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

Response to Will Weider

My main outstanding question is how much of the reduction in global productivity, biomass, and IAV with the new C-N model comes from actual N limitation on living biomass and the intended declines in CUE associated with N limitation vs. simply killing off plants by imposing N limitation. Specifically, the N model makes the bare ground bias in JULES even stronger (relative to the C-only model (Fig. 3). Thus, are lower C flux and stocks simulated by JULES-CN simply a product of having more dead plants in the model? It seems like these two points matter, especially if JULES-CN is going to be included in UKESM1 simulations where potential biases in bare ground fraction may influence the land energy and water balance in ways that feedback on the atmosphere and climate.

This paper documents the addition of a nitrogen cycle to JULES and how it modifies the carbon cycle. This is just once component of the configuration of JULES that is used in UKESM (JULES-ES). Other additions include a new competition scheme and additional PFTs. The combination of these three components are included in UKESM. Here, we have not done any model specific tuning to improve the land cover fractions and UKESM has very good representation of the land cover fraction (UKESM1: Description and Evaluation of the U.K. Earth System Model - Sellar - 2019 - Journal of Advances in Modeling Earth Systems - Wiley Online Library – Figure 15). Therefore, the bare ground bias was reduced by the model specific tuning for UKESM1. It is common practice (HadCM3LC, HadGEM2-ES, UKESM1) to tune these uncertain disturbance parameters to achieve a good vegetation distribution.

In this description of the component nitrogen model the changes described in productivity and biomass are a direct from implementing Nitrogen. The changes in biomass are a direct result of reduced net productivity. As noted, reduced biomass generally leads to a reduction in productivity. As JULES-CN is a fully dynamic model it is near impossible to separate the initial change in productivity from a biomass response. However, as no vegetation parameters are adjusted it is the case that any changes are driven by the productivity response to the inclusion of an N scheme.

On a related note, I appreciate the synthesis of many results in zonal mean plots and annual time series, but wonder if there are insights or information that could be gained from showing full spatial maps of initial results (e.g. vegetation cover, GPP, or LAI in the CN model and their difference from the C-only results?). Maybe it makes sense to put these in supplemental material, if the authors are worried about cluttering up their results.

At this stage of the review process we have not undertaken this task. Full spatial maps of the full UKESM configuration are being made available in the literature via model evaluation and assessments as part of CMIP6.

Line 80 – **new GCP paper has been cited.**

It should also be noted that comparisons with GCP2019 estimates of NEE and IAV are themselves a modelled product from the TRNEDY simulations, of which JULES-CN participated. These are quasi-independent estimates, not results residual of bookkeeping methods, as previously presented – The following text is in the paper - **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 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.** and the observational-based IAV is not dependent on the TRENDY

Response to Reviewer 3

Major comments:

1. *N demand vs uptake*

   Thanks for pointing this out. The code is implemented correctly but unfortunately the documentation needs correcting. This has been clarified in the manuscript with Dt, the given model timestep added to ensure the units are consistent. N{avail}/Dt is indeed a maximum uptake of inorganic nitrogen in that timestep. In this implementation it is assumed to be the equivalent of the entire pool taken up over the model timestep.

   The text now reads:

   {In JULES-CN the N available for plant uptake for each PFT i ($N_{avail,i}$ in $kg\,[N]\,m^{-2}$) is the the inorganic soil N pool (N_{in} in $kg\,[N]\,m^{-2}$) split equitably between the PFTs assuming there is no differential ability between PFTs to acquire N and the whole pool is available for uptake during the model timestep. The available N in JULES-CN$_{layer}$ is more complicated and takes into account the soil profile. This is discussed in Section \ref{sec:ninorgvert}.}

   And:

   If the N demand is less than the available N in a given timestep (Δt) ($\Phi_{g,i}$ $<$ (1-λ_i) $N_{avail,i} / \Delta t $) then growth is unlimited and the fluxes can be updated accordingly. Where N is limiting, growth N uptake is set equal to the available N ($\Phi_{g,i}$ $=$ (1-λ_i) $N_{avail,i} / \Delta t $) and the excess C for growth $\Psi_{g,i}$ can be derived.

   See also the response L450 and Eq 40.

2. Errors in equations

   a. *Units in equation 14:* **Units associated with Eq 14 are updated to make clear they are fluxes.**
   b. *response to query about equation 50*: **Eq 50 is now revised in the revised manuscript.**
   c. *response to query about equation 55:* **Equation 55 has been updated to reflect the fact the Ndep is only added to the top layer.**

All minor textural changes suggested in the handwritten annotated document have been made.

Line 12 - N limitation can slow soil decomposition - Perhaps it is later but of C to N or soil organic matter is fixed how does this work? – **Indeed this is discussed later. The C:N ratio of two of the soil carbon pools is fixed, but the C:N ratio of the litter pools will vary, which means the overall C:N ratio of the soil carbon will vary.**

Line 21 - The introduction of a N cycle improves the representation of interannual variability of global net ecosystem exchange which was much too pronounced in the C cycle only versions of JULES (JULES-C) – compared to what? Changed to : **The introduction of a N cycle improves the representation of interannual variability of global net ecosystem exchange which was more pronounced in the C cycle only versions of JULES (JULES-C) than shown in estimates from the Global Carbon Project.**

Line 25 - The abstract doesn't mention the effect of layered soil biogeochemistry – added: **JULES-CN$_{layer}$ improves the representation of soil biogeochemistry including turnover times in the northern high latitudes.**

Line 23 - It also reduces the present-day CUE from a global mean value of 0.45 for JULES-C to 0.41 for JULES-CN and 0.40 for JULES-CN1ayer – Is this less or more realistic? Isn't present day CUE more like 0.5? This paper: [Intercomparison of Terrestrial Carbon Fluxes and Carbon Use Efficiency Simulated by CMIP5 Earth System Models | SpringerLink]() provides estimates of the CUE from other models and from MODIS data. Figure 10 in this paper shows the CUE is latitudinally dependent and varies between 0.2 and 0.7 with the majority of estimates between 0.4 and 0.6. Uncertainties in the observed CUE are considerable so the JULES estimates of CUE fall within this range of uncertainties. Text changed to: **It also reduces the present-day CUE from a global mean value of 0.45 for JULES-C to 0.41 for JULES-CN and 0.40 for JULES-CN$_{layer}$ all of which fall within the observational range.**

Line 46 - In a changing climate Co2 drives an increase in the land C uptake and hence an increase in the gross primary productivity (GPP). – Text changed to **Any increase in atmospheric CO$_{2}$ drives an increase in the land C uptake and hence an increase in the gross primary productivity (GPP).**

Line 85 - 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 index (LAI) and biomass without the complex and uncertain impacts on leaf physiology – unclear what is meant here – changed to: **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 index (LAI) and biomass.**

Line 90 - 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$_2$m^{-2}s^{-1}). V_{cmax} has a dependency on the leaf N concentration.**-** photosynthesis-stomatal conductance coupling in general is not tied to vcmax. How photosynthesis is determined is related to (Ca-ci) gradient not vcmax – changed to - **At the core of surface exchange in JULES is a coupled stomatal conductance photosynthesis scheme with a dependency on the leaf N concentration.**

Line 94 - Implicit within JULES, even in simulations excluding the N cycle is the parameterisation of plant tissue level N concentrations and associated allometry \citep{gmd-13-483-2020} - please say that this is explained later – changed to: **Implicit within JULES, even in simulations excluding the N cycle is the parameterisation of plant tissue level N concentrations and associated allometry (discussed further in Section \ref{sec:allocup} and by \cite{gmd-13-483-2020})**

Line 100 - Each exchange of C is associated with a corresponding flux of organic N. – need a bit more elaboration- changed to - **At the ecosystem level, the C and N cycles are closely coupled with each flux of C associated with a corresponding flux of N linked through the N to N ratios.**

In JULES nutrient limitation operates through two mechanisms; the available C for vegetation uptake is reduced, **-** unclear C for veg uptake is in the atmosphere changed to **- Firstly, the vegetation cannot uptake as much C -- any C that the plants cannot uptake is denoted excess C.** Excess carbon is defined here and used subsequently throughout the document.

Lie 103 - and the decomposition of litter C is slowed. **-** please clarify, make the connections to N- changed to -**decomposition of litter C is slowed because there is insufficient N present**

Line 105 - This is achieved by explicitly representing the demand for N within the vegetation and soil modules and then reducing plant net C gain to match available nutrients. – please define gain – changed to - **reducing plant net primary productivity to match available nutrients**

Line 103 - In the soil module an additional decomposition rate modifier is introduced that slows decomposition to match available nutrients. – what is the process involved? – changed to - **In the soil module an additional decomposition rate modifier is introduced that slows respiration by microbes to match available nutrients.**

Line 111 - In reality the excess C (Ψ) – undefined what is this?- changed to - **In reality the C the plants are unable to use because of insufficient N (Ψ)**

Line 112 – goes to non structural carbohydrates – not strictly a loss term – changed to - **becomes to non structural carbohydrates, root exudates or biogenic volatile organic compounds**

Line 120 - This is consistent with field experiments enhancing N fertilisation that find increases in growth but no corresponding change in photosynthetic capacity \citep{brix1969effects,wang2012impact}. **-** what about Field and Mooney, 1986, Mcguire et al., 1995 - leaf level N is related to photosynthetic capacity. – **added both of these references.**

Line 125 - Within the fully coupled Earth Systems Models used in the Coupled Climate Carbon Cycle Model Intercomparison Project (C4MIP) for quantifying C feedbacks only four models include a N cycle representation – out of how many total? – added - **out of eleven models**

Line 139 - Within JULES, C dynamics in soils and vegetation and dynamic vegetation are provided by Top-Down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) \citep{cox2001} – changed to - **Within JULES, C stocks and fluxes in and between the soils and vegetation along with competition between different vegetation types are modelled by the Top-Down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) \citep{cox2001}**

Line 166 - TRIFFID employs fixed allometry such that the split between leaf, root and stem C – changed to - **TRIFFID employs fixed allometry such that the split of vegetation carbon between leaf, root and stem**

Line 168 - Biomass density increases via growth and is reduced by litter production and competition. - Changed to - **Biomass density increases via growth and is reduced by litter production and competition with other PFTs \citep{clarketal2011}.**

Line 232 - The total vegetation N increases with canopy height and biomass (Figure ~\ref{fig:npool}). – I don't understand why? – changed to - **Equations 1-8 show that the total vegetation N increases with canopy height and biomass (Figure ~\ref{fig:npool}).**

Line 256 - $n_{lc,i}$ is the mean canopy N content – units? – changed to – **concentration kg[N]/kg[C] Firstly, the vegetation cannot uptake as much C -- any C that the plants cannot uptake is denoted excess C. Secondly the decomposition of litter C is slowed because there is insufficient N present.**

Line 264 – changed to - **The formulation of the labile pool, in this configuration, means that around half of the N required for full leaf-out is taken from leaf retranslocation with a further quarter acquired during the dormant phase while the rest is acquired during the leaf-out period.**

Line 270 - changed to - **where $k_{n,i}$ is a constant representing the profile of N density and d represents the fraction of canopy above the layer. Based on observed N profiles in the Amazon basin \citep{carswell2000photosynthetic}, a value of 0.78 for $k_{n,i}$ was found \citep{mercado2007improving}. Equation \ref{eq:kn} is independent of leaf area and therefore equates to a constant of proportionality relating PFT-specific top leaf N to the mean canopy N concentration.**

Line 292 - What does subscript g mean? – 'growth' – this is now defined.

Line 294 - I think its incorrect to refer to this C as excess – this has now been properly defined earlier in the document and should now make more sense.

Line 302 on – N-avail is a pool and Dt representing the timestep has been added to compare it to the fluxes.

Line 302 – why is phi not a flux – units changed to /s.

Line 311 – retranslocation now defined as kappa not lambda so as to not confuse with other lambda

Line 320 – explained above what excess C is.

Line 330 now reads: **In JULES-CN, on a PFT basis, the N available for plant uptake ($N_{avail,i}$ in $kg\,[N]\,m^{-2}s^{-1}$) is the inorganic soil N pool (N_{in}) split equitably between the PFTs assuming there is no differential ability between PFTs to acquire N and the whole pool is available for uptake during the model timestep**. This should resolve the confusion between pools and fluxes for lines 319 to lines 331.

Line 355 now reads: - **The C and N allocated to spreading allow the vegetation to expand onto bare ground. Where space is limiting the PFTs compete for space.**

Line 366 – *aggregated tile* replaced by **grid box**

Equation 22 – Pi and Psi are defined with reference to other Equations in the document.

Line 380 – *pool being turned over replaced* by **the relative amount of stem, leaves and roots being turned over**

Line 383 - *The soil biogeochemistry in JULES-CN operates on aggregated tiles* – replaced by **- The soil biogeochemistry in JULES-CN operates at a grid box level**

Line 384 - *follows the Roth-C soil C model \citep{jenkinson1990,cj1999} used in JULES-C on the TRIFFID timestep, with the addition of a prognostic soil N model* – changed to - **The soil biogeochemistry in JULES-CN operates at a grid box level and is an extension of the Roth-C soil C model \citep{jenkinson1990,cj1999}. Roth-C is used in JULES-C - here we describe the addition of a prognostic soil N model.**

Line 450 – FN is also applied to immobilisation and mineralisation. This has been added: **The nitrogen limited mineralisation and immobilisation of the DPM and RPM pools (Equations \ref{eq:ipot} and \ref{eq:mpot}) are now effectively a function of R_{p}.**

Equation 40 - |Delta_t has been added which represents the timestep length.

Line 467 – have now shown that mineralisation and immobilisation can be reduced by N limitation.

Line 490 – tau has been changed to xi.

Line 504 – added - **Do(m2s−1) varies spatially depending on the freeze/thaw state of the soil**

Line 520 – f_lit is independent of PFT – text changed to **- Here $f_{lit}(z)$ is independent of the PFt type and hence the root distribution**

Line 513 -added - **and z is the mid-point of each layer**

Equation 52 – this is an additional gas loss term so the total gas loss is equation 42 plus equation 52. This is stated in line 545.

Equation 58 and 59 – the rate change equation (59) is an additional change that happens after the plant uptake, so it is an additional modification to equation 58 after the plant uptake has occurred which moves the accessible N away from equilibrium.

Equation 60 – this is now discrete.

Line 625 - *The total leaching is then the sum of all N that leaves the soil* -changed to - **The total leaching is then the sum of all N that leaves the soil both laterally from each layer or from the bottom of the soil profile**

Line 631 – added - **which include time varying climate, CO$_2$, and N deposition but pre-industrial land use.**

Line 669 - *Then we show spatial distributions and time series of the N stocks and fluxes* – changed to - **Then we show spatial distributions and time series of the N stocks and fluxes**

Line 678 – *CCI observations* – changed to - **The Climate Change Initiative (CCI) land cover observations**

Line 675 to 681 – The purpose if this paper is to document the nitrogen scheme. We have specifically not gone into too much detail of the vegetation distribution. This is because the configuration of JULES adopted here has been superseded by JULES-ES used in UKESM1. This includes additional improvements including a revised competition scheme and new PFTs. The text has been changed to - **In general, the models all tend to over-estimate the shrubs and underestimate the grass. However, \cite{ukesm1} shows that once the additional PFTs are included the model does a good job of representing the vegetation distribution.**

Figure 4- the litter fluxes have been added

Line 708 on – Figure 5 (now figure 6) shows the latitude vertically on the plot as might be expected on a spatial plot. I think this is a good way to show the zonal means rather than having the latitude horizontally.

Line 728 – The considerable uncertainties in the estimates of the CUE mean that it is hard to draw the conclusion that reducing NPP and not GPP may or may not be a good strategy in response to N limitation. The following is added: **However, considerable uncertainties remain in these estimates.**

Line 790 – the colorscales on the figure have been modified to make things clearer. We have left analysis using response ratio and NPPpot/NPPacheived because this is the way LeBauer and Treseder (2008) report their results.

Line 799 – Figure 9c implies no N limitation on 1860-1900 can you comment if this is realistic? - Figure 9c is an anomaly from the mean pre-industrial state which ahs a global mean value of 1.2-1.3. So there is nitrogen limitation in the pre-industrial state.

Line 825 – I agree, this is a confusing message, I have removed the lines.

Line 884 – this now reads: **Allowing for flexible stoichometry may lead to a lower litter quality but a comparable amount of litter. This reduction in litter quality will strengthen the soil turnover response possibly leading to an overall increase in soil organic matter.**