Response to Reviewer 2:

Robust Ecosystem Demography (RED): a parsimonious approach to modelling vegetation dynamics in Earth System Models

Arthur P. K. Argles, Jonathan R. Moore, and Peter M. Cox on behalf of co-authors. (*on behalf of the co-authors*)
24th March 2020

The referee was mainly concerned with specific detail, they did raise other points but mainly found that the paper was a bit confusing. We address each of the queries raised below. The relevant reviewer comments are written in italics below followed by our responses in plain font, changes are detailed in blue font.

> **Reviewer**:
> *The authors present a model development work on vegetation demography, and seek to incorporate it into an earth system model. The framework provides a simplified solution to model the global vegetation distribution based on the "Metabolic Scaling theory". Both the topic and the model concept are very interesting. However, there are numerous errors and ambiguous expressions throughout the current manuscript. The model descriptions are not clear enough, especially for the equations and units. At some points, I have to stop to calculate the units of each term. I'm also not fully convinced by the model outputs and validations. Extra information are necessary to be provided for a proper judgement, e.g., how the NPP data was created, which climate forcing and vegetation map were used. I suggest an overall revision and reorgnization of themanuscript. My major question about this approach is how it can be used in transit-time simulations, especially for the future projections. From a modelling aspect, the model simply ignored many factors that can be modfied due to climate change. Nevertheless, it would be very exciting if enough evidences support that some important emergent properties from land ecosystems would remain constant in a fast changing world.*

Response (1):
We thank the reviewer for their comments and have sought to make edits that make the model paper clearer and help clarify definitions. On the point of the NPP data, we ran RED offline using outputs from the UKESM climate model. UKESM calculates phenology and litter fluxes using climatic data per area of each PFT (rather than per gridbox). We have elaborate further within the discussion on how RED can be used in transient simulations of future climate simulations. RED was built to be parameter sparse to reduce uncertainty at the global level. As seen from the results within the paper it is possible to capture regional vegetation accurately even within such a parasimonious model.

Edit:

"RED is currently being integrated into the JULES Land Surface Model replacing TRIFFID as DGVM. Significant improvements in representation of biogeochemical cycle of droughts, simulating stomata conductance /xylem embolism (SOX) (Eller et al., 2018, 2020) along with the non-structural carbohydrate model (SUGAR) (Jones et al., 2019) and fire through the INFERNO model (Burton et al., 2019) are being developed. In the future size, related mortality and growth rates can be taken as inputs from these independent models and the updated demographic state given back. We see this a promising avenue for research understanding the resilience of regional ecosystems under climate change."

Specific Comments

> **Reviewer**:
> *P1 Abstract*
> *L7: cohort-based models?*

Response (2):
We further elaborate on this term within the abstract.

Edit:

"More advanced cohort-based patch models are now becoming established in the latest DGVMs. These models typically attempt to simulate the size-distribution of trees as a function of both tree-size (mass or trunk diameter) and age (time since disturbance)."

> **Reviewer**:
> *..L8:These models*

Response (3):
Corrected "These typically..." to "These models typically...".

> **Reviewer**:
> *..L14:I feel it should not be the major reason to argue that RED would be a great contribution. Only mentioning the computing cost is not convincible enough.*

Response (4):
We agree that this is not the definitive reason for the development of RED. Indeed the development of RED is driven by the need to have a robust and parameter sparse model of forest demography for global applicationslaw of parsimony. We therefore state that the additional problem arising from the balance of representation of ecological processes versus the number of uncertain parameters.

Edit:

"This approach can capture the overall impact of stochastic disturbance events on the forest structure and biomass, but at the cost of increasing the number of parameters and some ambiguity when updating the probability density function (pdf) in two-dimensions."

Reviewer:
..L15:pdf?

Response (5):
We have appended "(pdf)" to the initial mention of "probability density function..." in the sentence beforehand.

Reviewer:
..L19:solvable?

Response (6):
Corrected typo.

Reviewer:
..L26:Why only compared to this dataset

Response (7):
We compare to this dataset partly because this dataset is classified using the same PFTs used within the UKESM.

Reviewer:
..L41:2K? not clear enough, references needed

Response (8):
We have added in a reference to the Paris Agreement and changed the units to degree centigrade.

Edit:

"This is an important component of the total carbon budget consistent with avoiding global warming thresholds, such as 2°C (Schleussner et al., 2016)."

Reviewer:
..L47:keep update with the new results?

Response (9):
We have included the new data from GCB 2019 (Friedlingstein et al., 2019)

Reviewer:
..L44-51: The logic here is unclear. I assume that the authors want to stress the large uncertainties in modeling land C budget. But the topic of the study is model development, rather than uncertainty analysis. So I suggest to use 1-2 sentences to describe the uncertainty topic and go to the model development faster.

Response (10):

We agree that the motivation for including land C budget could be more concise. Uncertainty arising from the representation and parameterisation of processes is part of the motivation for RED. We have also included more discussion of other published models.

> **Reviewer**:
> *..L53: According to my knowledge, LUC prediction is from another sector, which is not from DGVM. Provide the LUC examples here seems irrelevant to the modeling of this study. Also, why the authors only picked examples from RCP8.5.*

Response (11):
Agreed. Therefore, we only mention it in passing;

Edit:

"Beyond the fertilisation effect and land-use change, significant uncertainty arises from the representation of vegetation demographics such as recruitment, compeitition and mortality (Brovkin et al., 2013; Ahlström et al., 2015)."

> **Reviewer**:
> *P2*
> *..Line 2: Rewrite the sentence and focus on the topic of this study. Generally, DGVM includes biochemical, biogeographical, biophysical processes and other factors influencing vegetation.*

Response (12):
We have changed the sentence to be more encompassing of what a DGVM includes.

Edit:

"The transient representation of plant communities within Earth System Models (ESMs) is achieved through the use of Dynamic Global Vegetation Models (DGVMs). DGVMs employ a variety of biophysical, biogeographical and biochemical processes to simulate growth, competition and recruitment of vegetation. The variety in the number and resolution of the processes helps to contribute to the differences found at the Earth System level."

> **Reviewer**:
> *..Line 5: How to define complex. What about the other "complex" models.*

Response (13):
We have clarified this as "individual based models".

> **Reviewer**:
> *..Line 10: Why non-individual based models cannot do that?*

Response (14):
Valid point, we now have redefined this as:

Edit:

"In the second-instance, individual models can explicitly represent a multitude of biological and ecosystem processes at a individual plant level (Smith, 2001; Sato et al., 2007)."

Reviewer:
..Line 13: What is top-down models? Area based?

Response (15):
Yes, we think of top-down models as phenomenological models such as Lotka-Volterra. We clarify this point in the introduction.

Edit:

"DGVMs often range from the simplistic, older, top-down approach to that of complex individual-based DGVMs. For example, in the first instance the TRIFFID model (Cox, 2001; **?**) simulates the fractional area of each Plant Functional Type (PFT) using phenomenological Lotka-Volterra equations."

Reviewer:
..Line 15: are significantly simpler and more computationally efficient(reference?).

Response (16):
We have edited the paragraph in the model description removing this statement.

Reviewer:
Line 17: over-estimated(reference?)

Response (17):
We have now provided a reference: (Burton et al., 2019).

Reviewer:
..Line 34: The previous paragragh only explain one benefit of RED: reduce computational cost. To me, it is at least not the major reason for the RED development. I feel it is necessary to mention the theoretical foundations for RED development, e.g., the scaling theory. Although this study is mainly about model development, the explanation of the underlying mechanisms is necessary to facilitate the understanding of the model concept.

Response (18):
A valid point. We have now stated the theoretical foundations of metabolic scaling theory. Added onto the last description of the introduction:

Edit:

"This paper presents a simplified cohort model (*Robust Ecosystem Demography (RED)*) which updates the number of trees in each mass class, but does not separately track tree-age or patch-age.

RED assumes that the tree size-distribution of a forest is determined by how the rates of tree growth and mortality vary with tree size (Kohyama et al., 2003; Coomes et al., 2003; Muller-Landau et al., 2006; Lima et al., 2016). We follow many other studies in assuming that tree-growth rates vary with the three-quarter power of tree mass ($m^{3/4}$), as suggested by metabolic scaling theory (West et al., 1997). Where tree mortality rate can also be assumed to be approximately independent of tree mass, the demographic equation yields equilibrium tree-size distributions which follow a Wiebull distribution – this is sometimes termed 'Demographic Equilibrium Theory (DET)' (see Appendix B). These simplifications significantly reduce the number of free parameters in RED, but still enable it to fit forest inventory data in North America (Moore et al., 2018) and South America (Moore et al., 2020)."

Reviewer:
Description of the model: Overall, the equations should be carefully checked, and the units need to be added in an appropriate way.

Response (19):
The units and equations have been thoroughly checked for this study and other related papers (Moore et al., 2018, 2020). We now also explicitly point to the table of variables, definitions and units in the Appendix A.

Edit:

"A full list of variables, definitions and units are given in appendix A."

Reviewer:
..Line 47-49: Check the symbol consistency between equ.1 and the corresponding descriptions. I suppose the equation has been simplified – it is assumed that gamma is independent from mass level already.

Response (20):
Edited for consistency.

Reviewer:
..Line 50: Any form of what?

Response (21):
Edited to say: "of relationship with size".

Reviewer:
..Line 53: follows a power..

Response (22):
Corrected.

Reviewer:

..Line 59: Correct the reference format

Response (23):
Corrected.

Reviewer:
..Line 70: Is that a basic requirement to build a vegetation model?

Response (24):
Yes - in the context of the carbon cycle and Earth System Modelling.

Reviewer:
..Line 86: keep unit unified throughout the MS. why using per plant per unit area previously but using explicit unit here?

Response (25):
We now declare units to keep consistency throughout the manuscript at first mention.

Reviewer:
..Line 88: why it is a concern? To keep mass and energy balance is basic to develop a model.

Response (26):
We have re-phrased this statement.

Reviewer:
..Line 66 the area term "a" does not appear before.

Response (27):
The mean crown area "a'" - is defined in the previous paragraph.

Reviewer:
P3:
..Line 8: P has been defined before. Again, units miss

Response (28):
We have now added units.

Reviewer:
..Line 17: This part is mainly derived from PPA and TRIFFID, or new for RED? If it is former, I suggest to provide main equations and introduce them briefly.

Response (29):
These equations are developed for use in RED. We have removed the reference to PPA in response to other reviewer comments.

Reviewer:
P4:..Line 1: I'm concerned about the "coupling" here. Based on the description, I feel RED has not been coupled with the ESM. Using prescribed NPP means an implicit vegetation distribution in itself. From equ.16, higher NPP would mean higher baseline growth-rate.

Response (30):
RED was run offline using NPP and litter outputs from a UKESM run, there is no coupling. The UKESM runs were in terms of PFT area instead of grid-box area, therefore multiplying by coverage circumvents this issue. We have clarified this point in our introduction.

Reviewer:
..Line 53-54: What is the loss of vegetation C due to plants growing beyond the modelled mass classes

Response (31):
The truncated growth $g_I N_I$ as seen within the demographic litter equation. However, this term is negligibly small because we resolve a large mass class range that is very unlikley to be exceeded.

Reviewer:
P7:
For the first paragraph of "Modelling results", Should it be part of the method section?

Response (32):
No we don't think so. This paragraph is part of the explicit set-up rather than then the method and helps the results section have improved 'flow'.

Reviewer:
..Line 1: What tests?

Response (33):
Response: Changed "tests" to "run".

Reviewer:
..Line 2: Again, I'm concerned about the use of prescribed NPP. How you get NPP? Using which climate forcing? What period of NPP you used. And most importantly, how the NPP data from JULES defines the vegetation distribution? A predefined data or from a model? All the info needs to be added for a proper judgement. If fed a similar pattern from the data: ESA LC CCI to RED, then it is not surprising that they would have the similar output as showed in Figure 7.

Response (34):
For the sake of clarity, we now state that the UKESM data is defined by unit of vegetation

area rather than grid-box and include about the timescale of the dataset. We already state that this is a model inversion and is therefore essentially tuning the mortality rate within RED to fit the data.

Edit:

"The UKESM simulation ran on a yearly time-step, and provides NPP and local litterfall per unit PFT. We multiply by PFT fraction to get the grid-box mean values required to drive RED (using ESA landcover data, as explained below)."

Reviewer:
..Line 10: Why choose this grid-box

Response (35):
We choose this grid-box because it demonstrates a successional tropical sequence with many PFTs from bare soil. We could have shown many others.

Reviewer:
P16:
..Line 1: Discussion. The comparisons between RED and the other similar models are needed. But before that, I think the method description needs to be greatly improved, and the corresponding results should be further clarified.

Response (36):
Agreed. We have now included a comparison to other DGVMs which include forest demography within the discuss. Further we have tried be more clearer within the model description by keeping consistency in the equations and by moving some of more mathematically excessive sections into Appendix B. In addition to the above edits on the results, we have also reorientated the sections within the results section to improve the papers flow.

Edit:

"In a similar vein a few other models have limited the number of cohort dimensions, for example looking at using patch-age while using allometric relationships to capture size scale. Firstly the POP model (Haverd et al., 2014), uses stand-age cohorts as the dimension for population dynamics, every time-step applying crowding and resource limited mortality rates. Another ex- ample is the ORCHIDEE-MICT (Yue et al., 2018), which disaggrates the populations of a PFT into patch "Cohort" functional types, with transitions between cohorts diagnosed when the average basal diameter passes a threshold."

Edit:

Finally, we assume that light-competition is only significant for the lowest 'seedling' mass class. This enables us to capture the impacts of light competition on seedling emergence through a simple 'gap' boundary condition. This represents a significant simplication compared to other approaches involving the Perfect Placisity Assumption (PPA), as used within other DGVMs such as LM3-PPA or CLM(ED) (Fisher et al., 2015; Weng et al., 2015), where canopies are assumed to perfectly fill gaps through photomorphism (Strigul et al., 2008). In LM3-PPA the radiative flux is limited by the available gap fraction in a given crown layer. PPA parallels our gap boundary condition at the lowest mass class (Equation (11)), but in RED the growth of a cohort is purely dictated by the the disaggregation of total growth assimilate assuming metabolic scaling (Equation (16)).

Bibliography

Ahlström, A., Xia, J., Arneth, A., Luo, Y., and Smith, B. (2015). Importance of vegetation dynamics for future terrestrial carbon cycling. *Environmental Research Letters*, 10(5):054019.

Brovkin, V., Boysen, L., Arora, V. K., Boisier, J. P., Cadule, P., Chini, L., Claussen, M., Friedlingstein, P., Gayler, V., Van den hurk, B. J., Hurtt, G. C., Jones, C. D., Kato, E., De noblet ducoudre, N., Pacifico, F., Pongratz, J., and Weiss, M. (2013). Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century. *Journal of Climate*, 26(18):6859–6881.

Burton, C., Betts, R., Cardoso, M., Feldpausch, T. R., Harper, A., Jones, C. D., Kelley, D. I., Robertson, E., and Wiltshire, A. (2019). Representation of fire, land-use change and vegetation dynamics in the joint uk land environment simulator vn4. 9 (jules). *Geoscientific Model Development*, 12(1):179–193.

Coomes, D. A., Duncan, R. P., Allen, R. B., and Truscott, J. (2003). Disturbances prevent stem size-density distributions in natural forests from following scaling relationships. *Ecology Letters*, 6(11):980–989.

Cox, P. M. (2001). Description of the" triffid" dynamic global vegetation model.

Eller, C. B., Rowland, L., Mencuccini, M., Rosas, T., Williams, K., Harper, A., Medlyn, B. E., Wagner, Y., Klein, T., Teodoro, G. S., et al. (2020). Stomatal optimisation based on xylem hydraulics (sox) improves land surface model simulation of vegetation responses to climate. *New Phytologist*.

Eller, C. B., Rowland, L., Oliveira, R. S., Bittencourt, P. R., Barros, F. V., da Costa, A. C., Meir, P., Friend, A. D., Mencuccini, M., Sitch, S., et al. (2018). Modelling tropical forest responses to drought and el niño with a stomatal optimization model based on xylem hydraulics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 373(1760):20170315.

Fisher, R. A., Muszala, S., Verteinstein, M., Lawrence, P., Xu, C., McDowell, N. G., Knox, R. G., Koven, C., Holm, J., Rogers, B. M., Spessa, A., Lawrence, D., and Bonan, G. (2015). Taking off the training wheels: the properties of a dynamic vegetation model without climate envelopes, clm4.5(ed). *Geoscientific Model Development*, 8(11):3593–3619.

Friedlingstein, P., Jones, M., O'Sullivan, M., Andrew, R., Hauck, J., Peters, G., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., et al. (2019). Global carbon budget 2019. *Earth System Science Data*, 11(4):1783–1838.

Haverd, V., Smith, B., Nieradzik, L. P., and Briggs, P. R. (2014). A stand-alone tree demography and landscape structure module for earth system models: integration with inventory data from temperate and boreal forests. *Biogeosciences*, 11(15):4039–4055.

Jones, S., Rowland, L., Cox, P., Hemming, D., Wiltshire, A., Williams, K., Parazoo, N. C., Liu, J., da Costa, A. C. L., Meir, P., Mencuccini, M., and Harper, A. (2019). The impact of a simple representation of non-structural carbohydrates on the simulated response of tropical forests to drought. *Biogeosciences Discussions*, 2019:1–26.

Kohyama, T., Suzuki, E., Partomihardjo, T., Yamada, T., and Kubo, T. (2003). Tree species differentiation in growth, recruitment and allometry in relation to maximum height in a bornean mixed dipterocarp forest. *Journal of Ecology*, 91(5):797–806.

Lima, R. A., Muller-Landau, H. C., Prado, P. I., and Condit, R. (2016). How do size distributions relate to concurrently measured demographic rates? evidence from over 150 tree species in panama. *Journal of Tropical Ecology*, 32(3):179–192.

Moore, J. R., Argles, A. P. K., Zhu, K., Huntingford, C., and Cox, P. M. (2020). Validation of demographic equilibrium theory against tree-size distributions and biomass density in amazonia. *Biogeosciences*, 17(4):1013–1032.

Moore, J. R., Zhu, K., Huntingford, C., and Cox, P. M. (2018). Equilibrium forest demography explains the distribution of tree sizes across North America. *Environmental Research Letters*, 13(8).

Muller-Landau, H. C., Condit, R. S., Harms, K. E., Marks, C. O., Thomas, S. C., Bunyavejchewin, S., Chuyong, G., Co, L., Davies, S., Foster, R., Gunatilleke, S., Gunatilleke, N., Hart, T., Hubbell, S. P., Itoh, A., Kassim, A. R., Kenfack, D., LaFrankie, J. V., Lagunzad, D., Lee, H. S., Losos, E., Makana, J. R., Ohkubo, T., Samper, C., Sukumar, R., Sun, I. F., Nur Supardi, M. N., Tan, S., Thomas, D., Thompson, J., Valencia, R., Vallejo, M. I., Muñoz, G. V., Yamakura, T., Zimmerman, J. K., Dattaraja, H. S., Esufali, S., Hall, P., He, F., Hernandez, C., Kiratiprayoon, S., Suresh, H. S., Wills, C., and Ashton, P. (2006). Comparing tropical forest tree size distributions with the predictions of metabolic ecology and equilibrium models. *Ecology Letters*, 9(5):589–602.

Sato, H., Itoh, A., and Kohyama, T. (2007). SEIB-DGVM: A new Dynamic Global Vegetation Model using a spatially explicit individual-based approach. *Ecological Modelling*, 200(3-4):279–307.

Schleussner, C.-F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E. M., Knutti, R., Levermann, A., Frieler, K., and Hare, W. (2016). Science and policy characteristics of the paris agreement temperature goal. *Nature Climate Change*, 6(9):827–835.

Smith, B. (2001). Lpj-guess-an ecosystem modelling framework. *Department of Physical Geography and Ecosystems Analysis. INES, Sölvegatan*, 12:22362.

Strigul, N., Pristinski, D., Purves, D., Dushoff, J., and Pacala, S. (2008). Scaling from trees to forests: tractable macroscopic equations for forest dynamics. *Ecological Monographs*, 78(4):523–545.

Weng, E. S., Malyshev, S., Lichstein, J. W., Farrior, C. E., Dybzinski, R., Zhang, T., Shevliakova, E., and Pacala, S. W. (2015). Scaling from individual trees to forests in an earth system modeling framework using a mathematically tractable model of height-structured competition. *Biogeosciences*, 12(9):2655–2694.

West, G. B., Brown, J. H., and Enquist, B. J. (1997). A general model for the origin of allometric scaling laws in biology. *Science*, 276(5309):122–126.

Yue, C., Ciais, P., Luyssaert, S., Li, W., McGrath, M. J., Chang, J., and Peng, S. (2018). Representing anthropogenic gross land use change, wood harvest, and forest age dynamics in a global vegetation model orchidee-mict v8.4.2. *Geoscientific Model Development*, 11(1):409–428.