a given depth". You mean "for a given soil layer" as opposed to "at a given depth". And, an  $i$  subscript seems to be missing here. Although, I wouldn't suggest using  $i$  which has been used for PFTs, DPM or RPM, and now soil layers. Very confusing!

Definitely confusing!  $i$  is actually for pft here. We have clarified and change the soil carbon pools to a  $p$ ! Also added the  $I$  where required on the  $f_{\text{root}}$  term.

64. Page 17, eqn. (50). Is the parameter  $\tau_{\text{resp}}$  tuned so that  $N_{\text{turnover}}$  is similar in the "bulk" and "layered" versions.

This has been added: Here  $\tau_{\text{resp}}$  was tuned to give a realistic estimate of soil carbon in a vertically resolved version of JULES-C as in [\cite{burke2016gmd}](#)

65. Page 17. Eqn (51). Assuming, the subscript  $i$  represents the PFT shouldn't there be  $(z)$  term here to indicate the nitrogen availability in each layer.

Added the z to this equation. Ive tried to clarify the i represents PFT.

66. Page 17. Eqn (52). I am unable to follow eqn. (51). Looking at eqn. (51) the term in parantheses in eqn. (52) should be zero since  $N_{in} = N_{avail}$  from eqn. (51).

Indeed this is correct – Equation 51 is for an equilibrium state whereas equation 52 is for a transient state.

The value/units of  $\gamma_{diff}$  is also confusing. I am not sure what  $100 [360 \text{ day}]^{-1}$  means.

Units of this parameter have been changed so it is per day instead of per 360 days.

67. Page 17, lines 471-474. "Any fixation goes directly into the available pool, and other fluxes are simply added according to the ratio of the available to total inorganic N pools at equilibrium (thus the available pool would always follow Equation 51 were it not for the fixation and uptake by plants)". I am sorry but I am unable to follow this sentence.

This has been rephrased to make it clearer – particularly focusing on the definition of equilibrium.

68. Page 17. Eqn. (54). In the absence of its units, I am not sure if the term  $dz_n$  is a single variable or do you mean  $\Delta z_n$ . And, I have no clue, what  $z_n$  is at this point in the manuscript.

We have rewritten this equation and text: Leaching is now done in a process-based manner, where the inorganic N is transported through the soil profile by the soil water fluxes. For any given soil layer  $n$  of thickness  $\Delta z_n$ , the inorganic N flux ( $N_{flux,n}$ ) of layer  $n$  is given by:

$$\text{\label{eq:layer\_leach}}$$

$$N_{flux,n} = \beta \Delta z_n \frac{d}{dz} \left( W_{flux,n} \frac{N_{in,n}}{\theta_n} \right)$$

$$\text{\end{equation}}$$

where  $\theta_n(z)$  is the soil water content of layer  $n$  in  $\text{kg m}^{-2}$  and  $W_{flux,n}$  is the flow rate of the water through soil layer  $n$  in  $\text{kg m}^{-2} \text{ s}^{-1}$ . Multiplying by  $\Delta z_n$  gives the change in N content for each layer,  $\Delta N_n$ . The total leaching is then the sum of all nitrogen that leaves the soil by lateral runoff or out of the bottom soil layer.

69. Page 17. Line 483. "... is then the sum of all nitrogen that leaves the soil by lateral runoff ...". Does the lateral runoff from each layer mean that JULES is capable of producing runoff based on slope of the ground? Please clarify what exactly lateral runoff means.

We have removed the more specific details of how the water leaves the soil as I think it complicates further an already complicated paper. However, JULES has a version of TOPMODEL which can be switched on to generate lateral flows

<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2004GL020919>

70. Page 18. Lines 501-502. "They were spun up by repeating the time period 1860- 1870 ...". This is confusing. Please consider rewording as "The models were spun up by using the meteorological data for the period 1860-1870 repeatedly..."

Changed

71. Page 19. Lines 522-524. "The main difference is the present-day NPP which is 12% higher in JULES-C than in JULES-CN. This is a direct consequence of nitrogen limitation which restricts the

ability of the plants to utilise all of the carbon". No this is the direct consequence of JULES-CN reducing NPP. I don't think, it is necessary to spin this in a more biological way.

### Changed

72. In Figure 4, it would be really useful to see separate estimates for mineralization and immobilization. In its current form, only net mineralization is reported.

This figure has been updated and now includes both immobilisation and mineralisation.

73. Page 20. Lines 580-582. "This [CUE] represents the capacity of the plants to allocate carbon from photosynthesis to the terrestrial biomass". I don't think this sentence is entirely correct. Since CUE is the fraction of GPP converted to NPP, it is a measure of autotrophic respiration.

Changed to: Plants with a higher CUE have a lower autotrophic respiration and allocate more carbon from photosynthesis to the terrestrial biomass and vice-versa.

74. Page 20, line 582-583. "In the model nitrogen limitation restricts the ability of plants to allocate carbon and reduces the carbon use efficiency". Here again, the "restriction of ability of plants to allocate carbon" appears as if carbon is there but somehow plants can not allocate it. In contrast, as JULES-CN is designed, there is simply less carbon to be allocated. I don't think, JULES' allocation module has been changed in JULES-CN to limit how much C flows to different components.

Changed to: In JULES-CN there is less carbon available to be allocated because it is constrained by the amount of N present. This reduces the carbon use efficiency.

75. Page 21. Line 596. "... by structural changes in the vegetation in particular ...". Please clarify if structural changes refer to changes in vegetation height, LAI, and rooting depth.

This is mainly the vegetation distribution – this has been made clearer in the text.

76. Page 22. Lines 626-628. "There remains a significant underestimate of NEE in the years following the Pinatubo volcanic eruption ...". Please make it explicit in which year Pinatubo erupted since it's not marked in Figure 12.

Pinatubo erupted in 1991 – this has been added.

77. Page 22. Line 646. Please change "tome" to "time".

this has been changed.

78. Page 23. Line 656. "In this model, nitrogen limitation affects NPP and how the carbon is allocated ...". As mentioned above, I think, it's more appropriate to say how much C is allocated since the underlying C allocation module has not changed between JULES-C and JULES-CN.

this has been changed.

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## JULES-CN: a coupled terrestrial Carbon-Nitrogen Scheme (JULES vn5.1)

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**Abstract.** Understanding future changes in the terrestrial carbon cycle is important for reliable  
30 projections of climate change and impacts on ecosystems. It is known that nitrogen could limit  
plants' response to increased atmospheric carbon dioxide and is therefore important to include in  
Earth System Models. Here we present the implementation of the terrestrial nitrogen cycle in ~~the~~  
~~JULESland surface model (JULES-CN)~~Joint UK Land Environment Simulator (JULES) - the land  
surface scheme of the UK Earth System Model (UKESM). Two ~~versions~~configurations are discussed  
35 - the ~~one implemented within the UK Earth System Model (UKESM1) which first one (JULES-CN)~~  
has a bulk soil biogeochemical model and ~~a development version~~the second one is a development  
configuration which resolves the soil biogeochemistry with depth ~~.-The nitrogen (JULES-CN<sub>layer</sub>).~~  
In JULES the nitrogen (N) cycle is based on the existing carbon cycle in the model. It (C) cycle  
and represents all the key terrestrial nitrogen processes in an efficient N processes in a parsimonious  
40 way. Biological N fixation is dependent on productivity, with ~~nitrogen-N~~N deposition as an external  
input. ~~Loss occurs~~Nitrogen leaves the vegetation and soil system via leaching and a bulk gas loss  
parameterisation. Nutrient limitation reduces carbon-use efficiency (CUE - ratio of net to gross pri-  
mary productivity) and can slow soil decomposition. We show that ecosystem level N limitation of  
net primary productivity ~~by nitrogen is consistent with observational estimates and that simulated~~  
45 ~~carbon and nitrogen~~(quantified in the model by the ratio of the potential amount of C that can be  
allocated to growth and spreading of the vegetation compared with the actual amount achieved in  
its natural state) falls at the lower end of the observational estimates in forests (approximately 1.0  
in the model compared with 1.01 to 1.38 in the observations). The model shows more N limitation  
in tropical savanna and tundra which falls within the range of the available observations. Simulated

50 C and N pools and fluxes are comparable to the limited available observations ~~-. The impact of N~~  
~~limitation is most pronounced in northern mid-latitudes. The~~ and model derived estimates. The in-  
troduction of a nitrogen-N cycle improves the representation of interannual variability of global net  
ecosystem exchange which was much too pronounced in the carbon-C cycle only versions of JULES  
(JULES-C). It also reduces the ~~CUE and alters its response~~ present-day CUE from a global mean  
55 value of 0.45 for JULES-C to 0.41 for JULES-CN and 0.40 for JULES-CN<sub>layer</sub>. The N cycle also  
alters the response of the C fluxes over the twentieth century and limits the CO<sub>2</sub>-fertilisation effect,  
such that the simulated current day land carbon-C sink is reduced by about 0.5 Pg C yr<sup>-1</sup>. The in-  
clusion of a prognostic land nitrogen-N scheme marks a step forward in functionality and realism  
for the JULES and UKESM models.

## 60 **1 Introduction**

Terrestrial ecosystems absorb around 25% of anthropogenic carbon emissions (Le Quéré et al., 2018;  
Friedlingstein et al., 2019), and changes in the future land carbon (C) sink will feedback to climate  
via the proportion of the emissions remaining in the atmosphere. Under projected climate change,  
the primary mechanism for increased terrestrial sequestration is an increase in plant productivity and  
65 biomass, which relies on sufficient availability of nitrogen (N) within the soil-plant system. There-  
fore the availability of nitrogen-N impacts the land carbon-C sink, both in the present and in a higher  
atmospheric carbon dioxide (CO<sub>2</sub>) future.

Nitrogen exists in the terrestrial system in organic and inorganic forms and is continually cycled.  
70 In a stable climate the external ~~inputs-biological fixation and nitrogen deposition-are inputs to~~  
~~the coupled vegetation and soil system-biological N fixation and N deposition-are~~ balanced by the  
~~external losses-leaching and losses from this system-N leaching and N gas loss.~~ Depending on the  
nutrient status of the vegetation and soil, changes in the balance of the inputs and outputs of nitrogen  
N can drive adjustments in vegetation biomass and soil organic matter. ~~Internally organic nitrogen~~  
75 ~~is lost from vegetation~~ Within the system organic N is transferred from the vegetation to the soil  
through the production of litter and disturbance. The litter decomposes into soil organic matter and  
in turn is mineralised into inorganic nitrogen-N. Both inorganic and organic nitrogen-N may become  
available for plant uptake, although the amount of organic N uptake by plants is small and typically  
not included in models (Weintraub and Schimel, 2005).

80

In a changing climate, rising atmospheric CO<sub>2</sub> drives an increase in the ~~terrestrial carbon cycle and~~  
~~Gross Primary Productivity-land C uptake and hence an increase in the gross primary productivity~~  
(GPP). This results in an extra demand for nitrogen will limit the potential N which could potentially  
limit the increase in future carbon-C stocks. For example, Zaehle (2013a) suggest that, in some ar-

85 eas, ~~nitrogen-N~~ could limit future ~~carbon-C~~ uptake by up to 70%. ~~Nitrogen-N~~ cycling also tends to  
reduce the sensitivity of land ~~carbon-C~~ uptake to temperature. Warmer conditions lead to increased  
plant respiration and soil respiration, which tends to reduce the land ~~carbon-C~~ sink. However, the in-  
creased soil respiration also leads to accelerated ~~nitrogen-N~~ mineralisation and increased ~~nitrogen-N~~  
availability to plants, which may provide a counteracting increase in GPP. This latter effect is absent  
90 from models that do not include a ~~nitrogen-N~~ cycle. As a result of neglecting these important effects,  
land-surface models without an interactive ~~nitrogen-N~~ cycle tend to overestimate both CO<sub>2</sub> and tem-  
perature effects on the land ~~carbon-C~~ sink (Wenzel et al., 2016; Cox et al., 2013). In addition, climate  
projections assessed by IPCC using CMIP5 Earth System Models that lacked terrestrial carbon cycle  
Ciais et al. (2014) have been shown to exhibit a major and systematic bias in their future projection  
of land carbon sink Zaehle et al. (2015); Wieder et al. (2015b). An increasing number of land surface  
95 and climate models now include constraints on the land ~~carbon-C~~ sink caused by ~~nitrogen-N~~ limita-  
tion (Zaehle et al., 2014; Wania et al., 2012; Smith et al., 2014). Recent In fact, recent simulations  
have generated a range of estimates for the sensitivity of the C cycle to N availability (Meyerholt  
et al., 2020a; Davies-Barnard et al., 2020; Arora et al., 2019). For example, Meyerholt et al. (2020a)  
100 use used a perturbed model ensemble and show that to show that N limitation reduces both the pro-  
jected future increase in land ~~carbon-store caused by C store due to~~ CO<sub>2</sub> fertilisation ~~is reduced by  
between 9 and 39 % due to nitrogen limitation and the projected losses in terrestrial carbon and  
the projected loss in land C~~ caused by climate change ~~are between a reduction of 39 % and a slight  
increase of 1 %~~. The inclusion of nitrogen cycle processes in many CMIP6 models has been a major  
advance Arora et al. (2019). Jones and Friedlingstein (2020) show how CMIP6 models have a much  
reduced spread in their simulation of airborne fraction than in CMIP5 and this is attributable to the  
inclusion of N-cycle in about half of these latest generation models. But process understanding and  
evaluation of these model is still in its infancy (Davies-Barnard et al., 2020).

110 The purpose of this paper is to describe and evaluate the implementation of a coupled ~~carbon  
and nitrogen-C and N~~ cycle within the Joint UK Land-Environment Simulator (Best et al., 2011;  
Clark et al., 2011) (JULES at vn5.1 - [http://jules-lsm.github.io/vn5.1/release\\_notes/JULES5.1.html](http://jules-lsm.github.io/vn5.1/release_notes/JULES5.1.html)).  
JULES is the land surface component of the later generation of Hadley Centre climate models in-  
cluding the UK Earth System Model (UKESM) (Sellar et al., 2019). The addition of the ~~nitrogen  
component described here N cycle to JULES described in this paper~~ was carried out alongside other  
115 developments such as improved plant physiology and extended plant functional types (Harper et al.,  
2018), an enhanced representation of surface exchange and hydrology (Wiltshire et al., 2020) and a  
new ~~managed-land-module-module for land management~~ (Robertson and Liddicoat, in prep.). These  
separate components have been combined to make the land surface component of UKESM and were  
120 used for the most recent Global Carbon Budget annual assessment (Friedlingstein et al., 2019).

The philosophy behind the developments described here is to produce a parsimonious model ~~that captures the~~ to capture the established first order emergent response of N addition on growth which translates into leaf area index (LAI) and biomass without the complex and uncertain impacts on leaf physiology. Our approach is therefore to simulate the large-scale role of ~~nitrogen limitation on carbon~~ N limitation on vegetation C use efficiency (CUE - ratio of net to gross primary productivity) and ~~net ecosystem productivity (NEP)~~ soil C turnover. This is achieved by extending the implicit representation of ~~nitrogen-N~~ N in the existing dynamic vegetation and plant physiology modules to ~~enable a more comprehensive nitrogen cycle within the land surface. Nutrient~~ be fully interactive. At the core of surface exchange in JULES is a coupled stomatal conductance photosynthesis scheme parameterised in terms of the maximum rate of Rubisco carboxylation,  $V_{cmax}$  ( $\text{mol CO}_2\text{m}^{-2}\text{s}^{-1}$ ).  $V_{cmax}$  has a dependency on the leaf N concentration. Similarly, plant maintenance respiration has a dependency on leaf, root and stem N concentration (Cox et al., 1998, 1999; Cox, 2001; Clark et al., 2011). Implicit within JULES, even in simulations excluding the N cycle is the parameterisation of plant tissue level N concentrations and associated allometry (Wiltshire et al., 2020). Simulations with an interactive C cycle therefore assume that enough N is available to meet vegetation growth and turnover. Here, we simply limit growth if not enough N is available. To do this requires a full representation of the N cycle in the land surface including a coupled soil C and N organic and soil inorganic N scheme.

At the ecosystem level, the C and N cycles are closely coupled with each exchange of C associated with a corresponding flux of organic N. In JULES nutrient limitation operates through two mechanisms; the available ~~carbon for growth and spreading C for vegetation uptake~~ is reduced, and the decomposition of litter ~~carbon into the soil carbon C~~ is slowed. This is achieved by explicitly representing the demand for ~~nitrogen-N~~ N within the vegetation and soil modules and then reducing plant net ~~carbon C~~ gain to match available nutrients. In the soil module an additional decomposition rate modifier is introduced that slows decomposition to match available nutrients. The current structure of the TRIFFID dynamic vegetation model (Cox, 2001), in particular the fixed allometry and ~~carbon C~~ allocation, is largely unchanged. As the aim of this scheme is to capture the impact on terrestrial ~~carbon stores, C stores, N~~ loss terms are aggregated and not speciated. The model's ~~reduction of vegetation growth and spreading due to nitrogen reduced uptake of vegetation C due to N~~ limitation will have only a minor impact on the GPP and ~~autotrophic respiration~~. Therefore the emergent impact of the ~~nitrogen-N~~ N scheme will be to reduce NPP and hence the carbon use efficiency (CUE) of the vegetation. ~~The excess carbon~~ In reality the excess C ( $\Psi$ ) which cannot be used ~~for growth~~ goes to non structural carbohydrates, root exudates and biogenic volatile organic compounds (Collalti and Prentice, 2019).

~~Two nitrogen model configurations are described here JULES-CN and However, to simplify the carbon balance in JULES-CN<sub>tajered</sub> both of which are directly derived from the JULES-C~~



~~configuration. JULES-C is~~, it is added to the autotrophic respiration.

160 A key assumption in the JULES representation of vegetation and common amongst complex  
DGVMs (Meyerholt and Zaehle, 2015) is of fixed plant stoichiometry (mass ratio of C to N atoms  
or C:N ratio). The implication is that leaf-level photosynthetic capacity does not vary with available  
N. This is consistent with field experiments enhancing N fertilisation that find increases in growth  
but no corresponding change in photosynthetic capacity (Brix and Ebell, 1969; Wang et al., 2012)  
165 . However, more recent analyses do make the link between nutrient availability and leaf level N  
concentrations (e.g. Mao et al. (2020)). In general, models make different assumptions about the  
tightness of the coupling mechanism between the C and N cycles leading to substantial uncertainty  
in their projections (Zaehle and Dalmonech, 2011). Within the fully coupled Earth Systems Models  
~~used in the land configuration of the HadGEM2-ES (Collins et al., 2011) Earth System Model used~~  
170 ~~in CMIP5 (Taylor et al., 2012), and is also used in the Global Carbon Budget annual assessments~~  
~~(Le Quéré et al., 2018) coupled carbon-nitrogen model based on JULES-C. The soil biogeochemistry~~  
~~is represented by a single level in JULES-CN whereas it varies as a function of depth in JULES-CN<sub>layered</sub>.~~  
~~This paper describes the additional model structure required for Coupled Climate Carbon Cycle~~  
~~Model Intercomparison Project (C4MIP) for quantifying C feedbacks only four models include a~~  
175 ~~N cycle representation and only two include both N and dynamic vegetation of which JULES is~~  
~~one of them (Arora et al., 2020). The representation of the N cycle in the two configurations; and~~  
~~assesses the simulated stocks and fluxes and their changes over the 20<sup>th</sup> century. full complexity~~  
Earth System Models remains challenging and there is clearly a need for simple models capturing  
the first order responses. This is the first time a N cycle has been incorporated in JULES and it is  
180 expected to be improved and developed with time as the knowledge of how important processes can  
be represented in existing frameworks improves.

## 2 Introduction to JULES model description

JULES is the land surface component of the new UK community Earth System model, ~~UKESM1~~  
185 ~~UKESM~~ (Sellar et al., 2019). JULES can also be run offline forced by observed meteorology glob-  
ally, regionally or at a single location. A full description of the main components of JULES is pro-  
vided by Best et al. (2011) and Clark et al. (2011). In particular, JULES represents the surface energy  
balance, a dynamic snowpack model (one dimensional), vertical heat and water fluxes, soil freezing,  
large scale hydrology, and ~~carbon fluxes and C fluxes and C~~ storage in both vegetation and soil.  
190 Typically JULES represents four soil layers down to a total depth of 3m. Within JULES, ~~carbon-C~~  
dynamics in soils and vegetation and dynamic vegetation are provided by Top-Down Representa-  
tion of Interactive Foliage and Flora Including Dynamics (TRIFFID) (Cox, 2001). In this version

of TRIFFID, five plant functional types (PFTs) are included: broadleaf tree, needleleaf tree,  $C_3$  grasses,  $C_4$  grasses and shrubs. The soil ~~carbon model in JULES-C~~ C model is based on the RothC model (Clark et al., 2011). Recently, ~~Burke et al. (2017); Chadburn et al. (2015)~~ Burke et al. (2017) and Chadburn et al. (2015) added a representation of permafrost soil processes to JULES, including a representation of the vertical distribution of soil ~~carbon-organic C~~ carbon-organic C which we build upon here. ~~JULES-C is the standard carbon cycle configuration (a configuration defines a specific set of switches and parameters) and was used in the Global Carbon Budget annual assessment in 2018~~ (Le Quéré et al., 2018).

### 3 Model developments

What follows is a description of the extension of the ~~carbon cycle used by~~ C cycle already used by the JULES-C ~~in HadGEM2-ES (Collins et al., 2011) and Global Carbon Budget annual assessment in 2018 (Le Quéré et al., 2018)~~ configuration to include an interactive ~~nitrogen cycle~~ N cycle. This results in two new model configurations: JULES-CN and JULES-CN<sub>layer</sub>. The soil biogeochemistry is represented by a single level in JULES-CN whereas it varies as a function of depth in JULES-CN<sub>layer</sub>. As standard, JULES-C includes an implicit representation of ~~nitrogen-N~~ N which has been extended to be fully interactive. ~~The N cycle is included within the TRIFFID dynamic vegetation and RothC soil C models.~~ The N cycle is included within the TRIFFID dynamic vegetation and RothC soil C models. For clarity we include a full description of the C and N cycle including the existing TRIFFID and RothC models and highlight where and how they have been extended.

~~The nitrogen model is included within the TRIFFID dynamic vegetation and RothC soil carbon models. The vegetation nitrogen component captures the nitrogen limitation on the C stock, and includes retranslocation and the presence of a labile N pool per PFT (Figure ??). The vegetation uptakes nitrogen from the inorganic nitrogen pool. In JULES-CN one inorganic nitrogen pool is shared between all of the different PFTs irrespective of their rooting profile. However, in the multi-layered soil biogeochemistry model (JULES-CN<sub>layered</sub>), the availability of inorganic nitrogen depends on the distribution of the plant roots. The soil nitrogen component simulates mineralisation and immobilisation, and during any periods of nitrogen limitation it slows the rate of litter decomposition into soil organic matter.~~

~~JULES-CN requires 7 new parameters (leaf and root retranslocation, the coefficient of fixation, inorganic nitrogen turnover, soil C:N ratios, a gas emission scalar and the effective solubility of nitrogen), 3 prognostics (organic nitrogen pools of decomposable and resistant plant material and an inorganic nitrogen pool) and 3 diagnostic nitrogen pools (plant labile nitrogen, and organic nitrogen pools of humified soil and microbial biomass). JULES-CN<sub>layered</sub> additionally includes the~~

plant available fraction of the inorganic nitrogen pool and a diffusion term to transfer the inorganic nitrogen from plant-unavailable to plant-available.

### 3 JULES developments

#### 230 3.1 ~~Vegetation carbon and nitrogen~~

At the core of the vegetation model is the TRIFFID Dynamic vegetation model (Cox, 2001). TRIFFID represents the vegetation-

#### 3.1 Vegetation C and N

The TRIFFID Dynamic vegetation model represents the core of the vegetation module (Cox, 2001).  
235 TRIFFID represents the vegetation cover at each location in terms of the fractional area covered, and  
the ~~leaf area index and canopy height of each PFT~~ leaf area index (LAI) and canopy height of each  
plant functional type (PFT). In JULES the C fluxes are calculated at the model timestep (typically 0.5  
- 1 hour) prior to any N limitation (if configured). These fluxes are then aggregated to the timestep  
required for running TRIFFID (once every 10 days in the current implementation) so that allocation  
240 of C can take place. TRIFFID employs fixed allometry such that the split between leaf, root and stem  
C are defined by a single state prognostic variable that defines the total biomass. Biomass density  
increases via growth and is reduced by litter production and competition. Biomass can also increase  
by spreading through an increase in covered area. N is implemented to limit growth and spreading  
such that the change in vegetation N cannot exceed the N available.

245

This section documents the vegetation model starting with the structure of the vegetation (Section  
3.1.1) including the additional complexity of labile N (Section 3.1.3). The following subsection  
describes how growth and spreading is limited by N availability (Section 3.1.3). The final subsection  
describes how vegetation C and N is turned over by disturbance and competition and aggregated  
250 from PFTs to the gridbox level (Section 3.1.4). Biological N fixation is input directly into the soil  
inorganic N pool and is described later in Section 3.3.1.

#### 3.1.1 Vegetation Structure

The mean canopy height per PFT  $i$  is converted via allometric equations into a maximum or *balanced*  
255 ~~leaf area index ( $\mathcal{L}_b$ )~~ balanced leaf area index for each PFT ( $\mathcal{L}_{b,i}$  in  $\text{m}^2\text{m}^{-2}$ ).  $\mathcal{L}_{b,i}$  is the prognostic  
variable used in JULES to describe the vegetation and is functionally the equivalent of the potential  
leaf area. Given  $\mathcal{L}_{b,i}$ , leaf, root and wood pools are diagnosed for each PFT. ~~The vegetation carbon~~  
as introduced in Cox (2001). The balanced leaf area index is updated interactively following the  
C balance and is coupled to the surface exchange via surface albedo, roughness and heat capacity.

260 This section is included to fully document the new scheme, but the equations can also be found in Clark et al. (2011).

The vegetation C density per PFT ( $C_{v,i}$  in  $\text{kg [C] m}^{-2}$ ) can be separated into leaf ( $L_c$ ), root ( $R_c$ ), fine root ( $R_{c,i}$  in  $\text{kg [C] m}^{-2}$ ) and total stem ( $W_c$  plus coarse root ( $W_{c,i}$  in  $\text{kg [C] m}^{-2}$ ) pools, each of which is related allometrically to  $\mathcal{L}_b$ : the balanced leaf area ( $\mathcal{L}_{b,i}$ ). Each component is then related to  $\mathcal{L}_{b,i}$ . Root C is set equal to leaf C, which is itself a linear function of  $\mathcal{L}_{b,i}$ , and total stem C is related to  $\mathcal{L}_{b,i}$  by a power law (Enquist et al., 1998):

$$C_{v,i} = L_{c,i} + R_{c,i} + W_{c,i} \quad (1)$$

270  $L_{c,i} = \sigma_{l,i} \mathcal{L}_{b,i} \quad (2)$

$$R_{c,i} = L_{c,i} \quad (3)$$

$$W_{c,i} = a_{wl,i} (\mathcal{L}_{b,i})^{b_{wl,i}} \quad (4)$$

275  $C_v = L_c + R_c + W_c$

$$L_c = \sigma_l \mathcal{L}_b$$

$$R_c = L_c$$

280  $W_c = a_{wl} (\mathcal{L}_b)^{b_{wl}}$

Where  $\sigma_l$ ,  $a_{wl}$  and  $b_{wl}$  Where  $\sigma_{l,i}$  ( $\text{kg [C] m}^{-2}$ ),  $a_{wl,i}$  ( $\text{kg [C] m}^{-2}$ ) and  $b_{wl,i}$  (dimensionless) are PFT dependent allometric parameters (defined in Table 1). By definition  $\mathcal{L}_b$   $\mathcal{L}_{b,i}$  does not have an explicit seasonal cycle but responds to changes in the vegetation carbon C on both short (seasonal) and long (centennial) timescales. A high  $\mathcal{L}_{b,i}$  is related to a high C density and tall canopies. It should be noted that leaf seasonality is represented by a separate phenology model. A high  $\mathcal{L}_b$  is related to a high carbon density and canopy height. The canopy height ( $h$ ) is defined allometrically by: and is not directly affected by N availability. TRIFFID combines Equation 4 with a "pipe model" approach (Shinozaki et al., 1964a, b) to obtain the canopy height for PFT  $i$  ( $h_i$  in m):

290 
$$h_i = \frac{W_{c,i}}{a_{wl,i} \eta_{sl,i}} \left( \frac{a_{wl,i}}{W_{c,i}} \right)^{1/b_{wl,i}} \quad (5)$$

$$h = \frac{W_c}{a_{wl}\eta_{sl}} \left( \frac{a_{wl}}{W_c} \right)^{1/b_{wt}}$$

where  $\eta_{sl}$  where  $\eta_{sl,i}$  (kg [C] m<sup>-2</sup> per unit LAI) relates respiring stem to leaf carbon C (Table 1).

We can combine equations 4 and 5 to relate ( $\epsilon_{b,i}$ ) to canopy height ( $h_{l,i}$ ) and these two variables can be used interchangeably to describe the state of the vegetation. During a simulation the C pools are updated interactively and the canopy height and balanced leaf area diagnosed for each PFT. This representation allows changes in vegetation C to feedback to surface exchange.

The root and total stem nitrogen N pools are defined using stoichiometric relationships as a function of the carbon C pools. These stoichiometric functions already exist in the model and are used in the calculation of plant maintenance respiration (Clark et al., 2011). We extend their use to explicitly define nitrogen N pools as part of the new scheme:

$$R_{n,i} = \mu_{rl,i} n_{l0,i} R_{c,i} \quad (6)$$

$$W_{n,i} = \mu_{sl,i} n_{l0,i} W_{c,i} \quad (7)$$

$$R_n = \mu_{rl} n_{l0} R_c$$

$$W_n = \mu_{sl} n_{l0} W_c$$

where  $\mu_{rl}$  and  $\mu_{sl}$  are where  $\mu_{rl,i}$  and  $\mu_{sl,i}$  are dimensionless stoichiometric parameters linking the top leaf nitrogen concentration ( $n_{l0}$  N concentration ( $n_{l0,i}$  in kg [N] kg [C]<sup>-1</sup>) to the total stem and root nitrogen pools ( $W_n$  and  $R_n$ , respectively N pools ( $W_{n,i}$  and  $R_{n,i}$  respectively in kg [N] m<sup>-2</sup>). The leaf nitrogen pool ( $L_n$  N pool ( $L_{n,i}$  in kg [N] m<sup>-2</sup>) has an additional dependency on phenological state (Section 3.1.3) and assumed distribution of nitrogen N in the canopy(?). Following Equation 1 the total vegetation nitrogen N store per PFT ( $N_{v,i}$  in kg [N] m<sup>-2</sup>) is given by:

$$N_{vv,i} = L_{nn,i} + R_{nn,i} + W_{nn,i} \quad (8)$$

The C:N ratio of the root and stem pools are constant fixed in time and leaf pool C:N ratio only varies with phenological state. However, the relative proportions of each pool vary with total biomass resulting in the whole plant C:N ratio increasing with total vegetation carbon (Fig.C for woody PFTs (Figure 1). This is due to the relatively greater proportion of stem carbon C at higher biomass.

Therefore woody vegetation has the highest Grasses show less variation with biomass due to their

**Table 1.** Default values of PFT-specific parameters for allometry, allocation and vegetation **nitrogen-N** and **carbon-C** stoichiometry in the JULES-CN and JULES-CN<sub>layered-layer</sub> configurations. The subscript (*i*) is present to show that it is a PFT-specific value.  $n_{l0,i}$  is the N concentration at the top of the canopy but is shown here as  $1/n_{l0,i}$  so that it is comparable to expected C:N ratios from the literature.

<u>Symbol (units)</u>	<u>Definition</u>	Broadleaf tree	Needleleaf tree
$a_{wt}\sigma_{l,i}$ (kg [C] m <sup>-2</sup> )	<u>Specific density of leaf C</u>	<u>0.0375</u>	<u>0.1000</u>
$a_{wl,i}$ (kg [C] m <sup>-2</sup> )	Allometric coefficient	0.65	0.65
$a_{ws}a_{ws,i}(-)$	Ratio <u>of total to respiring total C to respiring stem C</u>	<u>10.00-10.0</u>	<u>10.00-10.0</u>
$b_{wl,i}(-)$	<u>stem carbon <math>b_{wt}</math> Allometric exponent</u>	1.667	1.667
$\eta_{st}\eta_{sl,i}$ (kg [C] m <sup>-2</sup> per unit LAI)	Live stemwood coefficient	0.01	0.01
$\mu_{rt}\mu_{rl,i}(-)$	Ratio <u>of root root N to top leaf nitrogen-N</u>	<u>1.00-1.0</u>	<u>1.00-1.0</u>
$\mu_{st}\mu_{sl,i}(-)$	Ratio <u>of stem stem N to top leaf nitrogen-N</u>	<u>0.10-0.1</u>	<u>0.10-0.1</u>
$n_{l0}$ (kg [N]/n <sub>l0,i</sub> ((kg [C])(kg [C]/[N]) <sup>-1</sup> ))	<u>Top leaf nitrogen concentration C:N ratio at canopy top</u>	<u>0.046-21.7</u>	<u>0.033-30.3</u>
$k_n-k_{n,i}(-)$	<u>nitrogen-N profile coefficient</u>	0.78	0.78
$\lambda_r-\lambda_{r,i}(-)$	<u>root nitrogen retranslocation coefficient Root N retranslocation coef.</u>	0.2	0.2
$\lambda_l-\lambda_{l,i}(-)$	<u>leaf nitrogen retranslocation coefficient Leaf N retranslocation coef.</u>	0.5	0.5
$\mathcal{L}_{min}\mathcal{L}_{min,i}(-)$	Minimum balanced <u>leaf area index-LAI</u>	3.0	3.0
$\mathcal{L}_{max}\mathcal{L}_{max,i}(-)$	Maximum balanced <u>leaf area index-LAI</u>	9.0	9.0
$n_{l0}$ (kg [N]) (kg [C]) <sup>-1</sup> $f_{DPM,i}(-)$	<u>Top leaf nitrogen concentration Decomposable litter fraction</u>	<u>0.046-0.25</u>	<u>0.033-0.25</u>

comparatively small amount of structural C relative to leaf area, which also results in woody PFTs having higher C:N ratios due to the greater proportion of stem wood in comparison to grasses. The total vegetation **nitrogen-N** increases with canopy height (Fig. and biomass (Figure 2).)

### 325 **3.1.2 Biological Nitrogen Fixation Labile C and N: Phenology and Mobilisation**

Biological nitrogen fixation (BNF) is assumed to be the largest supplier of nitrogen to the terrestrial ecosystem. Following Cleveland et al. (1999), the nitrogen fixation is determined as a proportion of the net primary production before nitrogen limitation ( $NPP_{pot}$ ).

$$F = \zeta NPP_{pot}$$

330 The rate of fixation ( $\zeta$ ) is set such that global present day net primary productivity of approximately 60 Pg C yr<sup>-1</sup> results in approximately 100 Tg N yr<sup>-1</sup> fixation (0.0016 kg N kg C<sup>-1</sup>), within the range most recent global estimate of BNF (Davies-Barnard and Friedlingstein, 2020). In JULES-CN

335 this fixation is directly transferred into the inorganic soil nitrogen pool and becomes available as inorganic nitrogen. However, in JULES-CN<sub>layered</sub> the vertical distribution of the fixed nitrogen in the soil depends on the root distribution and the freeze/thawed status (being distributed proportionally to the fraction of roots in each layer, discounting any frozen layers). If the whole soil is frozen, fixed nitrogen goes into the inorganic nitrogen pool in the top layer. This parameterisation results in a latitudinal gradient with the highest rates of fixation in the tropics and lowest in boreal forests and arctic tundra which is consistent with some estimates of BNF (Houlton et al., 2008) though not  
 340 recent observation meta-analyses (Davies-Barnard and Friedlingstein, 2020).

### 3.1.3 Phenology and Mobilisation

The leaf carbon pool ( $L_c$ , total leaf C pool per PFT ( $L_{c,i}$ , Equation 2) varies allometrically with the vegetation carbon C state on both short (seasonal) and long (centennial) timescales but not with changes in phenological state. Implicit within TRIFFID is a labile leaf carbon C pool that acts as a  
 345 reserve of carbon C during spring and a store during fall.  $L_c$  is therefore the sum of  $L_{c,i}$  therefore includes a labile pool from which carbon C can be mobilised during leaf out plus an allocated pool representing the actual leaf area index LAI. The labile pool is zero at full leaf out and at the allometrically defined maximum during the no leaf period. This distinction is inconsequential in the carbon-only mode but is more critical when considering nitrogen interactions as the implication is  
 350 that at all times the plant has enough nitrogen in reserve to maintain full leaf. We therefore include a As part of the N coupling we introduce the ability for plants to retranslocate some of the allocated N to the labile N pool according to the phenology. The new parameterisation of retranslocation and labile nitrogen that is N is therefore dependent on the phenological state. Leaf leaf phenological state as well as the fixed stoichiometry. In JULES, leaf phenology is controlled by a second state variable  
 355 ( $p_i$ ) which relates the leaf area index LAI ( $\mathcal{L}_i$ ) at any moment in time to the balanced leaf area index ( $\mathcal{L}_b$ ),  $\mathcal{L}_{b,i}$ .

$$\mathcal{L}_i = p_i \mathcal{L}_{b,i} \quad (9)$$

where  $p_i$  is a scalar between 0 and 1 that describes the phenological state of the system (Clark et al., 2011). For evergreen plants  $p_i$  is a constant of 1. The two state variables  $\mathcal{L}_b$  and  $p_i \mathcal{L}_{b,i}$  and  
 360  $p_i$  combine to define the vegetation state  $\tau_i$  for each PFT  $i$ . Using the phenological state we extend the equivalent approach to leaf carbon to include the role of retranslocation of nitrogen from the leaves during leaf fall. The leaf nitrogen pool is the sum of allocated and labile components with additional dependencies on the distribution of nitrogen in the canopy and phenological state. This means that the stoichiometry of the allocated and labile components are different. During leaf-off the labile component is the equivalent of the  
 365 retranslocated leaf nitrogen plus an additional store of nitrogen in preparation for the following bud burst. Higher retranslocation implies a larger labile nitrogen store.  $L_n$  C such that the leaf

N pool ( $L_{n,i}$ ) has fixed allometry dependent on the phenological state and the magnitude of leaf retranslocation. We introduce this simple parameterisation under the assumption that higher leaf retranslocation during autumn implies a higher labile N store. The leaf N pool therefore becomes:

$$L_{n,i} = p_i n_{lc,i} L_{c,i} + (1 - p_i) \left( \frac{1 + \lambda_{l,i}}{2} \right) n_{lc,i} L_{c,i} \quad (10)$$

$$L_n = p n_{lc} L_c + (1 - p) \left( \frac{1 + \lambda_l}{2} \right) n_{lc} L_c$$

where  $\lambda_l$  is the leaf nitrogen retranslocation coefficient and  $n_{lc}$  is the mean canopy nitrogen content (Eq. 11). Here  $\lambda_{l,i}$  is set to 0.5 for all PFTs (Zaehle and Friend, 2010). The labile pool is formulated so formulation of the labile pool, in this configuration, means that around half of the nitrogen N required for full leaf-out is taken from retranslocation with a further quarter acquired during the dormant phase, while the rest is acquired during the active period.

### 3.1.3 Canopy nitrogen

JULES includes JULES assumes a process-based scaling-up of leaf level photosynthesis to the canopy level. There are two options for the canopy scaling-up including the ‘big-leaf’ and a ‘multi-layer’ approach. In both the JULES-CN and JULES-CN<sub>layered layer</sub> configurations, to be consistent with the JULES-C model, we assume a multi-level canopy with leaf nitrogen N decreasing exponentially through the canopy (CanRadMod 5). The mean canopy nitrogen content plant physiology routines uses this assumed distribution to calculate penetration through the canopy and photosynthesis on individual layers before scaling back to the canopy (Clark et al., 2011). In the application here, we use this distribution to be fully consistent with the physiology. The vertical distribution of leaf N content in the canopy is described by (Mercado et al., 2007):

$$n_{lc,i}(d) = n_{l0,i} \exp(-k_{n,i} d) \quad (11)$$

$$n_{lc} = n_{l0} \exp(-k_n z)$$

where  $k_n$  where  $k_{n,i}$  is a constant representing the profile of nitrogen and  $z$  N and  $d$  represents the fraction of canopy above the layer. Based on observed nitrogen N profiles in the Amazon basin (Carswell et al., 2000), a value of 0.78 for  $k_n$  was found (Mercado et al., 2007). Equation 11 is independent of leaf area and therefore equates to a constant of proportionality relating PFT-specific top leaf nitrogen ( $n_{l0}$  Table 1) N to the mean canopy nitrogen concentration. Canopy Leaf N concentration. The mean canopy leaf C:N ratios are resultingly ratio is consequently ~44% higher



than ~~top leaf ratios~~ the top leaf ratio.

400 ~~Here we probably should include something on n on layers in photosynthesis~~

### 3.1.3 Vegetation Growth and Allocation

The previous section describe how the vegetation C ( $C_{v,i}$ , Equation 1) and vegetation N ( $N_{v,i}$ , Equation 8) for each PFT vary with vegetation size and phenological state. This section ~~was supposed to differentiate those two components~~ describes how growth and spreading are limited by available N. Growth is the increase in C density and spreading is the increase in vegetation cover from recruitment and reproduction.

### 3.1.4 **Allocation**

Net Primary Productivity (NPP) in JULES-C is simply the difference between GPP and autotrophic respiration ( $R_a$ ). In JULES-CN the ~~GPP,  $NPP_{pot}$  and autotrophic respiration are calculated at the model timestep (1-hour potential NPP or  $NPP_{pot}$  is defined in the same way as the NPP in JULES-C) prior to any N limitation. These fluxes are then aggregated to the timestep for running TRIFFID (once every 10 days in the JULES-C configuration) so that allocation of carbon can take place.  $NPP_{pot}$  supplied to TRIFFID represents before the explicit N cycle was included, i.e.~~ the potential amount of carbon C that can be allocated to growth and spreading (~~spreading is the increase in PFT fractional coverage~~). ~~In by TRIFFID. In JULES-CN and in~~ order for the NPP to achieve its potential it needs to be able to uptake sufficient inorganic nitrogen N. If not enough inorganic nitrogen N is available, the system is nitrogen N limited and an additional term is required in the carbon C balance representing excess carbon C which cannot be assimilated into the plant due to lack of available nitrogen ( $\Psi_c N$ ) ( $\Psi$  in  $\text{kg [C] m}^{-2}$ ). A positive  $\Psi_c \Psi$  results in a reduction of carbon use efficiency. ~~The PFT carbon balance is therefore: (CUE).~~

The C balance per PFT  $i$  is given by:

$$\frac{dC_{v,i}}{dt} = (1 - \lambda_i)\Pi_{c,i} - \Lambda_{l_{c,i}} - \Psi_{g,i} \quad (12)$$

$$425 \quad \frac{dC_v}{dt} = (1 - \lambda)\Pi_c - \Lambda_{l_c} - \Psi_c$$

where  $\Pi_c$  is the net primary productivity where  $\Pi_{c,i}$  is the potential NPP per unit area of PFT (prior to nutrient limitation) and  $\Lambda_{l_c} \Lambda_{l_{c,i}}$  ( $\text{kg [C] m}^{-2}$ ) is the PFT specific litterfall rate (Section 3.1.4). Any excess carbon ( $\Psi_c C$  from growth ( $\Psi_{g,i}$ )) is considered an additional plant respiration term and at the end of the TRIFFID timestep is used to reduce  $NPP_{pot}$  the potential NPP for each PFT to

430 its actual value.  $\lambda_i$  is the coefficient for partitioning the NPP between growth and spreading— $\lambda_i$  is utilised in increasing the fractional coverage of the vegetation and  $(1 - \lambda_i)$  increases the carbon content of the existing vegetated area.  $\lambda_i$  is a function of the vegetation carbon C which itself is a function of the balanced LAI ( $\mathcal{L}_b$ ) for PFT  $i$  ( $\mathcal{L}_{b,i}$ ):

$$\lambda_i = \begin{cases} 1 & \mathcal{L}_{b,i} > \mathcal{L}_{max,i} \\ \frac{\mathcal{L}_{b,i} - \mathcal{L}_{min,i}}{\mathcal{L}_{max,i} - \mathcal{L}_{min,i}} & \mathcal{L}_{min,i} < \mathcal{L}_{b,i} \leq \mathcal{L}_{max,i} \\ 0 & \mathcal{L}_{b,i} \leq \mathcal{L}_{min,i} \end{cases} \quad (13)$$

435 
$$\lambda = \begin{cases} 1 & \mathcal{L}_b > \mathcal{L}_{max} \\ \frac{\mathcal{L}_b - \mathcal{L}_{min}}{\mathcal{L}_{max} - \mathcal{L}_{min}} & \mathcal{L}_{min} < \mathcal{L}_b \leq \mathcal{L}_{max} \\ 0 & \mathcal{L}_b \leq \mathcal{L}_{min} \end{cases}$$

The equivalent N balance per PFT is given by:

$$\frac{dN_{v,i}}{dt} = (1 - \lambda_i)\Phi_i - \Lambda_{ln,i} \quad (14)$$

Should  $\mathcal{L}_b$  fall below  $\mathcal{L}_{min}$  then the carbon available for spreading is decreased and  $\mathcal{L}_b$  set equal to  $\mathcal{L}_{min}$  and the carbon pools re-diagnosed. If  $\mathcal{L}_b$  rises above  $\mathcal{L}_{max}$  then the carbon available for spreading is increased and  $\mathcal{L}_b$  set equal to  $\mathcal{L}_{max}$  and the carbon pools re-diagnosed.

The equivalent PFT nitrogen balance is

$$\frac{dN_v}{dt} = (1 - \lambda)\Phi - \Lambda_{ln}$$

445 where  $\Phi$  is the plant nitrogen where  $\Phi_i$  (kg [N] m<sup>-2</sup>) is the PFT specific N uptake (see below) and  $\Lambda_{ln}$  is the retranslocation of nitrogen Equation 19) and  $(1 - \lambda_i)\Phi_i$  is equal to  $\Phi_{g,i}$ , the N uptake available for growth.  $\Lambda_{ln,i}$  is the PFT N litter flux after retranslocation of N from leaves and roots into the plant labile pool (Section 3.1.4 below). The nitrogen available for spreading is a fraction  $\lambda_i$  of the total available nitrogen and  $(1 - \lambda)$  is N with a fraction  $(1 - \lambda_i)$  available for growth.

In JULES-CN, on a PFT basis, the nitrogen available for plant uptake is the inorganic soil N pool,  $N_{in}$ , split equitably between the PFTs assuming there is no differential ability between PFTs to acquire nitrogen. On a grid cell basis, since the competition for nitrogen depends on the change in carbon over the timestep, larger PFTs have an advantage. The nitrogen uptake in JULES-CN<sub>layered</sub> is more complicated and is discussed in Section 3.3.2.

455 The nitrogen available for growth is the total available nitrogen ( $N_{avail}$ ) multiplied through by  $(1 - \lambda)$ . Litter is produced by the turnover of the leaf, wood and root pools for each PFT, defined as

$$\Lambda_{lc,i} = \gamma_{l,i}L_{c,i} + \gamma_{r,i}R_{c,i} + \gamma_{w,i}W_{c,i} \quad (15)$$

and

$$\Lambda_{ln,i} = (1 - \lambda_{l,i})\gamma_{l,i}L_{n,i} + (1 - \lambda_{r,i})\gamma_{r,i}R_{n,i} + \gamma_{w,i}W_{n,i} \quad (16)$$

460 for litter C ( $\Lambda_{lc,i}$  in  $\text{kg [C] m}^{-2}$ ) and litter N ( $\Lambda_{ln,i}$  in  $\text{kg [N] m}^{-2}$ ) respectively.  $\gamma_{r,i}$  and  $\gamma_{w,i}$  are turnover rates in  $\text{s}^{-1}$  (Table 6 of Clark et al. (2011)). The leaf turnover rate ( $\gamma_{l,i}$ ) is a temperature dependent turnover rate consistent with the phenological state and defined in Clark et al. (2011). The equivalent term for N allows for retranslocation of N from leaves into the labile store and a reduced N cost of maintaining fine roots.  $\lambda_{l,i}$  and  $\lambda_{r,i}$  are the dimensionless coefficients for the retranslocation of leaf and root N shown in Table 1 (Zachle and Friend, 2010).

465

Equations 12 and 14 ~~are then solved by bisection such that the nitrogen~~ have two unknowns for each PFT: the plant N uptake for growth ( $\Phi_g$ ) and the excess C from growth ( $\Psi_{g,i}$ ). The litter fluxes are functions of the total vegetation pool and therefore can be solved at the same time. Solving for the case where  $\Psi_{g,i} = 0.0$  gives the total vegetation N demand for growth. If the N demand is less than ~~or~~ that available ( $\Phi_{g,i} < (1 - \lambda_i) N_{avail,i}$ ) growth is unlimited and the fluxes updated accordingly. Where N is limiting, growth N uptake is set equal to the available ~~nitrogen and the balanced LAI~~ ( $\mathcal{L}_b$ ) ~~remains within the specified upper and lower limits~~ ( $\mathcal{L}_{min}, \mathcal{L}_{max}$ ) N ( $\Phi_{g,i} = (1 - \lambda_i) N_{avail,i}$ ) and the excess assimilate  $\Psi_{g,i}$  solved for. Following the solution of  $\frac{dN_v}{dt}$  ~~the carbon~~  $\frac{dN_{v,i}}{dt}$  the C store and balanced LAI ( $\mathcal{L}_b$ ) ~~is~~  $\mathcal{L}_{b,i}$  are updated and the leaf, root and wood pools for each PFT can be derived following the allometric equations (Equations 2-4).

475

In JULES-CN, on a PFT basis, the N available for plant uptake ( $N_{avail,i}$ ) is the inorganic soil N pool ( $N_{in}$ ) split equitably between the PFTs assuming there is no differential ability between PFTs to acquire N. The available N in JULES-CN<sub>layer</sub> is more complicated taking into account the soil profile and is discussed in Section 3.3.2.

480

The remaining proportion ( $\lambda_i$ ) of NPP and ~~nitrogen after growth~~ N is allocated to spreading. The ~~nitrogen~~ N demand for spreading is equal to the ~~carbon~~ C allocated to spreading scaled by the whole plant stoichiometry:

$$485 \quad \Phi_{s,i} = \frac{N_{v,i}}{C_{v,i}} \left( \Pi_{c,i} - \frac{dC_{v,i}}{dt} - \Psi_{s,i} \right) \quad (17)$$

$$\Phi_s = \frac{N_v}{C_v} \left( \Pi_c - \frac{dC_v}{dt} - \Psi_s \right)$$

where  $\Psi_s$  ~~where~~  $\Psi_{s,i}$  (or  $\lambda_i \Psi_i$ ) is the excess ~~carbon~~ C term from spreading and  $\frac{N_v}{C_v}$  defines the  $\frac{N_{v,i}}{C_{v,i}}$  is the inverse of the the whole plant C:N ratio. ~~The equation is solved such that~~ ( $\Phi_s + \Phi_g$ )  $\leq N_{avail}$  and  $\Psi_s$  is minimised. As with growth limitation, equation 17 is first solved to find the N

490 demand for spreading ( $\Psi_{s,i} = 0.0$ ). If the arising demand is less than the available N ( $\Phi_{s,i} < \lambda_i N_{avail,i}$ ) spreading is unlimited. If N demand is in excess of that available, the uptake is set equal to the available N ( $\Phi_{s,i} = \lambda_i N_{avail,i}$ ) and the excess ( $\Psi_{s,i}$ ) assimilate solved for.

Total excess ~~carbon C~~ per PFT is therefore the combination of ~~those from growth and spreading that~~  
 495 from growth plus spreading:

$$\Psi_i = \Psi_{s,i} + \Psi_{g,i} \quad (18)$$

~~Total nitrogen~~ Similarly total N uptake per PFT is therefore the combination of ~~those from growth and spreading~~  
N uptake from growth plus N uptake from spreading:

$$\Phi_i = \Phi_{s,i} + \Phi_{g,i} \quad (19)$$

500 The ~~total gridbox nitrogen~~ PFT level N uptake and excess ~~carbon are therefore~~ C are weighted by  
 the PFT fraction ( $v_i$ ) ~~weighted total~~  
and summed to get the totals:

$$\Phi = \sum_i v_i \Phi_i \quad (20)$$

$$\Psi = \sum_i v_i \Psi_i \quad (21)$$

505 This ~~is the excess carbon~~ excess C ( $\Psi$ ) ~~that~~ is considered an additional plant respiration term and  
 at the end of the TRIFFID timestep ~~and~~ is used to reduce ~~NPP<sub>pot</sub>~~ the potential NPP to its actual  
 value.

~~Carbon and nitrogen~~ The C and N allocated to spreading allow the vegetation to expand onto bare  
 510 ground. Where space is limiting the vegetation competes for space with some ~~carbon C and N~~ being  
 turned over as litter. ~~This~~ The competition is handled in the Lotka-Volterra competition routines (see  
 Clark et al. (2011) for full details). ~~Nitrogen N~~ only indirectly affects competition through the PFT  
 specific allometric relationships. The competition code subsequently updates the vegetation fractions  
 ( $v_i$ ).

515

### 3.1.4 Vegetation Turnover and Total Litter Production

~~Litter is produced by the turnover of the leaf, wood and root pools and through the vegetation dynamics due to~~

The previous sections describe how N interacts to limit both growth and spreading of vegetation  
 520 in the dynamic vegetation model. This final section describes the turnover of C and N through large-  
 scale disturbance and ~~density-dependent litter production~~. The PFT specific litter production ( $\Lambda_{lc}$ ) is

defined as: competition.

$$\Lambda_{lc} = \gamma_l L_c + \gamma_r R_c + \gamma_w W_c$$

525 where  $\gamma_r$  and  $\gamma_w$  are parameters and  $\gamma_l$  is a temperature dependent turnover rate consistent with the phenological state (Clark et al. (2011)). Total litterfall Turnover is aggregated across PFTs to provide a litter flux term to the soil biogeochemistry which acts on an aggregated tile. Total litter C ( $\Lambda_c$ , kg [C] m<sup>-2</sup>) is made-up of the area-weighted sum of the litterfall-litter C from each PFT ( $\Lambda_{lc,i}$ ), along with large-scale PFT-dependent disturbance rate, and a density dependent component from  
530 intra-PFT competition for space. Large-scale disturbance is implemented in TRIFFID as a constant disturbance rate per PFT and captures processes such as wind-throw and other mortality events. Density dependent litter production arises through competition for space with increased turnover when space is limiting and plants are competing for space and light.

$$\Lambda_c = \sum_i v_i \left( \Lambda_{lc,i} + \gamma_{vi} C_{v,i} + (\Pi_i - \Psi_i) \sum_j c_{i,j} v_j \right) \quad (22)$$

535 
$$\Lambda_c = \sum_i v_i \left( \Lambda_{lc,i} + \gamma_{vi} C_{vi} + (\Pi_i - \Psi_i) \sum_j c_{ij} v_j \right)$$

where  $c_{ij}$  where  $c_{i,j}$  are the competition coefficients describing the effect of PFT  $i$  on PFT  $j$ ,  $\gamma_{vi}$   $\gamma_{vi}$  is a large scale disturbance term of PFT  $i$  and  $v_i$  is the vegetation fraction of PFT  $i$ . The effect of nitrogen-N limitation on the litter carbon-C flux is captured in the excess carbon-term  $\Psi_i C$  term per PFT ( $\Psi_i$ ).

540 The nitrogen-equivalent of the PFT-specific litter production ( $\Lambda_{ln}$ ) allows for retranslocation of nitrogen from leaves and roots into the labile store.

$$\Lambda_{ln} = (1 - \lambda_l) \gamma_l L_n + (1 - \lambda_r) \gamma_r R_n + \gamma_w W_n$$

where  $\lambda_l$  and  $\lambda_r$  are the retranslocation of leaf and root nitrogen coefficients, set at 0.5 and 0.2 (Zachle and Friend, 2010). Similarly to the total litter carbon C, total litter nitrogen N ( $\Lambda_n$ , kg [N] m<sup>-2</sup>)

545 is given by:

$$\Lambda_n = \sum_i v_i \left( \Lambda_{ln,i} + \gamma_{vi} N_{v,i} + \Phi_i \sum_j c_{i,j} v_j \right) \quad (23)$$

Both  $\Lambda_c$  and  $\Lambda_n$  vary according to the vegetation type and the pool being turned over. This means that the C:N ratio also varies in time and space.

$$550 \quad \Lambda_n = \sum_i v_i \left( \Lambda_{ln,i} + \gamma_{vi} N_{vi} + \Phi_i \sum_j c_{ij} v_j \right)$$

### 3.2 Soil Biogeochemistry

The soil biogeochemistry in JULES-CN operates on aggregated tiles and follows the Roth-C soil carbon-C model (Jenkinson et al., 1990; Jenkinson and Coleman, 1999) used in JULES-C on the TRIFFID timestep, with the addition of a prognostic soil N model. The soil N model simulates  
555 immobilisation and mineralisation in the four pools and, if nitrogen-N is limiting, slows the decomposition rate of litter into soil organic matter (SOM).

The soil carbon-C model comprises four carbon-pools-C pools ( $p$ ). Plant litter input is split between two carbon-C pools of decomposable (DPM-DPM) and resistant (RPM-RPM) plant material, with  
560 the fraction that goes to each depending on the overlying vegetation type and parameterised via  $f_{DPM,i}$ . Grasses provide a higher fraction of decomposable litter input and trees provide a higher fraction of resistant litter input. The other two carbon-C pools are microbial biomass (BIO-BIO) and long-lived humified (HUM-HUM) pools. The DPM and RPM-DPM and RPM pools can be characterised as representing litter and BIO and HUM-BIO and HUM as representing soil  
565 organic matter. Carbon-C from decomposition of all four-carbon-of the pools is partly released to the atmosphere, and the rest-enters-the-BIO-and-HUM-remaining fraction ( $\beta_R$ ) enters the BIO and HUM pools. The carbon-C pools are updated according to:

$$\frac{dC_{DPM}}{dt} = \sum_i (v_i f_{DPM,i} \Lambda_{c,i}) - R_{DPM} \quad (24)$$

$$\frac{dC_{DPM}}{dt} \frac{dC_{RPM}}{dt} = f_{DPM} \sum_i \left( v_i (1 - f_{DPM,i}) \Lambda_{c,i} \right) - R_{DPMRPM} \quad (25)$$

$$570 \quad \frac{dC_{RPM}}{dt} = (1 - f_{DPM}) \Lambda_c - R_{RPM}$$

$$\frac{dC_{BIO}}{dt} = 0.46 \beta_R R_{tot} - R_{BIO} \quad (26)$$

$$\frac{dC_{HUM}}{dt} = 0.54 \beta_R R_{tot} - R_{HUM} \quad (27)$$

where  $R_{tot} = R_{DPM} + R_{RPM} + R_{BIO} + R_{HUM}$  is the total respiration in  $\text{kg C m}^{-2} \text{s}^{-1}$ ,  $t$  is the time in s, the  $C_i$  are the carbon-;  $C_p$  are the C pools in  $\text{kg C [C]} \text{m}^{-2}$  (where  $p$  is one of DPM,

575  $R_{PMT}$ ,  $f_{DPM}$  is the  $BIO$ ,  $HUM$ );  $\Lambda_{c,i}$  is the litter input for PFT  $i$  in  $\text{kg [C] m}^{-2} \text{ s}^{-1}$  (term in  
brackets in Equation 22);  $f_{DPM,i}$  represents the fraction of litter from each PFT  $i$  that goes into  
DPM-DPM with the rest  $(1 - f_{DPM,i})$  going into the RPM pool (dependent on vegetation type);  
A<sub>c</sub> amount of woody vegetation); and  $R_{tot}$  is the total litter input in  $\text{kg C turnover in kg [C] m}^{-2}$   
580  $\text{s}^{-1}$  (equation 22) and  $(1 - \beta_R)$  is the fraction of soil respiration that is emitted, where the  $R_p$   
represent the turnovers of each C pool:

$$R_{tot} = R_{DPM} + R_{RPM} + R_{BIO} + R_{HUM} \quad (28)$$

The soil respiration to the atmosphere ( $r_h$ ) is given by:

$$r_h = (1 - \beta_R)R_{tot} \quad (29)$$

585 where  $\beta_R$  depends on soil texture (see Clark et al. (2011) for more details). The nitrogen clay  
content (clay in %) and ranges from 0.25 for a soil with no clay content to 0.15 for a clay soil:

$$\beta_R = \frac{1}{4.09 + 2.67e^{(-0.079\text{clay})}} \quad (30)$$

590 The N pools follow a similar structure to the carbon pools: C pools:

$$\frac{dN_{DPM}}{dt} = \sum_i (v_i f_{DPM,i} \Lambda_{n,i}) - M_{DPM} \quad (31)$$

$$\frac{dN_{DPM}}{dt} \frac{dN_{RPM}}{dt} = f_{DPM} \sum_i \left( v_i (1 - f_{DPM,i}) \Lambda_{Nn,i} \right) - M_{DPMRPM} \quad (32)$$

$$\frac{dN_{RPM}}{dt} = (1 - f_{DPM}) \Lambda_N - M_{RPM}$$

$$\frac{dN_{BIO}}{dt} = 0.46I_{tot} - M_{BIO} \quad (33)$$

595  $\frac{dN_{HUM}}{dt} = 0.54I_{tot} - M_{HUM} \quad (34)$

Inputs into the litter pools (DPM, RPM, DPM, RPM) are from the litter nitrogen flux ( $\Lambda_n$  in  $\text{kg N}$   
N flux ( $\Lambda_{n,i}$  in  $\text{kg [N] m}^{-2} \text{ s}^{-1}$ , equation Equation 23) and losses are determined by the pool specific  
mineralisation of organic nitrogen into inorganic nitrogen ( $M_i$  in  $\text{kg N}$  N into inorganic N ( $M_p$  in

600 ~~kg [N] m<sup>-2</sup> s<sup>-1</sup>). Input into the BIO and HUM nitrogen pools comes~~ Following the framework of  
the RothC model, input into both the *BIO* and *HUM* N pools is from the total immobilisation of  
inorganic nitrogen into organic nitrogen where  $I_{tot} = I_{DPM} + I_{RPM} + I_{BIO} + I_{HUM}$  (in kg N N  
into organic N ( $I_{tot}$  in kg [N] m<sup>-2</sup> s<sup>-1</sup>)). The C to N ratio of the DPM and RPM pools is a function  
of litter quality and varies temporally and spatially depending on the contributions of the different  
PFTs within the grid cell. The C to N ratios of the soil organic pools (HUM and BIO) are fixed by  
605 a model parameter ( $CN_{soil}$ ) with a default value of 10. Mineralisation ( $M_i$ ) and immobilisation ( $I_i$ )  
fluxes take values that maintain this constant C: N ratio for the HUM and BIO pools.;

$$I_{tot} = I_{DPM} + I_{RPM} + I_{BIO} + I_{HUM} \quad (35)$$

610 For each soil carbon pool C pool ( $p$ ), the potential respiration turnover - i.e. the respiration turnover  
rate when the nitrogen N in the system is not limiting - is given by ( $R_{i,pot}$ ):

$$R_{i,pot} = k_{ip} C_{ip} F_T(T_{soil}) F_{s\theta}(s\theta) F_v(v) \quad (36)$$

where the  $k_i, k_p$  are fixed constants in s<sup>-1</sup> (Clark et al., 2011). The functions of temperature ( $F_T(T_{soil})$ )  
615 and moisture ( $F_s(s) F_\theta(\theta)$ ) depend on the temperature ( $T_{soil}$ ) and moisture content ( $s\theta$ ) near the soil  
surface. The function  $F_v(v)$  depends on the vegetation cover fraction ( $v$ ) (Clark et al., 2011). The  
potential mineralisation of organic N when the system is not N limited ( $M_{i,pot}$ ) is related to  
the potential respiration turnover rates by the C to N ratio of each pool ( $CN_i$ ):

$$M_{i,pot} = \frac{R_{i,pot}}{CN_p} \quad (37)$$

$$M_{i,pot} = \frac{R_{i,pot}}{CN_i}$$

620 Similarly, the potential immobilisation of inorganic nitrogen N into the organic nitrogen pools  
( $I_{i,pot}$ ) is related to pool potential respiration turnover ( $R_{i,pot}$ ), the respired  
fraction retained fraction of respiration ( $\beta_R$ ), and the C to N ratio of the destination pool in the  
decomposition chain ( $CN_i$ ):

$$I_{i,pot} = \beta_R \frac{R_{i,pot}}{CN_{soil}}$$

$$I_{i,pot} = \beta_R \frac{R_{i,pot}}{CN_{soil}} \quad (38)$$



Where  $CN_{soil}$  is a model parameter that fixes the C to N ratios of the two destination soil organic pools (*HUM* and *BIO*) and has a default value of 10. The C to N ratio of the *DPM* and *RPM* litter pools is a function of litter quality and varies temporally and spatially depending on the contributions of the different PFTs within the grid cell. Potential mineralisation ( $M_p$ ) and potential immobilisation ( $I_p$ ) fluxes are defined before any N limitation is applied and take values that maintain the constant C:N ratio for the *HUM* and *BIO* pools.

When **nitrogen-N** is limiting, the ~~respiration of the DPM and RPM pools~~ turnover of the two litter pools (*DPM* and *RPM*) into the soil organic matter pools is additionally limited by the availability of **nitrogen-N**:

$$R_{i,potp} = k_{ip} C_{ip} F_T(T_{soil}) F_{s\theta}(s\theta) F_v(v) F_N(N) \quad (39)$$

where  $i_p$  is one of *RPM* or *DPM*.  $F_N(N)$  is the litter decomposition rate modifier and is given by the ratio of the **nitrogen-N** available in the soil to the **nitrogen-N** required by decomposition (Equation 40).  $F_N$  is limited to a range of 0.0 to 1.0. When  $F_N$  is equal to 1, the decomposition, mineralisation and immobilisation take place at the potential rate and the system is not **nitrogen-N** limited. Where  $F_N$  is less than 1, the availability of N limits the decomposition of litter into soil organic matter. This limitation is because respiration is carried out by microbes who require sufficient N to convert the *RPM* and *DPM* pools into *BIO* and *HUM* pools.  $F_N$  is given by:

$$F_N = \frac{(M_{BIO} + M_{HUM} - I_{BIO} - I_{HUM} + N_{avail})}{(D_{DPM} + D_{RPM})} \frac{(M_{BIO} + M_{HUM} - I_{BIO} - I_{HUM} + N_{in})}{(D_{DPM} + D_{RPM})} \quad (40)$$

where  $N_{avail}$  is the soil available inorganic nitrogen in kg N  $N_{in}$  is the total soil inorganic N pool in kg [N] m<sup>-2</sup> (discussed in Section 3.3 and defined in Equation 51).  $D_{DPM}$  and  $D_{RPM}$  are the net demand associated with decomposition of each of the litter pools:

$$D_{ip} = I_{i,potp,pot} - M_{i,potp,pot} \quad (41)$$

where  $i_p$  is one of *RPM* or *DPM*. This demand is always positive because the C to N ratio of soil is very much less than the C to N ratio of the *DPM* and *RPM* pools. When the net demand is in excess of the available inorganic **nitrogen-N**, the system is **nitrogen limited and  $F_N(N)$  N limited and  $F_N < 1.0$** . This available N is mainly the net mineralised N from the turnover of *BIO* and *HUM* pools but also from the inorganic N pool. N limitation reduces the soil respiration, mineralisation and immobilisation of the two litter pools (~~RPM and DPM~~ *RPM* and *DPM*). The ~~other two organic matter pools (BIO and HUM) always respire, are mineralised and immobilised at the potential rate.~~

The C:N ratio of these two pools are ~~therefore~~ variable in time and are represented as prognostic variables. The other two organic matter pools (*BIO* and *HUM*) always respire and are mineralised and immobilised at the potential rate (so  $F_N$  is effectively 1.0).

If the net mineralisation is positive some of the ~~nitrogen-N~~ is emitted as gas, according to:

$$N_{gas} = f_{gas}(M_{tot} - I_{tot}) \quad (42)$$

where  $N_{gas}$  is one component of the gas emission in  $\text{kg N [N]} \text{ m}^{-2} \text{ s}^{-1}$  ~~and~~,  $f_{gas}$  is a parameter that sets the fraction of the ~~nitrogen-N~~ flux that is emitted as gas to the atmosphere.  ~~$M_{tot} = M_{DPM} + M_{RPM} + M_{BIO} + M_{HUM}$~~  and is the total mineralisation flux in  $\text{kg N m}^{-2} \text{ s}^{-1}$ . Following Thomas et al. (2013a), it is assumed that 1% of net mineralisation is emitted as gas ( $f_{gas}$  is set to 0.01).  $M_{tot}$  is the the total mineralisation flux in  $\text{kg [N]} \text{ m}^{-2} \text{ s}^{-1}$ :

$$M_{tot} = M_{DPM} + M_{RPM} + M_{BIO} + M_{HUM} \quad (43)$$

If pool sizes become too small  $N_{gas}$  could become negative to ensure N is conserved.

### 3.2.1 Vertical discretisation

The vertical discretisation of the soil ~~carbon and nitrogen-C and N~~ follows Burke et al. (2017). There is a set of four soil ~~carbon and nitrogen-C and N~~ pools (*DPM*, *RPM*, *BIO*, *HUM*) in every soil model layer. ~~Following Burke et al. (2017) the respiration~~ As in Burke et al. (2017) the turnover rate is determined for each soil layer depending on the temperature, moisture conditions and ~~nitrogen-N~~ availability in that layer. An extra reduction of ~~respiration with depth~~ turnover with depth ( $z$ ) is included to account for factors that are currently missing in the model such as priming effects, anoxia, soil mineral surface and aggregate stabilisation. The potential ~~respiration~~ turnover of each layer is given by:

$$R_{p,pot}(z) = k_p C_p(z) F_T(T_{soil}(z)) F_\theta(\theta(z)) F_v(v) \exp(-\tau_{resp} z) \quad (44)$$

$$\underline{R_{i,pot}(z) = k_i C_i(z) F_T(T_{soil}(z)) F_s(s(z)) F_v(v) \exp(-\tau_{resp} z)}$$

$F_T(T_{soil}(z))$ ,  ~~$F_s(s(z))$  and  $C_i(z)$~~   $F_\theta(\theta(z))$  and  $C_p(z)$  are now all dependent on depth.  $T_{soil}(z)$  and  ~~$s(z)$~~   $\theta(z)$  are the simulated layered soil temperature and soil moisture content and  ~~$C_i(z)$~~   $C_p(z)$  is the simulated soil ~~carbon-C~~ content for each layer and pool  $i$ . The additional reduction of ~~respiration~~ turnover with depth is exponential, with  $\tau_{resp}$  an empirical parameter (in  $\text{m}^{-1}$ ) that controls the magnitude of the reduction (Burke et al., 2017). The larger the value of  $\tau_{resp}$ , the more inhibited the respiration is with increasing depth. ~~When nitrogen~~ Here  $\tau_{resp}$  was tuned to give a realistic estimate of soil C in a vertically resolved version of JULES-C as in Burke et al. (2017). When N is

limiting, the respiration of the ~~DPM and RPM~~ DPM and RPM pools are reduced by a factor of  $F_N(N(z))$  which is also now a function of depth and dependent on the available nitrogen-N in the relevant layer.  ~~$M_r$  and  $I_r$~~   $M_p$  and  $I_p$  are also calculated as a function of depth based on their relationship with respiration.

The vertical mixing of each soil nitrogen-N pool follows that of the soil carbon-C pools:

$$\frac{\partial N_{DPM}(z)}{\partial t} = \frac{\partial}{\partial z} \left( D(z) \frac{\partial CN_{DPM}(z)}{\partial z} \frac{\partial N_{DPM}(z)}{\partial z} \right) + \sum_i \left( v_i f_{dpm,DPM,i} \Lambda_{n,n,i} f_{lit}(z) \right) - M_{DPM}(z) \quad (45)$$

$$\frac{\partial N_{RPM}(z)}{\partial t} = \frac{\partial}{\partial z} \left( D(z) \frac{\partial CN_{RPM}(z)}{\partial z} \frac{\partial N_{RPM}(z)}{\partial z} \right) + \sum_i \left( v_i (1 - f_{dpm,DPM,i}) \Lambda_{n,n,i} f_{lit}(z) \right) - M_{RPM}(z) \quad (46)$$

$$\frac{\partial N_{BIO}(z)}{\partial t} = \frac{\partial}{\partial z} \left( D(z) \frac{\partial CN_{BIO}(z)}{\partial z} \frac{\partial N_{BIO}(z)}{\partial z} \right) + 0.46 I_{tot}(z) - M_{BIO}(z) \quad (47)$$

$$\frac{\partial N_{HUM}(z)}{\partial t} = \frac{\partial}{\partial z} \left( D(z) \frac{\partial CN_{HUM}(z)}{\partial z} \frac{\partial N_{HUM}(z)}{\partial z} \right) + 0.54 I_{tot}(z) - M_{HUM}(z) \quad (48)$$

~~$I_{tot}$~~   $I_{tot}(z)$  is the total immobilisation in  $\text{kgN} [\text{N}] \text{m}^{-2} \text{s}^{-1}$  in each layer (following Equation 35).

$D(z)$  is the diffusivity in  $\text{m}^2 \text{s}^{-1}$  and varies both spatially and with depth (Burke et al., 2017). ~~The~~

700 ~~litter inputs:~~ litter inputs:

$$D(z) = \begin{cases} D_o & ; & z \leq 1\text{m} \\ \frac{D_o}{2}(3-z) & ; & 1\text{m} < z < 3\text{m} \\ 0.0 & ; & z \geq 3\text{m} \end{cases} \quad (49)$$

Without permafrost,  $D_o$  ( $\text{m}^2 \text{s}^{-1}$ ) is given by a bioturbation mixing rate equivalent to  $1 \text{ cm}^2 \text{ year}^{-1}$ .

When permafrost is present, the mixing represents cryoturbation and  $D_o$  increases to a value equivalent to  $5 \text{ cm}^2 \text{ year}^{-1}$ . This parameterisation of  $D(z)$  means that the soil organic pools can transfer

705 between the active layer and the permanently frozen soils in a steady state climate albeit at a relatively slow rate. The PFT dependent litter inputs ( $f_{lit}(z) \Lambda_{v,i}$ ) are distributed so that they decline exponentially with depth, with an e-folding depth of 0.2 m. ~~Mineralised~~ This profile is independent of the root distribution:

$$f_{lit}(z) = \frac{\exp(-\tau_{lit}z)}{\int_0^{z_{max}} \exp(-\tau_{lit}z) dz} \quad (50)$$

710 Where  $\tau_{lit}$  is a parameter to reduce the litter input with increasing depth. The mineralised gas emissions are calculated now a function of depth ( $N_{gas}(z)$ ) and are calculated by repeating Equation 42) for each soil layer, based on the balance of mineralisation and immobilisation in that layer (i.e. Equation 42 is repeated for every layer). Similarly, the litter decomposition rate modifier ( $F_N$ ) is calculated by repeating a slightly modified version of Equation 40 for each soil layer. In the vertically  
 715 resolved version of Equation 40, if the soil layer is frozen  $N_{in}$  is not available so effectively zero.

### 3.3 Inorganic Nitrogen

The inorganic nitrogen-N pool is the sum of deposition, fixation, immobilisation losses, mineralisation inputs, gridbox mean plant uptake and inorganic N losses through leaching and gaseous  
 720 emission. For the non-layered bulk case (JULES-CN), these terms are simply added together:

$$\frac{dN_{in}}{dt} = N_{dep} + \sum_i v_i FBNF_i - \sum_i v_i \Phi_i + M_{net} - N_{leach} - N_{turnover\ gas\ I} \quad (51)$$

where  $N_{in}$  is the inorganic nitrogen in kgN-N in kg [N] m<sup>-2</sup>,  $N_{dep}$  is prescribed nitrogen-N deposition in kgN-[N] m<sup>-2</sup> s<sup>-1</sup>. The plant fixation ( $F_i$ ) and  $v_i$  the fractional cover of each PFT  $i$ . The biological N fixation ( $BNF_i$ ) for each PFT  $i$  is described in Section 3.3.1 below and plant uptake  
 725 ( $\Phi_i$ ) are described in Sections 3.3.1 and 3.1.3. (for each PFT  $i$  is described in Section 3.1.3.  $M_{net}$ ) is the net mineralisation which is the difference between  $M_{tot}$  (Equation 43) and  $I_{tot}$  reduced by  $N_{gas}$ . (Section 3.2 (Equation 35) reduced by  $N_{gas}$  (Equation 42)). The loss of nitrogen from the N from the system via the inorganic pool is a function the sum of leaching ( $N_{leach}$ ) and an additional  
 730 turnover ( $N_{turnover}$ ) in kg [N] m<sup>-2</sup> s<sup>-1</sup> plus an additional gas loss to the atmosphere ( $N_{gas\ I}$  in kg [N] m<sup>-2</sup> s<sup>-1</sup>):

$$N_{gas\ I} = \gamma_n N_{in} \quad (52)$$

$$N_{turnover} = \gamma_n N_{in}$$

where  $\gamma_n$  is a tunable parameter. This additional term (in s<sup>-1</sup>). The total N gas loss is the sum of  
 735  $N_{gas\ I}$  above and  $N_{gas}$  from Equation 42 with  $N_{gas\ I}$  representing approximately 90% of the total gas loss. This additional gas loss term ( $N_{gas\ I}$ ) represents missing processes relating to the gaseous loss of inorganic nitrogen-N and limits the effective mineral N pool size. Without this additional  
 turnover available N may Including  $N_{gas\ I}$  ensures that available N does not increase excessively, potentially due to excessive biological N fixation in regions that are generally unlimited where the  
 NPP is very close or equal to the  $NPP_{pot}$ . In the current model configuration this parameter  $\gamma_n$  is  
 740 set to 1.0 (360 day<sup>-1</sup>) 0.0028 day<sup>-1</sup> such that the whole pool turns over once every model year. This results in an effective saturation limit of 0.002 KgN m<sup>-2</sup> consistent with Parton et al. (1993).

The leaching of **nitrogen-N** ( $N_{leach}$  in  $\text{kg [N] m}^{-2} \text{ s}^{-1}$ ) through the profile is assumed to be a function of the net flux of moisture through the soil profile, the concentration of inorganic N, and a parameter ( $\beta\alpha$ , dimensionless) representing the effective solubility of **nitrogen**.  $\beta$  has N.  $\alpha$  is assumed to have a value of 0.1 based on the sorption buffer coefficient of Ammonia (Gerber et al., 2010) although here it represents the and in JULES-CN represents the combined sorption of all inorganic nitrogen species.

N species (Wania et al., 2012).

$$N_{leach} = \beta\alpha(N_{in}/\theta_{1m})Q_{subsurface}Q_{subs} \quad (53)$$

where  $\theta_{1m}$  is the soil water content in the top 1m of soil in  $\text{kg m}^{-2}$  (so the inorganic **nitrogen-N** is assumed to occupy the top 1m of soil), and  $Q_{subsurface}Q_{subs}$  is the total subsurface runoff in  $\text{kg m}^{-2} \text{ s}^{-1}$ .

### 3.3.1 Biological Nitrogen Fixation (BNF)

Biological nitrogen fixation (BNF) is the largest natural supplier of N to the terrestrial ecosystem. Following the secondary model of Cleveland et al. (1999), N fixation is determined as a linear proportion of the net primary production before N limitation of each PFT  $i$  ( $NPP_{pot,i}$ ):

$$BNF_i = \zeta NPP_{pot,i} \quad (54)$$

$NPP_{pot,i}$  is defined in the same way as the net primary productivity in JULES before the explicit N cycle was included, i.e. before the excess carbon ( $\Psi$ ) is removed. BNF as a function of NPP is an established method used and assessed in other models (Meyerholt et al., 2016; Wieder et al., 2015a; Thomas et al., 2013b). While some models utilise more complex BNF representations (Fisher et al., 2010), a lightweight approach is preferred here while the benefits of extra computational expense on BNF are not yet established, and evidence is lacking that a different simple representation (e.g. evapotranspiration) would perform better (Davies-Barnard and Friedlingstein, 2020). However, changes in NPP may not accurately reflect changes in BNF with forcings such as elevated atmospheric carbon dioxide (Liang et al., 2016) or additional N (Thomas et al., 2013b; Ochoa-Hueso et al., 2013).

The rate of fixation ( $\zeta$ ) is set such that global present day net primary productivity of approximately  $60 \text{ Pg C yr}^{-1}$  results in approximately  $100 \text{ Tg N yr}^{-1}$  fixation ( $0.0016 \text{ kg [N] kg C}^{-1}$ ), within the range of recent global observation-based estimates of BNF (Davies-Barnard and Friedlingstein, 2020; Vitousek et al., 2013). The parameterisation based on NPP results in a latitudinal gradient with the highest rates of fixation in the tropics and lowest in boreal forests and arctic tundra which is consistent with some estimates of BNF (Houlton et al., 2008; Cleveland et al., 1999) though not recent observational meta-analyses (Davies-Barnard and Friedlingstein, 2020).

In JULES-CN which has a bulk soil biogeochemistry parameterisation the BNF is directly transferred into the single inorganic soil N pool and becomes available as inorganic N. However,

in JULES-CN<sub>layer</sub> the *BNF* is distributed vertically in the soil depending on the fraction of roots in each layer. If a soil layer is frozen there is no *BNF* into that layer. If the whole soil is frozen, fixed N goes into the inorganic N pool in the top layer.

### 3.3.2 Vertical discretisation of inorganic nitrogen

780 In JULES-CN<sub>layered, layer</sub> there is an inorganic **nitrogen-N** pool in each soil layer. The dynamics are very similar to Equation 51, but ~~every component now varies with depth, so:~~ most of the components now vary with depth:

$$\frac{dN_{in}(z)}{dt} = N_{dep} + \sum_i v_i BNF_i f_{R,i}(z) - \sum_i v_i \Phi_i f_{I,i}(z) + M_{net}(z) - N_{flux}(z) - N_{gasI}(z) \quad (55)$$

The modifications to each term to ensure they vary appropriately with depth are discussed below.

785 The additional parameters in Equation 55 are  $f_{R,i}(z)$  - the fraction of roots in each layer for PFT  $i$  (Equation 56);  $f_{I,i}(z)$  - the fraction of available inorganic N in each layer for PFT  $i$  (Equation 60) and  $N_{flux}(z)$  - the transport of inorganic N through the layer by the soil water fluxes (Equation 61).

As in Equation 51 the net mineralisation flux ( $M_{net}(z)$ ) is the difference between  $M_{tot}(z)$  and  $I_{tot}(z)$  reduced by  ~~$N_{gas}(z)$  from  $N_{gas}(z)$~~  for each layer (see Section 3.2.1). ~~Nitrogen deposition ( $N_{dep}(z)$ ) is N deposition ( $N_{dep}$ ) is only~~ added to the uppermost soil layer. Inputs from **plant nitrogen biological N** fixation from PFT  $i$  are distributed according to the root profile of the **plants, i.e. PFT under consideration ( $f_{R,i}(z)$ ):**

$$f_{1,iR,i}(z) = \frac{f_{root,i}(z)}{\int_0^{z_{max}} f_{root,i}(z) dz} \quad (56)$$

795 where  ~~$f_{root}(z)$  -  $f_{root,i}(z)$~~  is the volumetric root fraction of PFT  $i$  at a given depth-

~~Turnover ( $N_{turnover}(z)$ ) soil level and  $z_{max}$  is the maximum depth of the soil in m. Gas loss from the inorganic N ( $N_{gasI}(z)$ ) occurs in each layer, but with an ~~exponential decay with depth as additional exponential decay term which is a function of depth (similar to that used in Equation 44 for the soil decomposition, which).~~ This term empirically represents the factors that reduce the soil activity with depth. The ~~turnover~~ additional gas loss term thus becomes:~~

$$N_{turnover gasI}(z) = \gamma_n N_{in}(z) \exp(-\tau_{resp} z) \quad (57)$$

This leaves two terms in Equation 55: the plant uptake term ( ~~$(\sum_i v_i \Phi_i f_{z,i}(z))$~~   $\sum_i v_i \Phi_i f_{I,i}(z)$ ) which is PFT dependent and the  $N_{flux}(z)$  term, which replaces the leaching term from Equation 51. These have a more process-based representation in the layered case. ~~Plants~~ When calculating the plant uptake term we assume that plants cannot access all the inorganic **nitrogen-N**. Firstly, ~~we assume that~~ if a soil layer is frozen then plants cannot uptake any of the **nitrogen-N** in that layer. Secondly,

we assume that they only have direct access to a certain fraction of the soil, according to their root fraction,  $f_{root,i}$  (which reduces with depth). So for each PFT,  $i$ , there is an ‘available’ inorganic ~~nitrogen pool~~ N pool ( $N_{avail,i}(z)$ ), which at equilibrium is as follows:

$$810 \quad N_{avail,i}(z) = f_{root,i}(z)N_{in}(z)T(z) \quad (58)$$

~~As nitrogen is~~ Where  $T(z)$  is zero when the soil temperature is  $0^\circ C$  or colder and 1 when it is above  $0^\circ C$ . However, the system is not necessarily in equilibrium - as N is taken up from the available pool around the roots, there will be a delay in ~~the area around the roots this volume~~ getting ‘re-filled’. We assume that ~~it~~ the inorganic N is constantly diffusing back to the equilibrium state where

815 the concentration is constant both horizontally and vertically within each layer, and thus after the extraction on a particular TRIFFID timestep we update the available N pool according to:

$$\frac{N_{avail,i}(z)}{dt} = \gamma_{diff} (f_{root,i}(z)N_{in}(z) - N_{avail,i}(z)) \quad (59)$$

where  $\gamma_{diff}$  is the rate of diffusion back to the equilibrium, set by default to ~~100-360 day~~  $0.28 \text{ day}^{-1}$ . ~~Any or approximately 100 year<sup>-1</sup>.  $N_{avail,i}(z)$  is then multiplied by  $T(z)$  to incorporate the~~ frozen soil effect. Any biological N fixation goes directly into the available pool, ~~and other fluxes are simply added according to the ratio of the available to total inorganic N pools at equilibrium (thus the available pool would always follow Equation 58 were it not for the fixation and uptake by plants).~~ Plant uptake is extracted entirely from the available N pool, and the dependence on depth is according to the same profile as the available N, i.e.

$$825 \quad f_{2,i}(z) = \frac{N_{avail,i}(z)}{\int_0^{z_{max}} N_{avail,i}(z) dz} \quad (60)$$

All of the other fluxes are simply added in such a manner so as to maintain the ratio of the available to total inorganic N pools that would be present if the available and total pools were in equilibrium. Therefore the only two processes which take the available and total pools out of equilibrium are biological N fixation and uptake.

830 Leaching is now done in a process-based manner, where the inorganic N is transported through the soil profile by the soil water fluxes. ~~Thus in Equation 55 we have the following term:~~ For any given soil layer of thickness  $\delta z$ , the inorganic N flux ( $N_{flux}$ ) is given by:

$$N_{flux}(z) = \beta \delta z \alpha \frac{d}{dz} \left( W_{flux} \frac{N_{in}(z)}{\theta} \right) \quad (61)$$

where  $\theta(z)$  is the soil water content of the layer in  $\text{kg m}^{-2}$  and  $W_{flux}$  is the flow rate of the water through the soil layer in  $\text{kg m}^{-2} \text{ s}^{-1}$ . Multiplying by  $\delta z$  gives the change in N content for each layer,  $\delta z$ . The total leaching is then the sum of all nitrogen N that leaves the soil ~~by lateral runoff or out of the bottom soil layer.~~

<u>Variable</u>	<u>Value</u>	<u>Description</u>	<u>Equation</u>
<b>Bulk soil nitrogen</b>			
$\zeta$	$0.0016 \text{ kg [N] kg [C]}^{-1}$	Rate of <i>BNF</i>	Equation 54
$CN_{soil}$	$10 \text{ kg [C] kg [N]}^{-1}$	CN ratio of <i>BIO</i> and <i>HUM</i> pools	Equation 41
$f_{gas}$	0.01 (proportion)	Fraction of net mineralisation emitted as gas to atmosphere	Equation 42
$\gamma_e$	$3.215e-08 \text{ s}^{-1}$	Imposed turnover coefficient to determine $N_{gasI}$ release from $N_{in}$	Equation 52
$\alpha$	0.1 (proportion)	Effective solubility of nitrogen in water	Equation 53
<b>Vertically resolved soil carbon</b>			
$\tau_{resp}$	$0.8 \text{ m}^{-1}$	Parameter to control reduction of respiration with depth	Equation 44
$D_o$	bioturbation - $0.001 \text{ m}^2 \text{ s}^{-1}$ cryoturbation - $0.005 \text{ m}^2 \text{ s}^{-1}$	Soil carbon and nitrogen mixing rate	Equation 49
$\tau_{lit}$	$5 \text{ m}^{-1}$	Parameter to control reduction of litter input with depth	Equation 50
<b>Vertically resolved soil carbon and nitrogen</b>			
$\tau_{dif}$	100 per 360 days	Rate of diffusion transferring the inorganic nitrogen from $N_{in}$ to $N_{avail}$	Equation 59

**Table 2.** A summary of the extra parameters required for the soil biogeochemistry component of JULES-CN and JULES-CN<sub>layer</sub>.

840 Table 3.3.2 summarises the extra parameters required for the soil biogeochemistry component of JULES-CN and JULES-CN<sub>layer</sub> alongside their values.

#### 4 Historical simulations

Global transient simulations were carried out following the protocol for the S2 experiments in TRENDY (Sitch et al., 2015). Forcing consisted of time-varying CO<sub>2</sub>, and climate from the CRU-NCEP data-set (v4, 1901-2012, Viovy N. 2011 CRU-NCEPv4. CRUNCEP dataset). The fraction of agriculture in each grid cell (Hurtt et al., 2011) was set to the pre-industrial value. Nitrogen-N deposition was time-varying and was taken from a ACCMIP multi-model data set interpolated to annual fields (Lamarque et al., 2013). The model resolution was N96 (1.875° longitude x 1.25° latitude).

Results from three different JULES model configurations are presented here:



- 850 – ~~JULES-C represents the~~ JULES-CN includes the newly developed soil and vegetation carbon cycle in a manner comparable with HadGEM2-ES (Jones et al., 2011) coupled C and N cycle.
- ~~JULES-CN is the nitrogen enabled version of JULES-C~~ JULES-C is shown for comparison purposes and represents the soil and vegetation C cycle as used in Le Quéré et al. (2018).
- 855 – ~~JULES-CN~~ JULES-CN<sub>layered layer</sub> is a version of JULES-CN with which has identical above ground processes to JULES-CN but additionally includes vertically discretised soil biochemistry.

In each case five PFTs were used: broadleaf trees, needleleaf trees (NET), C3 and C4 grass and shrubs. Plant competition was allowed, with TRIFFID updating vegetation fractions on a 10 day time step. These three configurations of JULES adopt the standard 4 layer soils with a maximum depth of 3 m. However it should be noted that Burke et al. (2017) and Chadburn et al. (2015) adopt a configuration which increases both the maximum soil depth and number of soil layers - a configuration which is recommended for detailed scientific study of northern high latitudes. The sole difference between JULES-C and JULES-CN is the inclusion of the nitrogen-N cycle. JULES-CN<sub>layered layer</sub> additionally has vertically discretised soil biogeochemistry. There are no differences in any of the shared model parameters -which were initially tuned for the JULES-C configuration. This enables a

860 direct comparison between the different configurations.

865

The simulations were initialised using pre-industrial conditions. ~~They~~ The models were spun up by repeating the time period 1860-1870 using the meteorological data for the period 1860-1879 repeatedly until the change in the carbon stocks was less than 0.01 % decade<sup>-1</sup> globally. The soil carbon-C distribution in JULES-CN<sub>layered layer</sub> is particularly slow to reach equilibrium. Therefore the ‘modified accelerated decomposition’ technique (modified-AD) described by Koven et al. (2013) was used to spin the soil carbon-C in these versions up to an initial pre-industrial equilibrium distribution (Burke et al., 2017). Further spin up was then carried out for these layered models using repeated pre-industrial conditions until the change in soil carbon was C was again less than

870 0.01 % decade<sup>-1</sup> globally. It should be noted that neither transient land-use change or fertiliser were included in any of these simulations.

875

## 5 Results

This paper mainly focuses on the differences between selected model configurations introduced by including the explicit nitrogen cycle within JULES in JULES output when including the N cycle in the model configuration. When available, we additionally use any observational based estimates to evaluate the quality of the simulations. First a broad-brush comparison between JULES-CN, JULES-C and JULES-CN<sub>layered layer</sub> is made. This is followed by a more complete discussion comparing JULES-CN with JULES-C. of the impact of the N cycle on the carbon stocks and fluxes and their

880

changes over time. Then we show more details of the N stocks and fluxes. Finally the extra processes supplied by JULES-CN~~layered layer~~ are assessed. For completeness figures often include both JULES-CN and JULES-CN~~layered layer~~ but JULES-CN~~layered layer~~ is only discussed at the end of the results.

## 5.1 Summary of carbon and nitrogen stocks and fluxes

It should be noted that the addition of the N cycle in JULES is only one component of the recent developments. In future configurations of JULES the N cycle will be combined with a new competition scheme Harper et al. (2018) which will modify the global vegetation distribution. Therefore we are most interested in the changes in the vegetation distribution between the different versions which will be caused by the N cycle. Figure 3 shows the total area covered by each type of vegetation. The CCI observations Hartley et al. (2017) are added for completeness. As expected the configurations with the N cycle have more bare soil and less vegetation than JULES-C. This is mainly observed as a decrease in the shrub and grass regions in JULES-CN. As we shall see later (Figure 10) this is because the tropical forests dominate the tree region and their growth is not limited by N in the model. JULES-CN~~layer~~ has a reduction in trees compared to JULES-CN, which is focused in the boreal region where it is more likely to simulate grass or shrubs.

## 5.1 Summary of C and N stocks and fluxes

Figure 6 provides an overview of the stocks and fluxes of ~~carbon and nitrogen~~ C and N in JULES-CN and JULES-CN~~layered layer~~ and compares them with JULES-C. As expected for a present-day simulation, the majority of C stocks and fluxes are very similar for JULES-C and JULES-CN. The main difference is the present-day NPP which is ~12% higher in JULES-C than in JULES-CN. ~~This is a direct consequence of nitrogen limitation which restricts the ability of the plants to utilise all of the carbon.~~ There is also a small reduction in the GPP of ~4% caused by ~~small~~ some differences in the vegetation ~~distribution~~ fractional cover distribution (Figure 3) and indirectly resulting from the nitrogen N limitation.

Soil organic ~~nitrogen and vegetation nitrogen~~ N and vegetation N are both consistent with the available observation-based estimates of stocks ~~as are the nitrogen fixation, nitrogen losses and nitrogen deposition. Fixation.~~ The biological N fixation is tuned to be approximately  $100 \text{ Tg N year}^{-1}$  in the present day ~~and the N deposition is prescribed.~~ The majority of N losses ~~from the land surface~~ occur via the gaseous pathway with total losses of  ~~$135 \text{ Tg N/yr}^{-1}$~~   $111 \text{ Tg N year}^{-1}$  for JULES-CN. Leaching is fairly low at  $7 \text{ Tg N/yr}^{-1}$  ~~for JULES-CN~~  $\text{Tg N year}^{-1}$  compared to estimates of leaching, which are as high as ~25 - 55% of N inputs in European forests (Dise

et al., 2009) and range between 59 and 118  $TgN/yr^{-1}$   $Tg N year^{-1}$  in the available observations  
920 (Boyer et al., 2006; Galloway et al., 2004; Gruber and Galloway, 2008). Nitrogen (Boyer et al., 2006; Galloway et al., 2004)  
. There is no N fertilizer applied in the model which might partially explain why the leaching is so  
low. In reality there is ~200 Tg N applied annually as either manure or fertilizer Potter et al. (2010)  
. a proportion of this will be leached resulting in an increase of global leaching. N uptake and  
net N mineralisation are relatively high and are fairly similar-comparable in magnitude implying  
925 a largely closed cycling of nutrients between vegetation and soil. However, there is no nitrogen  
fertiliser applied to the soil in the model meaning nitrogen inputs are expected to be lower than in  
reality. These nitrogen-These N stocks and fluxes are also consistent with results from other models  
such as: Xu-Ri and Prentice (2008), Smith et al. (2014), Zaehle (2013b) and von Bloh et al. (2018).

## 930 5.2 Impact of nitrogen limitation on net primary productivity Comparing C stocks and fluxes

Figure 10 shows the biome-based response ratio of net primary productivity. The response ratio is  
defined as the ratio of the NPP when nitrogen is unlimited ( $NPP_{pot}$ ) compared with the nitrogen  
limited NPP. Both of these diagnostics are output from the JULES simulations. All biomes have  
a response ratio of greater than 1 in both the model and observations which means that adding  
935 extra nitrogen to the system will enhance the achieved NPP. Globally the response ratio falls within  
the observed error bars and for the majority of the biomes including the tropical forests and the  
tundra the model response ratios fall within the range of uncertainties of the observations. However,  
LeBauer and Treseder (2008) suggests tropical savannah is not very nitrogen limited, whereas in  
JULES-CN tropical savannah is a highly limited biome. Further work is required to understand  
940 why tropical savannah is so limited. Figure 9 shows the spatial distribution of the model simulated  
response ratio. Green areas are not very nitrogen limited and yellow areas are more nitrogen limited.  
There are distinct regions of nitrogen limitation – northern Australia, the Sahel, western Europe and  
parts of Siberia. Much of the global land surface has relatively weak nitrogen limitation.

In the model the soil carbon decomposition can be limited when the nitrogen available in the soil  
945 is less than the nitrogen required by decomposition. This process does not play a major role in our  
simulations.

### 5.2.1 Ecosystem residence times

The zonal total soil and vegetation carbon-C stocks are shown in Figure 5. The vegetation carbon  
C is very similar for both JULES-C and JULES-CN as expected from Figure 6 and is consistent  
950 with the available observations. There are some differences in the soil carbon-C in the northern high  
latitudes with JULES-CN having slightly less soil carbon-C than JULES-C. This is a consequence  
of the higher nitrogen-N limitation on JULES-CN leading to less litter fall and subsequently less soil  
carbon-C. The corresponding nitrogen-N limitation induced reduction in soil decomposition is not

strong enough to offset the decrease in carbon-C input leading to a smaller pool size. ~~The ecosystem residence time is defined as the total ecosystem carbon divided by the GPP. This is shown in Figure 8 for the biomes introduced in Figure 10. These residence times have been estimated annually on a grid-cell-by-grid-cell basis and then aggregated to a multi-annual mean per biome. The observational values were derived in a similar way using spatial data from Carvalhais et al. (2014). In general the residence times are fairly similar for JULES-C and JULES-CN except for the tundra biome where the residence time for JULES-CN is much longer than that for JULES-C. This is an over estimation of the residence time for this biome, however, JULES-CN is missing some key permafrost processes which will lead to an improvement (see Section 3.2.1).~~

~~The soil organic nitrogen (Figure ??) shows a similar distribution to the soil carbon (Figure 5) reflecting the relatively consistent C to N ratio of the soil within the model. The observed soil organic nitrogen content is slightly higher at all latitudes than simulated by JULES-CN particularly in the northern tundra region.~~

### 5.2.1 Carbon-use efficiency

Carbon use efficiency (CUE) is defined as the ratio of net carbon-C gain to gross carbon-C assimilation during a given period (NPP/GPP). ~~This represents the capacity of the plants to allocate carbon~~ Plants with a higher CUE have a lower autotrophic respiration and allocate more C from photosynthesis to the terrestrial biomass ~~. In the model nitrogen limitation restricts the ability of plants to allocate carbon and reduces the carbon and vice-versa. In JULES-CN there is less C available to be allocated because it is constrained by the amount of N present. This reduces the C~~ use efficiency.

975 Figure 6 shows the zonal total GPP and NPP for JULES-CN and JULES-C. As expected from Figure 6 the NPP and GPP have very similar latitudinal profiles for the two model configurations. Both JULES-C and JULES-CN have a higher GPP in the tropics that than the observations but they are more comparable in the extra-tropical latitudes where the GPP tends to be smaller. The NPP in JULES-CN is less than JULES-C and generally closer to the MODIS observations particularly in

980 the tropics. Figure 6 also shows the zonal mean CUE. JULES-CN has a lower CUE than JULES-C for all latitudes. On average it is 0.44 for JULES-CN and 0.49 for JULES-C. JULES-CN ~~has a consistently high bias of ~0.09~~ is consistently low compared to the Kim et al. (2018) observation-based data set with a bias of ~0.09. This bias is relatively constant with latitude. ~~Figure ??~~

985 Figure 6 also shows the changes in these carbon-C fluxes for the period 1860-2007 with respect to the multi-annual mean period of 1860-1899. Changes over time are shown to enable the differences between the two different model configurations to be more easily compared. Apparently small differences between JULES-C and JULES-CN in the NPP and GPP become more noticeable in the CUE. The small differences between JULES-C and JULES-CN in GPP are ~~caused by structural~~

990 ~~changes in the vegetation in particular~~ mainly caused by small changes in the vegetation distribution and a slight increase in bare soil in JULES-CN. In the case of NPP - JULES-C increases quicker than JULES-CN because JULES-CN becomes progressively more ~~nitrogen-N~~ limited. The change in CUE shows the impact of the ~~nitrogen-N~~ cycle on the uptake of ~~carbon-C~~ by the vegetation in JULES-CN over the twentieth century. There is an increase in CUE in both configurations, mainly  
995 caused by CO<sub>2</sub> fertilisation, but this is limited by ~~nitrogen-N~~ in the JULES-CN configuration.

### 5.2.1 Net ecosystem exchange

A key measure of a land ~~carbon-C~~ cycle model is how well it simulates the temporal variation of the land ~~carbon-C~~ sink, which is the difference between Net Ecosystem Exchange (NEE) and  
1000 the flux of ~~carbon-C~~ to the atmosphere from land-use change. The interannual variability in the sink is dominated by the variability of NEE, which is itself correlated with the magnitude of the temperature-carbon cycle feedback in the tropics (Cox et al., 2013). As a result, simulation of NEE variability is highly relevant to climate-carbon cycle projections (Wenzel et al., 2016).

Figure 7 compares global annual mean values of Net ecosystem exchange (NEE; defined as NPP  
1005 - heterotrophic respiration) for JULES-C and JULES-CN to observation-based estimates from the Global Carbon Project. We specifically focus on the years from 1960 to 2009, which is the maximum overlap period between the model simulations and the GCP annual budget data (Friedlingstein et al., 2019). To avoid the circularity of using GCP estimates of NEE which are themselves derived from land-surface models, we instead calculate the GCP estimates of NEE as the residual of the best  
1010 estimates of the total emissions from fossil fuel ( $FF$ ) plus land-use change ( $LU$ ), and the rate of increase of the carbon content of the atmosphere ( $F_a$ ) plus the ocean ( $F_o$ ):

$$NEE_{gcp} = FF + LU - F_a - F_o \quad (62)$$

The observations and both of the models show an upward trend in NEE but with very significant interannual variability (Figure 7). Due to ~~nitrogen-N~~ limitations on CO<sub>2</sub> fertilization, mean NEE  
1015 in JULES-CN (1.66 Pg C ~~yr~~year<sup>-1</sup>) is lower than in JULES-C (2.06 Pg C ~~yr~~year<sup>-1</sup>), and also lower than the estimate from GCP (2.11 Pg C ~~yr~~year<sup>-1</sup>). This absolute value will be sensitive to the vegetation cover which is much improved by including the height-based competition as has been done in UKESM1 Sellar et al. (2019). However, JULES-CN outperforms JULES-C on all of the other key metrics of the NEE variation. JULES-CN produces a smaller but much more realistic  
1020 trend in NEE, and a smaller and more realistic interannual variability about that trend (see Table 5.2.1). The correlation coefficient for NEE between the JULES-CN and GCP estimates (r=0.71) is also improved compared to JULES-C (r=0.63). There remains a significant underestimate of NEE in the years following the Pinatubo volcanic eruption in 1991, most likely due to the neglect of diffuse-

	Mean (Pg C $\text{Ayr}^{-1}$ year $^{-1}$ )	Trend (Pg C $\text{Ayr}^{-1}$ year $^{-1}$ year $^{-1}$ )	IAV (Pg C $\text{Ayr}^{-1}$ year $^{-1}$ )	r
<u>JULES-CN</u>	<u>1.66</u>	<u>0.025</u>	<u>0.86</u>	<u>0.71</u>
JULES-C	2.06	0.034	1.31	0.63
JULES-CN <sub>layer</sub>	<del>1.66</del> <u>1.75</u>	<del>0.025</del> <u>0.026</u>	<del>0.86</del> <u>0.83</u>	<del>0.71</del> <u>0.64</u>
GCP(residual)	2.11	0.027	1.01	

**Table 3.** Statistics of NEE from JULES-CN, JULES-C, JULES-CN<sub>layer</sub>, and the GCP observation-based estimates (Friedlingstein et al. 2019), over the period from 1960 to 2009 inclusive. Columns 2-4 show respectively the mean, linear trend, and the interannual variability (standard deviation) around that trend. Column 5 shows the correlation coefficient between each model NEE timeseries and the GCP timeseries.

radiation fertilization in these versions of JULES (Mercado et al., 2009). However, it is especially  
1025 notable that JULES-CN significantly reduces the systematic overestimate of NEE seen in JULES-C  
during extended La Nina periods, such as the years centred around 1974 and 2000 (Figure 7).

### 5.3 Impact of vertical discretisation of soil biochemistry

#### 5.2.1 Residence times

~~Over the tropics and southern latitudes,~~ In general, carbon residence times of the soil and ecosystem  
1030 are given by the stocks divided by the fluxes. These are emergent properties of the model and  
thus a valuable metric to evaluate. Figure 8 shows the ecosystem residence time and the soil C  
residence times for different biomes. Here, the land surface is split into biomes based on the 14 World  
Wildlife Fund terrestrial ecoregions (Olson et al., 2001) and characterised by Harper et al. (2018).  
The ecosystem residence time defined as the total ecosystem C divided by the GPP is shown  
1035 in Figure 8(a). These residence times have been estimated from a multi-annual mean on a grid  
cell by grid cell basis and then aggregated to biomes. The observational values were derived in  
a similar way using spatial data from Carvalhais et al. (2014). In general the ecosystem residence  
times are slightly reduced in JULES-CN ~~layered is very comparable to~~ compared with JULES-C,  
both of which are slightly lower than in the observations. The largest difference between observed  
1040 and modelled ecosystem residence time occurs in the tundra and boreal regions and the grasslands  
where the observed residence times are much longer than either JULES-C or JULES-CN. ~~The main  
differences occur in the northern regions where there is soil freezing—adding vertically discretised  
soil biogeochemistry to~~ The soil carbon residence time is shorter than the observational-based  
measure in the tundra and the boreal regions but longer in the grassland regions. Overall, this leads  
1045 to the the global soil carbon residence time in the model being too short. When vertical discretisation,  
including additional permafrost processes, is added in JULES-CN ~~has the most impact in the northern  
high latitudes. The soil in~~ <sub>layer</sub> the residence times in the boreal and tundra increase notably (see

Section 3.2.1 for further discussion).

### 1050 **5.3 Impact of N limitation**

IN JULES-CN ~~taayered~~ has more inorganic nitrogen (Figure 6) but it is not all accessible for the plants to uptake because the nitrogen uptake is limited by frozen soil. This means that in regions with frozen soil and JULES-CN ~~taayered~~ is slightly more nitrogen limited than JULES-CN (Figure 10). Globally ~~taayer~~ the N limitation mainly acts through reducing the NPP. This can be quantified using  
1055 the response ratio which is defined as the ratio of the potential amount of C that can be allocated to growth and spreading of the vegetation ( $NPP_{pot}$ ) compared with the actual amount achieved in the natural state (NPP). Both of these diagnostics are output from the JULES simulations. Figure 9 shows the spatial distribution of the model simulated response ratio. Green areas are not very N limited with a response ratio close to 1.0 and yellow areas are more N limited with a larger  
1060 response ratio. There are distinct regions of N limitation - in Australia and south Africa, the Sahel, western Europe and parts of Siberia. However much of the global land surface, particularly the forested regions has relatively weak N limitation. Figure 9(c) also shows the JULES-CN ~~taayered~~ is possible also slightly more limited than the observations suggest (Figure 10) response ratio has obvious inter-annual variability superimposed on an increasing trend over the twentieth century,  
1065 indicating increasing N limitation which will limit the increase in carbon use efficiency shown in Figure 6(f). ~~The biggest difference between-~~

Figure 10 shows the biome-based response ratio of net primary productivity. All biomes have a response ratio of greater than 1 in both the model and observations which means that adding  
1070 extra N to the system will enhance the NPP achieved. Globally the response ratio is lower than the observations but for the majority of the biomes including the tropical forests and the tundra the model response ratios fall within the range of uncertainties of the observations. However, LeBauer and Treseder (2008) suggests the tropical forest is somewhat N limited, whereas in JULES-CN ~~taayered and~~ tropical forest is not a N limited biome. Phosphorus has long been considered as the most limiting nutrient in  
1075 tropical regions (Yang et al., 2014), therefore we expect JULES to simulate a larger response ratio in the future once a phosphorus cycle is added.

In the model the soil C decomposition can be limited when the N available in the soil is less than the N required by decomposition. This process does not play a major role in our simulations.

1080

### **5.4 Nitrogen stocks and fluxes**

The zonal profile of soil organic nitrogen (Figure 11) shows a similar distribution to the soil organic C (Figure 5) reflecting the relatively consistent C to N ratio of the soil within the model.  $CN_{soil}$  - the C to N ratio of the HUM and BIO pools - is a spatially constant parameter set to 10 in these simulations.

1085 The observed soil N content is slightly higher at all latitudes than simulated by JULES-CN ~~is for the boreal and coniferous biome where the response ratio (potential NPP/achieved NPP) for JULES-CN is 1.32 of that of~~ particularly in the northern tundra region. This is likely caused by the turnover times of the soil being too fast (Figure 8) leading to not enough soil N. In addition the C to N ratios in JULES-CN ~~layered is 1.48~~ are too small for the northern high latitudes (mean of  $\sim 14$ ) whereas up

1090 to 25% of soils in tundra regions are peat with C to N ratios of around 30 (Hugelius et al., 2020). In contrast to the zonal distribution of soil organic nitrogen, the soil inorganic nitrogen in JULES-CN is larger in the tropics than in the northern high latitudes. Figure 12 shows the net soil N mineralisation fluxes are large in the tropics and smaller in the northern regions. This is reflected in the spatial distribution of the N uptake. As might be expected the spatial distribution of the N uptake as a

1095 fraction of N demand is similar to the N limitation shown in Figure 9. Biological N fixation and N gas losses are an order of magnitude smaller than the N uptake and net N mineralisation. However, again the spatial patterns are very comparable. N leaching is generally very small except in parts of south America and south-east Asia. Figure 13 shows a slight increase in the N demand and N uptake over the twentieth century associated with the increase in vegetation growth (Figure 6). Similarly

1100 there is an increase in the BNF which is parameterised such that it is proportional to the NPP.

~~This additional limitation of nitrogen uptake caused by frozen soils means that~~

## 5.5 Impact of vertical discretisation of soil biochemistry

This section discusses the differences between JULES-CN ~~layered has less total vegetation. However~~

1105 ~~it~~ and JULES-CN<sub>layer</sub>. In general over the tropics and southern latitudes, JULES-CN<sub>layer</sub> is very comparable to JULES-CN. The majority of the differences occur in the northern regions where there is soil freezing—either permafrost or seasonally frozen soils. The reduction in global mean tree covered area seen in Figure 3 is caused by a reduction in the boreal regions which have a larger proportion of shrubs and grasses in JULES-CN<sub>layer</sub>. In the higher latitudes the soil in JULES-CN<sub>layer</sub>

1110 also has more ~~soil organic carbon and soil organic nitrogen (Figure ??) because the colder soil temperatures~~ organic C (Figure 5). This increase in soil organic C represents a store of permafrost carbon more comparable to the carbon found by Batjes (2014) and Carvalhais et al. (2014). This build up of carbon in JULES-CN<sub>layer</sub> occurs because the decomposition deeper in the soil ~~profile inhibits soil carbon decomposition. This improves the estimate of the residence time of carbon in the~~

1115 ~~tundra (Figure 8) is reduced with the lower soil temperatures at depth - the soil C in JULES-CN only respond to the soil temperatures near the surface which are warmer. This also causes in increase in the residence time of the soil carbon shown in Figure 8(b). The modelled soil C residence time in~~



JULES-CN<sub>layer</sub> is now much longer and more comparable to that observed.

1120 The spatial distributions of N fluxes in JULES-CN<sub>layer</sub> (not shown) are very similar to those  
of JULES-CN. In addition, the time series of changes in N fluxes over the twentieth century are  
also comparable (Figure 13). The ~~extra inorganic nitrogen~~ main differences are in the N gas loss  
which is larger in JULES-CN<sub>layer</sub> and the N leaching which is larger in JULES-CN. Figure 11  
1125 shows an increase in both organic and inorganic N in JULES-CN<sub>layer</sub> over that in JULES-CN in  
the northern high latitude similar to that seen in the organic C. As is the case for soil organic C,  
in the colder regions the soil N builds up within the frozen soil because of the limitation of the  
decomposition rates by cold temperatures, therefore larger pools deeper in the soil are maintained in  
an equilibrium climate. The parameterisation of the vertically resolved soil biogeochemistry means  
that, once JULES-CN<sub>layer</sub> is spun-up there is inorganic N within the soil profile which cannot be  
1130 taken up by the vegetation, either because the soil is frozen or because the roots cannot readily access  
it. This means that the extra inorganic N in JULES-CN~~layered~~ (Figure ??<sub>layer</sub> (Figure 11) is mainly  
stored deeper in the soil profile and ~~some of it~~ within the permafrost itself. ~~The vertical discretisation~~  
of the soil organic carbon and nitrogen results in a longer soil residence time in JULES-CN~~layered~~  
(defined as soil organic carbon / soil respiration) and is typically inaccessible in the current climate.  
1135 This improved representation of the soil biogeochemistry will have implications for simulations of  
climate change ~~in~~ feedbacks from the northern high latitudes.

## **6 ~~Next steps~~ Discussion**

~~Importance of flexible stoichiometry.~~ This study presents the first implementation of nutrient cycles  
1140 into the UK land and earth system models. The scheme is parsimonious in that it captures the  
first order and large scale effects of interacting carbon and nitrogen on the land surface in the  
simplest way possible. One important assumption is that of fixed plant stoichiometry and that a  
plant strives to achieve stoichiometric homeostasis to maintain ecosystem structure, function and  
stability under change environments (Sternner and Elser, 2002). This assumption has some support  
1145 in the literature (e.g Brix and Ebell (1969); Wang et al. (2012)) and is a common approach amongst  
complex DGVMs (Meyerholt and Zaehle, 2015). However, recent meta analyses of field observations  
show a distinct increase in foliar N to additional N availability (Mao et al., 2020) and a modelling  
study found that assuming fixed C : N ratios and/or scaling leaf N concentration changes to other  
tissues, as employed here, were not supported by available evaluation data (Meyerholt and Zaehle, 2015)  
1150 . Employing flexible stoichiometry has the potential to significantly affect the modelled biogeochemical  
feedbacks. For instance, nutrient limitation tends to limit the production of litter, the input to soil  
organic matter, leading to a reduction in soil carbon that the nutrient limitation in soil turnover is too

1155 weak to oppose. Allowing for flexible stoichiometry may lead to a lower litter quality but a similar  
total under limitation, where the reduction in litter quality will strengthen the soil turnover response  
possibly leading to an overall increase in soil organic matter. Plant stoichiometric relationships  
are therefore a key uncertainty in assessing the carbon cycle feedbacks to climate change. Future  
versions of this model will explore the use of plant trait information (Harper et al., 2016) to parameterise  
leaf, root and wood C:N ratios for individual PFTs, and further developments to allow for flexible  
stoichiometry.

1160

While the total BNF in JULES-CN is in the range of Davies-Barnard et al. (2020) and Vitousek et al. (2013)  
the spatial distribution of BNF more heavily favours the tropics than recent observations suggest  
(Sullivan et al., 2014; Davies-Barnard et al., 2020). The response of BNF to the multiple factors likely  
to occur in future varies between factor (e.g. warming, elevated atmospheric carbon dioxide, drought,  
1165 N deposition, etc.), biome, and BNF type (nodulating, bryophyte, litter, etc.) (Zheng et al., 2020).  
Therefore how BNF will change is spatially variable and not controlled by a single factor. A move  
from an empirical to a process driven BNF function may provide better fit to present day BNF  
distribution and more robust future projections.

1170 Further work is required to explore the impact of a spatially varying soil C to N ratio which  
can vary widely depending on the amount and decomposition of organic matter within the soil.  
For example, peat soils have relatively high C to N ratios up to 30-40 Hugelius et al. (2020). This  
type of soil is not yet included within JULES. In addition, N leaching is very low in the model,  
notwithstanding the lack of N fertiliser. One reason for this could be that too much mineral N is  
1175 assumed to be sorped within the soil. This requires further evaluation and potential modifications to  
the scheme.

In this paper we have not explicitly separated the impact of CO<sub>2</sub> fertilization from climate change  
or from the impact of N deposition. However, this was explored by Davies-Barnard et al. (2020)  
1180 who put the response of JULES in context by comparing it with the responses from 4 additional land  
surface models and a meta-analysis of site observations. Davies-Barnard et al. (2020) used a slightly  
different configuration of JULES (JULES-ES) which is the configuration used in UKESM1 with  
a bulk soil biogeochemistry (Sellar et al., 2019). They found that JULES-ES has a relatively small  
increase in NPP caused by the addition extra N in the form of deposition compared with both the  
1185 meta-analyses and CLM / LPJ-GUESS. However, it is comparable to that found in JSBACH. This  
small response is, in part, caused by the smaller initial N limitation in JULES-ES. However, JULES'  
increase in NPP in response to CO<sub>2</sub> fertilisation is aligned with the majority of the models and the  
meta-analyses. ~~...feedback on SOM through litterquality...~~

## 1190 7 Conclusions

In this paper we have documented a model to quantify the impact of coupling the nitrogen cycle with the carbon cycle in a fully dynamic vegetation model. In ~~this model, nitrogen~~ the model, N limitation affects NPP and how ~~the carbon~~ much C is allocated but it only indirectly affects the photosynthesis via leaf area development. This enables the carbon use efficiency (ratio of net carbon gain to gross carbon assimilation) to respond to changing ~~nitrogen~~ N availability. Since the CUE affects the ability of the land surface to uptake carbon in a changing climate, this will impact carbon budgets under future projections of climate change. This scheme (based on JULES-CN) is only one of the new components of JULES that has been included within UKESM1 (Sellar et al., 2019). Relevant additions to the JULES-ES configuration used in UKESM1 includes more plant functional types with improved plant physiology and vegetation dynamics (Harper et al., 2016) plus a new land use module (Robertson and Liddicoat, in prep.).

Overall the ~~nitrogen~~ N enabled configuration of JULES – JULES-CN – produces a more realistic trend in the net ecosystem exchange (NEE) and the interannual variability of NEE about that trend. It also produces an improved estimate of NPP in the northern high latitudes. For other regions and diagnostics the simulation of present-day state and behaviour is not substantially different between JULES-C and the ~~nitrogen-enabled~~ N-enabled configuration, JULES-C. This is largely because JULES-C has been tuned to replicate observed carbon stores and fluxes and therefore implicitly includes a level of ~~nitrogen~~ N availability. What JULES-C lacks is a mechanism for this to change substantially in time – either under more limiting conditions as elevated CO<sub>2</sub> outpaces demand for nutrients (e.g. Zaehle (2013b)), or under conditions of increased ~~nitrogen~~ N availability due to anthropogenic deposition or ~~climate-induced mineralisation~~ accelerated soil decomposition caused by climate change leading to increased mineralisation rates (Meyerholt et al., 2020b; Zaehle and Dalmonech, 2011). The response of the ~~nitrogen~~ N cycle in JULES under changes in climate and CO<sub>2</sub> ~~conditions~~ Link to Ts work ~~–which conditions–~~ which will be affected by nutrient limitations–will be quantified and assessed in subsequent work.

1220 An extended version of the nitrogen-enabled model additionally includes the vertical discretisation of the soil biogeochemistry model. This configuration improves the ecosystem residence times in the tundra and boreal regions. This more detailed representation of permafrost biogeochemistry in the northern high latitudes will be used to understand the impact of the coupled carbon and nitrogen cycle on the permafrost carbon feedback.

1225

## Code Availability

The JULES code used in these simulations is available from the Met Office Science Repository Service (registration required) at <https://code.metoffice.gov.uk/trac/jules>. To access the code a freely available non-commercial research licence is required (<https://jules-lsm.github.io/>). The suites required for running JULES are available here: <https://code.metoffice.gov.uk/trac/roses-u>. JULES-CN is u-ah896, JULES-C is u-ah932 and JULES-CN<sup>layered layer</sup> is u-ai571.

## Competing Interests

The authors declare that they have no conflict of interest.

*Author contributions.* Andy Wiltshire designed the model in collaboration with the rest of the co-authors and wrote the first draft of the text. Eleanor Burke and Sarah Chadburn added the layered soil biogeochemistry. Peter Cox performed the analysis of inter-annual variability. All authors reviewed the paper and proposed improvements.

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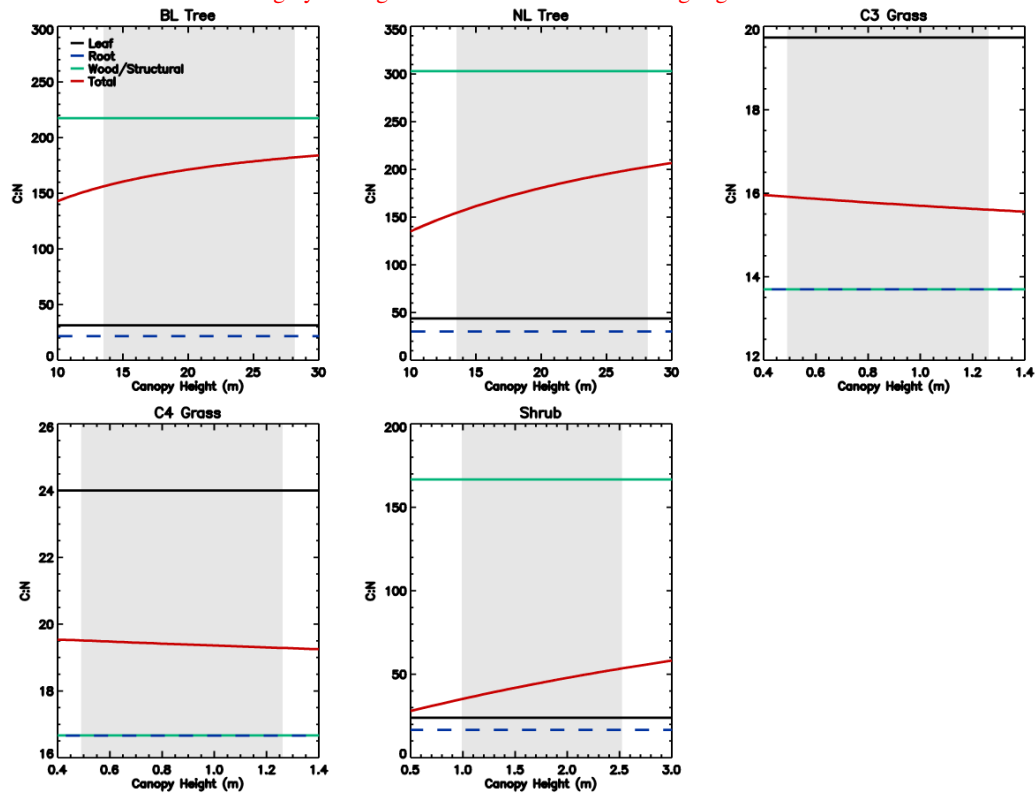
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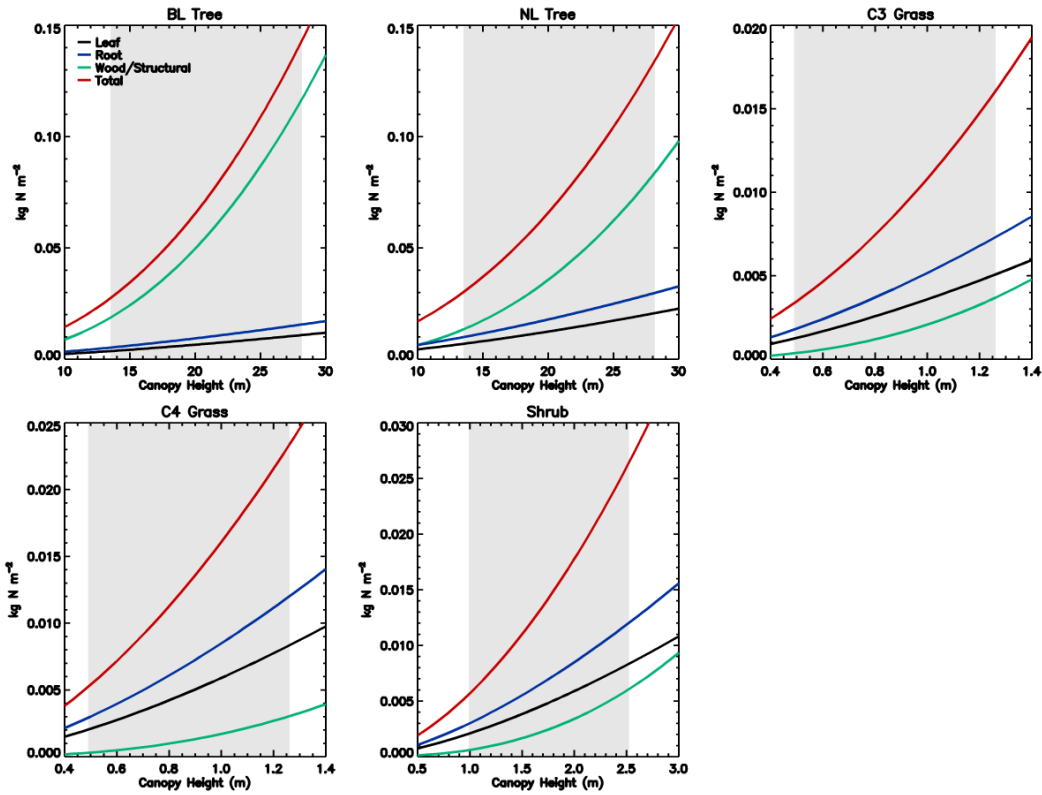
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**Figures**

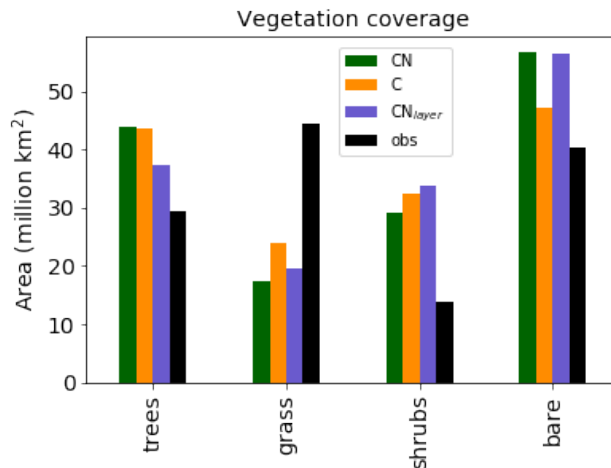
Schematic of the nitrogen cycling within the JULES-CN model. Carbon fluxes are shown in red, Nitrogen fluxes in grey. Nitrogen limited carbon fluxes are highlighted in blue:



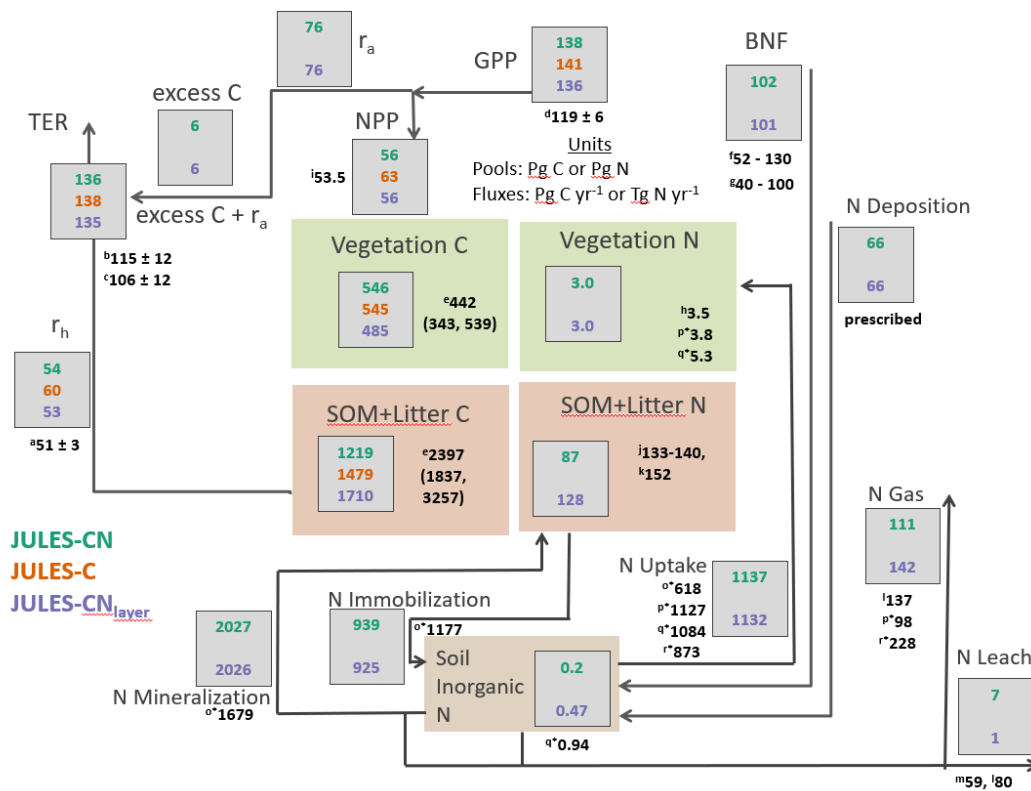
**Figure 1.** Stoichiometry-Stoichiometry of the vegetation nitrogen pools as a function of canopy height for individual PFTs at full leaf. Leaf N concentration are defined at the canopy level and are approximately % higher than those for the top leaf. The grey region shows the defined range of canopy height within the model. Note: both the x- and y-scales are very different for each PFT.



**Figure 2.** Total vegetation and component nitrogen N along with N pools of leaf, root and wood as a function of canopy height for individual PFTs at full leaf. The grey region shows the defined range of canopy height within the model. Note: both the x- and y-scales are very different for each PFT.



**Figure 3.** Total area covered by each vegetation type for the three different JULES configurations. The observations are derived from the European Space Agency (ESA) Climate Change Initiative (CCI) Land Cover data for 2010 Poulter et al. (2015) converted to JULES PFTs by Hartley et al. (2017).

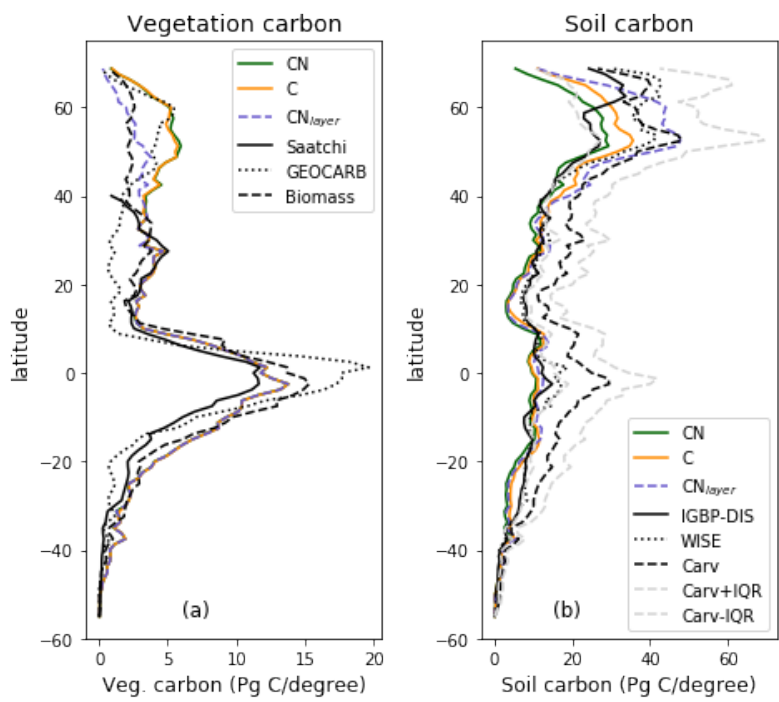


The response ratio nitrogen uptake, is the ratio of net primary productivity produced when fully fertilised vegetation nitrogen and nitrogen emissions Zaehle et al. (2010); ( $NPP_{pot}q^*$ ) compared with that achieved for the natural state nitrogen uptake and inorganic nitrogen content Xu-Ri and Prentice (2008); and ( $NPP_r^*$ ). A value greater than one means that the addition of nitrogen will enhance NPP. In the model the globe is split into biomes representing the following –TF: Tropical Forests; MF: Temperate Mixed Forests; BF: Boreal Forests; TS: Tropical Savannah; TG: Temperate Grasslands; TU: Tundra; MED: Mediterranean Woodlands; uptake and D: Desert total nitrogen emissions Wania et al. (2012). The different biomes were characterised by Harper et al. (2018) based the 14 World Wildlife Fund terrestrial ecoregions (Olson et al., 2001). The mean of JULES-CN and JULES-CN<sub>layers</sub> are shown for the period 1996-2005. The observational constraint is taken from Table 1 in LeBauer and Treseder (2008), with the black bars showing the mean and the red lines the uncertainty.

The spatial distribution of the response ratio defined as the potential NPP ( $NPP_{pot}q^*$ ) when fully fertilised as a fraction of the NPP achieved in the natural state for, ( $a^*$ ) JULES-CN, ( $q^*$ ) and ( $b^*$ ) JULES-CN<sub>layers</sub> are model derived estimates. This is the spatial distribution of the metric shown in 10.

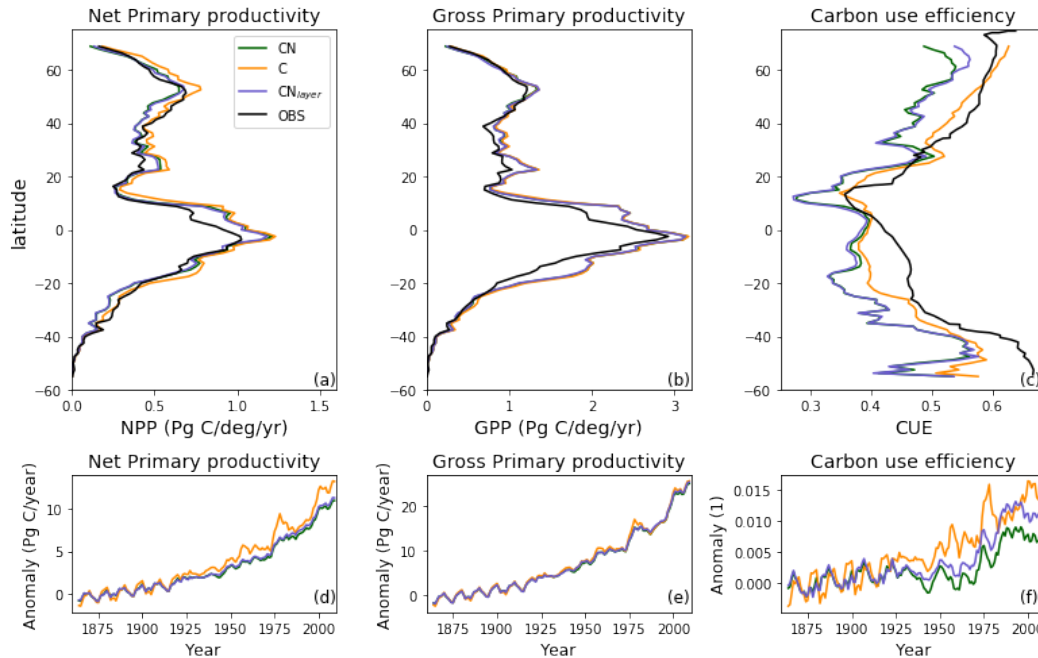
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**Figure 5.** Zonal total values of ~~soil and~~ (a) ~~vegetation carbon and~~ (b) ~~soil C~~ for JULES-C, JULES-CN and JULES-CN~~ayered-layer~~ simulations for the period 1996-2005 in Pg C / degree of latitude. For the ~~vegetation carbon~~ C the observational-based constrains are Saatchi: Saatchi et al. (2011); GEOCARB: Avitabile et al. (2016); and Biomass: Ruesch and Gibbs (2008). The ~~observational-based constraint~~ ~~observational-based constraints~~ for the soil carbon are IGBP-DIS: Global Soil Data Task Group (2000); WISE: Batjes (2016); and Carvahlais: Carvalhais et al. (2014).





Biome-based ecosystem turnover times calculated on a grid-cell-by-grid-cell basis then aggregated temporally to biome level. JULES-C, JULES-CN and JULES-CN<sub>layer</sub>s are shown for the period 1996-2005. The biomes are discussed in more detail in Figure 10. The observations are derived from the Carvalho et al. (2014) global data set.

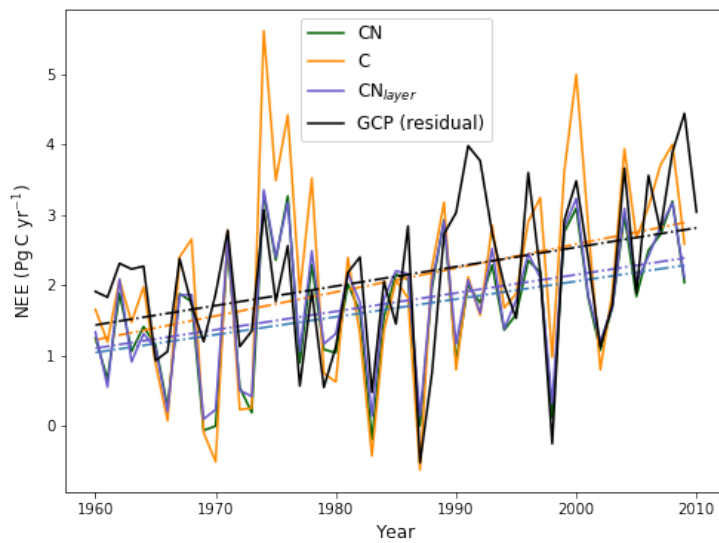
The zonal total soil organic and inorganic nitrogen stocks in Pg N / degree of latitude. The organic nitrogen stocks are from Global Soil Data Task Group (2000). Also shown are the residence times as the ratio of total soil organic carbon divided by the soil respiration.

Change Also shown are changes in (d) NPP, the response ratio (potential NPP / NPP achieved), GPP and (f) CUE for JULES-CN and JULES-C over the historical period with respect to the multi-annual mean period of 1860-1899.

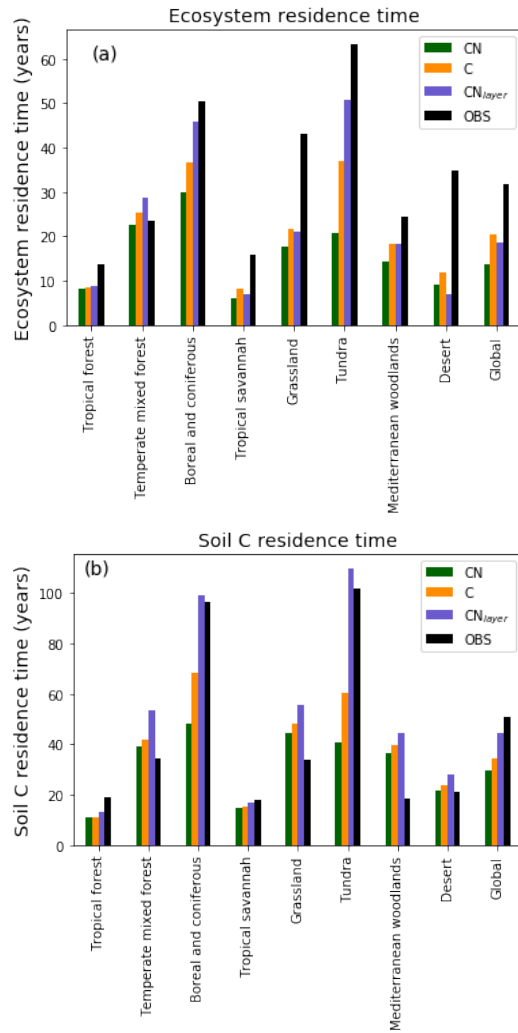
Change Also shown are changes in (d) NPP, the response ratio (potential NPP / NPP achieved), GPP and (f) CUE for JULES-CN and JULES-C over the historical period with respect to the multi-annual mean period of 1860-1899.

**Figure 6.** Zonal total values of (a) net primary productivity (NPP) and (b) gross primary productivity (GPP) for JULES-C, JULES-CN and JULES-CN<sub>layer</sub> simulations for the period 1996-2005 in Pg C / degree of latitude / year. The observational constraint for NPP is from MODIS (Zhao and Running, 2010) and that for GPP is from Jung et al. (2011). The zonal mean carbon use efficiency (CUE = NPP/GPP) is also shown in (c). The CUE observational constraint was digitised from Kim et al. (2018).

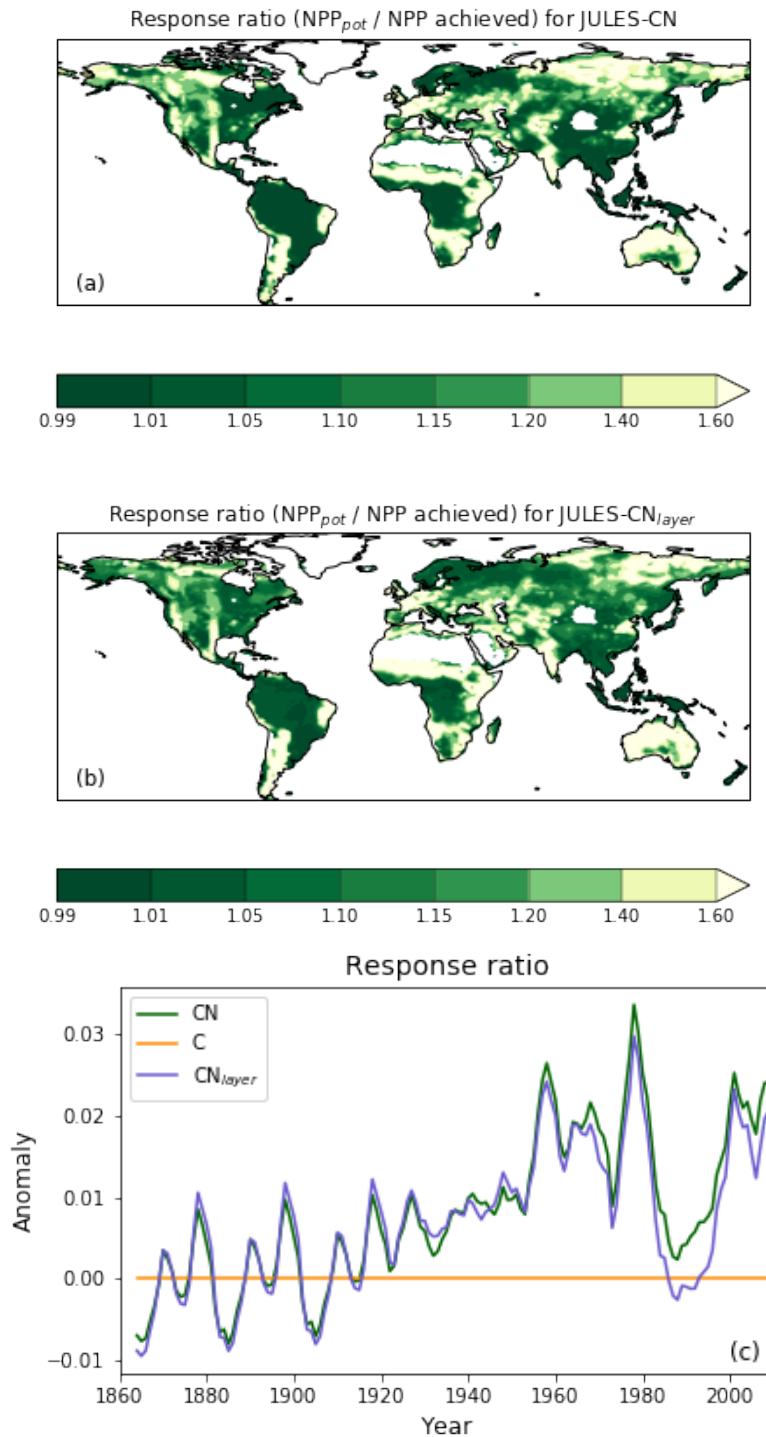
Change Also shown are changes in (d) NPP, the response ratio (potential NPP / NPP achieved), GPP and (f) CUE for JULES-CN and JULES-C over the historical period with respect to the multi-annual mean period of 1860-1899.



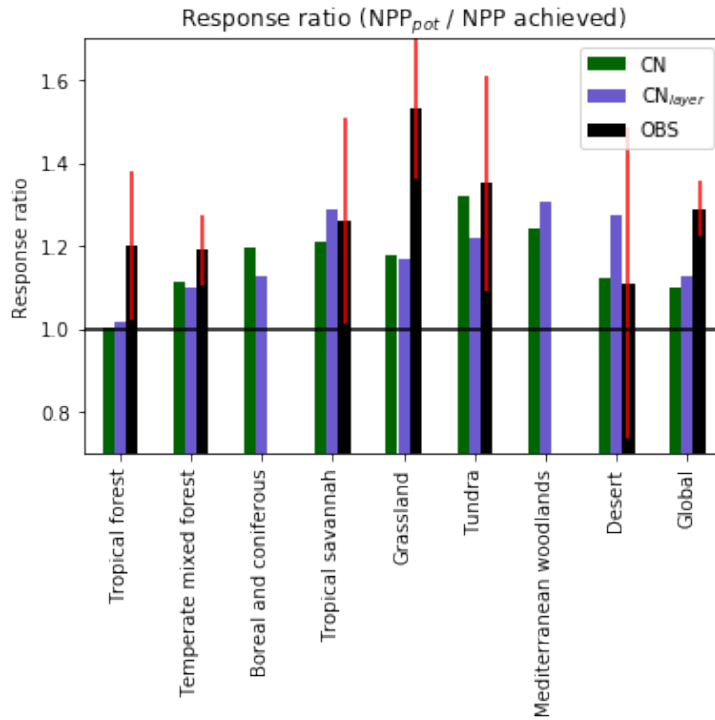
**Figure 7.** Evaluation of global annual mean NEE from JULES-CN, JULES-C and JULES-CN, ~~against~~ observation<sub>layer</sub> compared with observations based on estimates from GCP (Friedlingstein et al. 2019), (Friedlingstein et al., 2019) over the period from 1960 to 2009 inclusive. Positive values represent the land surface as a net sink of carbon. The solid lines are the data and the dashed-dotted lines represent a linear fit of the data against time.



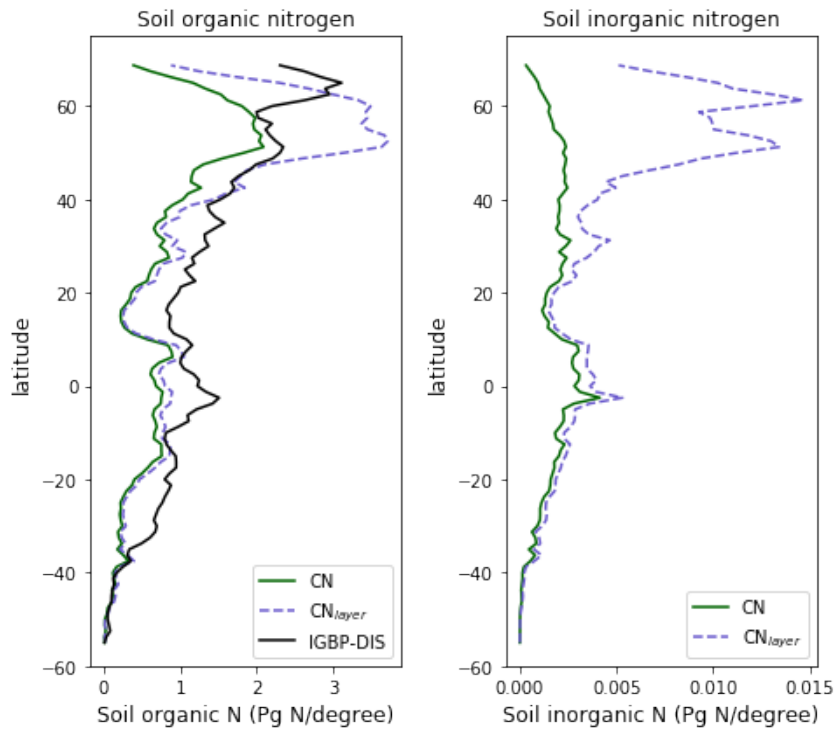
**Figure 8.** Biome-based (a) ecosystem turnover times and (b) soil carbon turnover times calculated on a grid-cell by grid-cell basis then aggregated temporally to biome level. JULES-C, JULES-CN and JULES-CN<sub>layer</sub> are shown for the period 1996-2005. The land surface is split into biomes based on the 14 World Wildlife Fund terrestrial ecoregions (Olson et al., 2001) and characterised by Harper et al. (2018). The observed ecosystem residence times are derived from the Carvalhais et al. (2014) global data set and the observed soil residence times are from the WISE: Batjes (2016) soil carbon combined with the Hashimoto et al. (2015) soil respiration.



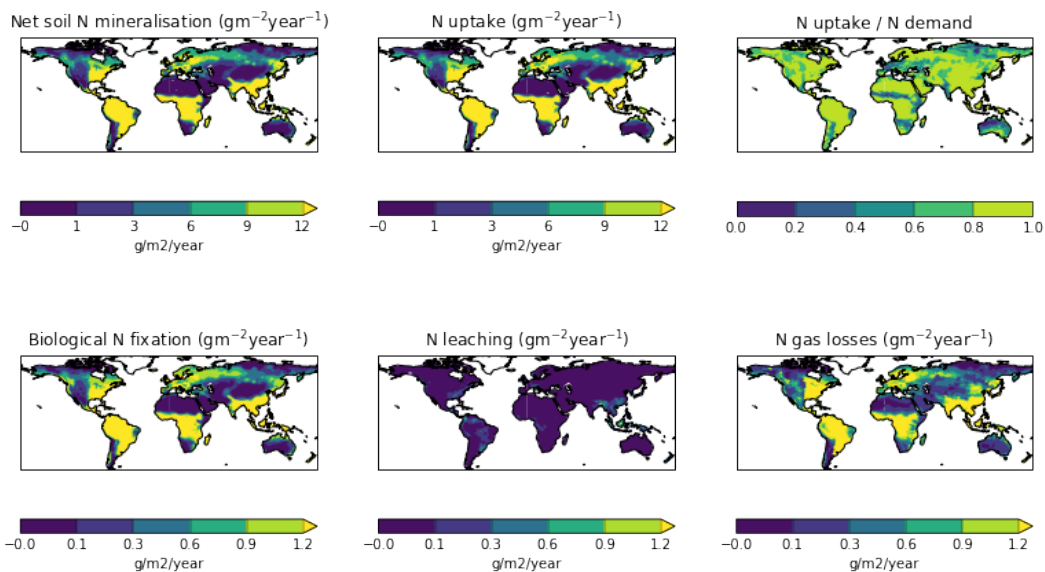
**Figure 9.** The spatial distribution of the response ratio defined as the potential amount of carbon that can be allocated to growth and spreading of the vegetation ( $NPP_{pot}$ ) as a fraction of the NPP achieved in the natural state for (a) JULES-CN, and (b) JULES-CN<sub>layer</sub>. A value greater than one means that the addition of nitrogen will enhance NPP. Any grid cells with an annual NPP of less than  $0.016 \text{ g [C] m}^{-2}$  are set to missing. This is the spatial distribution of the metric shown in Figure 10. (c) shows the change in the response ratio over the historical period with respect to the multi-annual mean from the period of 1860-1899.



**Figure 10.** The response ratio is the ratio of the potential amount of carbon that can be allocated to growth and spreading of the vegetation ( $NPP_{pot}$ ) compared with the actual amount achieved in the natural state (NPP). As in Figure 9, any grid cells with an annual NPP of less than  $0.016 \text{ g [C] m}^{-2}$  are set to missing. The median of JULES-CN and JULES-CN<sub>layer</sub> are shown for each biome for the period 1996-2005. The biomes are discussed in more detail in Figure 8. The observational constraint is taken from Table 1 in LeBauer and Treseder (2008) which summarises a meta analysis of nitrogen addition experiments. The black bars show the mean of the observations and the red lines the uncertainty.



**Figure 11.** The zonal total soil organic and inorganic nitrogen stocks in Pg N / degree of latitude. JULES-CN<sub>layer</sub> shows the stocks for the top 1 m of soil. The observations of nitrogen stocks are from Global Soil Data Task Group (2000).



**Figure 12.** Spatial distribution of N fluxes for JULES-CN for the period 1996-2005. JULES-CN<sub>layer</sub> is not shown because the spatial patterns are very similar to those for JULES-CN.

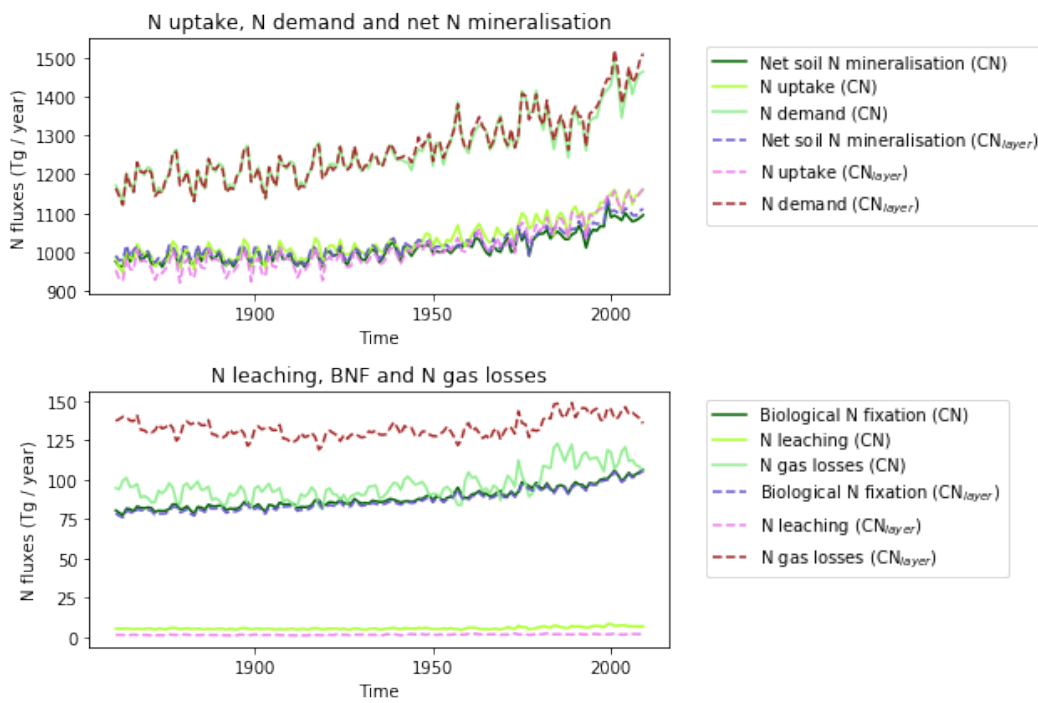


Figure 13. N fluxes for JULES-CN and JULES-CN<sub>layer</sub> over the historical period.