Robust Ecosystem Demography (RED) DGVM:

a simple approach to modelling vegetation with novel implications

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Introduction

- Climate projections of the terrestrial uptake of carbon are uncertain under emission scenarios (Arora 2019).
- Sources of uncertainty include the varied methods used to represent plant community growth, competition and mortality through DGVMs - Dynamic Global Vegetation Models (Brovkin 2013, Ahlström 2015, Pugh 2019)
- Model complexity ranges from simplistic top down models that are area-average based, towards more complex individual based models. In an intermediate category are *cohort* based models, that partition a population between stand-ages and/or sizes (Fisher 2018).
- There is a trade-off between ecological realism and the necessity of simplicity at scale.

Arora, Vivek K., et al. "Carbon-concentration and carbon-climate feedbacks in CMIP6 models, and their comparison to CMIP5 models." *Biogeosciences Discussions* (2019): 1-124.
Brovkin, Victor, et al. "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 (2013): 6859-6881.
Ahlström, Anders, et al. "Importance of vegetation dynamics for future terrestrial carbon cycling." *Environmental Research Letters* 10.5 (2015): 054019.
Pugh, Thomas AM, et al. "Role of forest regrowth in global carbon sink dynamics." *Proceedings of the National Academy of Sciences* 116.10 (2019): 4382-4387.
Fisher, Rosie A., et al. "Vegetation demographics in Earth System Models: A review of progress and priorities." Global change biology 24.1 (2018): 35-54.

RED

Here we present *Robust Ecosystem Demography (RED),* a new cohort DGVM. RED reduces the number of demographic dimensions to just one: plant size. We minimise the number of free parameters, while retaining the important representation of plant size.

Model Paper: Argles, A. P. K., Moore, J. R., Huntingford, C., Wiltshire, A. J., Jones, C. D., and Cox, P. M.: Robust Ecosystem Demography (RED): a parsimonious approach to modelling vegetation dynamics in Earth System Models, Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2019-300, in review, 2019.

Driving Equations

The change of population density, n, over carbon mass and time, is described by the Fokker-Plank equation:

$$\frac{\partial n}{\partial t} - \frac{\partial (ng)}{\partial m} = -\gamma n$$

g describes the rate of growth of an individual of carbon mass m. We assume that this follows allometric scaling relative to the boundary class m_0 (Niklas 2004), with $\phi_g = 3/4$:

$$g = g_0 \left(\frac{m}{m_0}\right)^{\phi_g}$$

γ describes the mortality rate of the population. Dynamically this is made up of two components, the baseline mortality, which is assumed invariant over mass, and mortality arising from disturbances (drought, fires etc.), which is taken as an independent model input.

Niklas, Karl J., and Hanns-Christof Spatz. "Growth and hydraulic (not mechanical) constraints govern the scaling of tree height and mass." *Proceedings of the National Academy of Sciences* 101.44 (2004): 15661-15663.

Recruitment and Competition (1)

We assume that a fraction, α, of the total plant assimilate P, is devoted to the production of seedlings (F_0):

$$F_0 = \frac{\alpha P}{m_0} \cdot s$$

s describes the total amount of shading that a Plant Functional Type (PFT) k experiences from itself and other PFTs:

$$s_k = 1 - \sum_l c_{lk} \cdot \nu_l$$

Where c_{lk} are competition coefficients ($\in [0,1]$) and ν_l is the vegetation fraction. This allows RED to simulate gap like behaviour among PFTs.

Recruitment and Competition (2)

The total structural growth, G is given as:

$$G = \int_{m_0}^{\infty} n \cdot g_0 (m/m_0)^{\phi_g} dm$$

As the total assimilate is split between recruitment and structural growth we can find g_0 by:

$$g_0 = \frac{(1-\alpha)P}{\int_{m_0}^{\infty} n \cdot (m/m_0)^{\phi} dm}$$

The total coverage is given by (assuming Niklas and Spatz $\phi_a = 1/4$):

$$\nu = \int_{m_0}^{\infty} n \cdot a_0 (m/m_0)^{\phi_a} dm$$

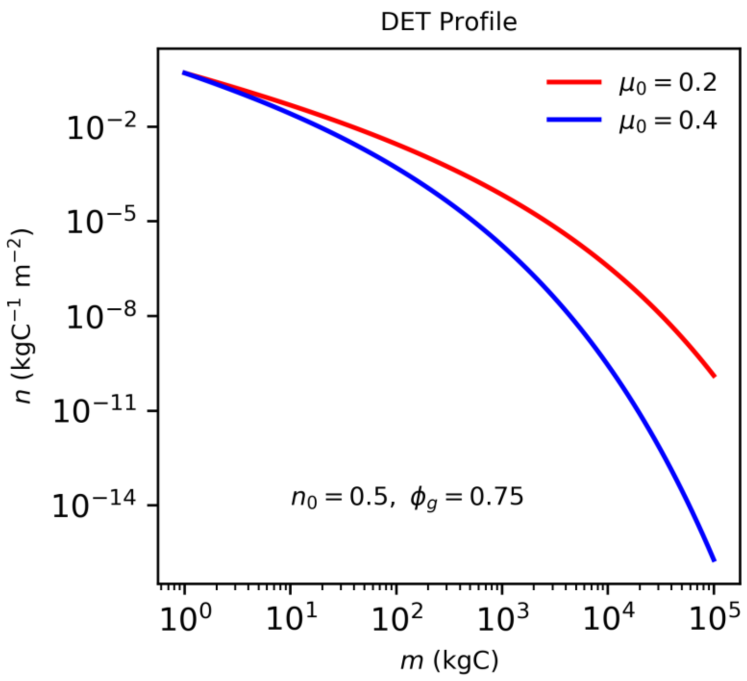
Equilibrium Solutions

With the assumption of size-independent mortality and metabolic scaling of growth, we get an analytical solution for the equilibrium:

$$n = n_0 \left(\frac{m}{m_0}\right)^{-\phi_g} \exp\left\{\frac{\mu_0}{1-\phi_g}\left[1-\left(\frac{m}{m_0}\right)^{1-\phi_g}\right]\right\}$$

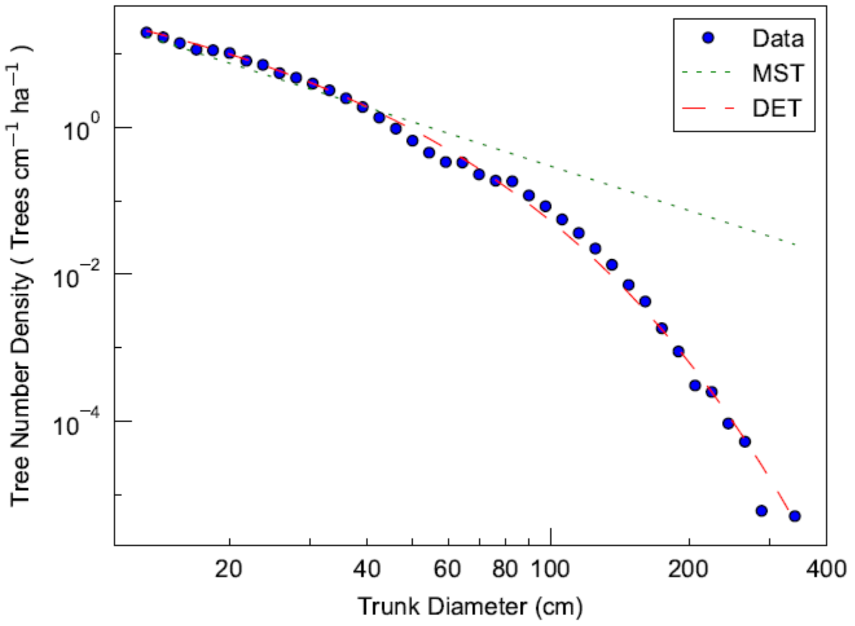
The parameter $\mu_0 = \gamma m_0 / g_0$ describes the shape of the distribution (see right).

This is more commonly known as Demographic Equilibrium Theory (DET)

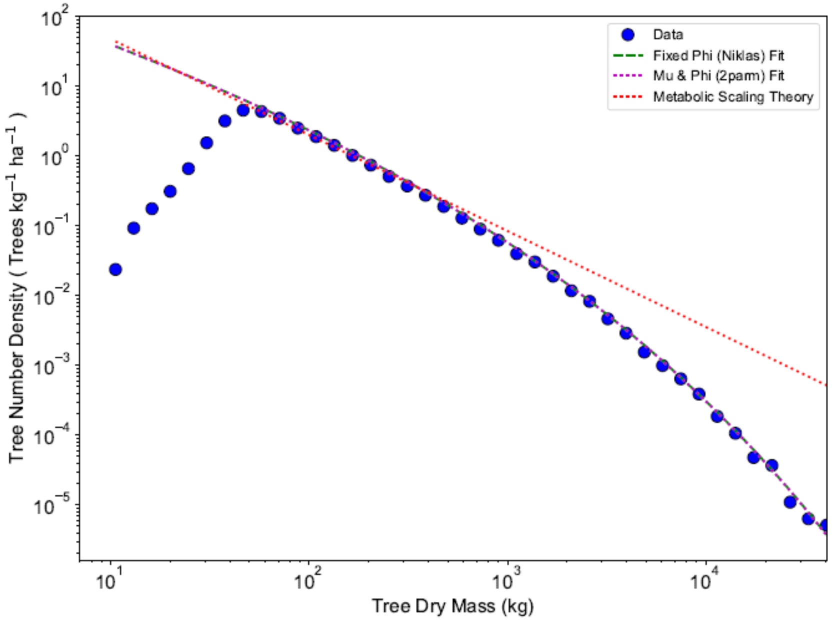


Muller-Landau, Helene C., et al. "Comparing tropical forest tree size distributions with the predictions of metabolic ecology and equilibrium models." *Ecology letters* 9.5 (2006): 589-602.
Moore, Jonathan R., et al. "Equilibrium forest demography explains the distribution of tree sizes across North America." *Environmental Research Letters* 13.8 (2018): 084019.
Moore, Jonathan R., et al. "Validation of demographic equilibrium theory against tree-size distributions and biomass density in Amazonia." Biogeosciences Discussions (2019): 1-41.

DET captures distributions at regional scales



Number Density against basal diameter of US Forest Inventory Data fitted to DET and MST (Moore 2018). MST (metabolic scaling theory), describes the distribution when ignoring mortality.



Number Density against tree dry mass from South American RAINFOR dataset fitted to DET and MST(Moore 2018) . The lower end peak arises as an artifact from the allometric conversion from basal diameter to dry mass.

Moore, Jonathan R., et al. "Equilibrium forest demography explains the distribution of tree sizes across North America." *Environmental Research Letters* 13.8 (2018): 084019.
Moore, Jonathan R., et al. "Validation of demographic equilibrium theory against tree-size distributions and biomass density in Amazonia." Biogeosciences Discussions (2019): 1-41.

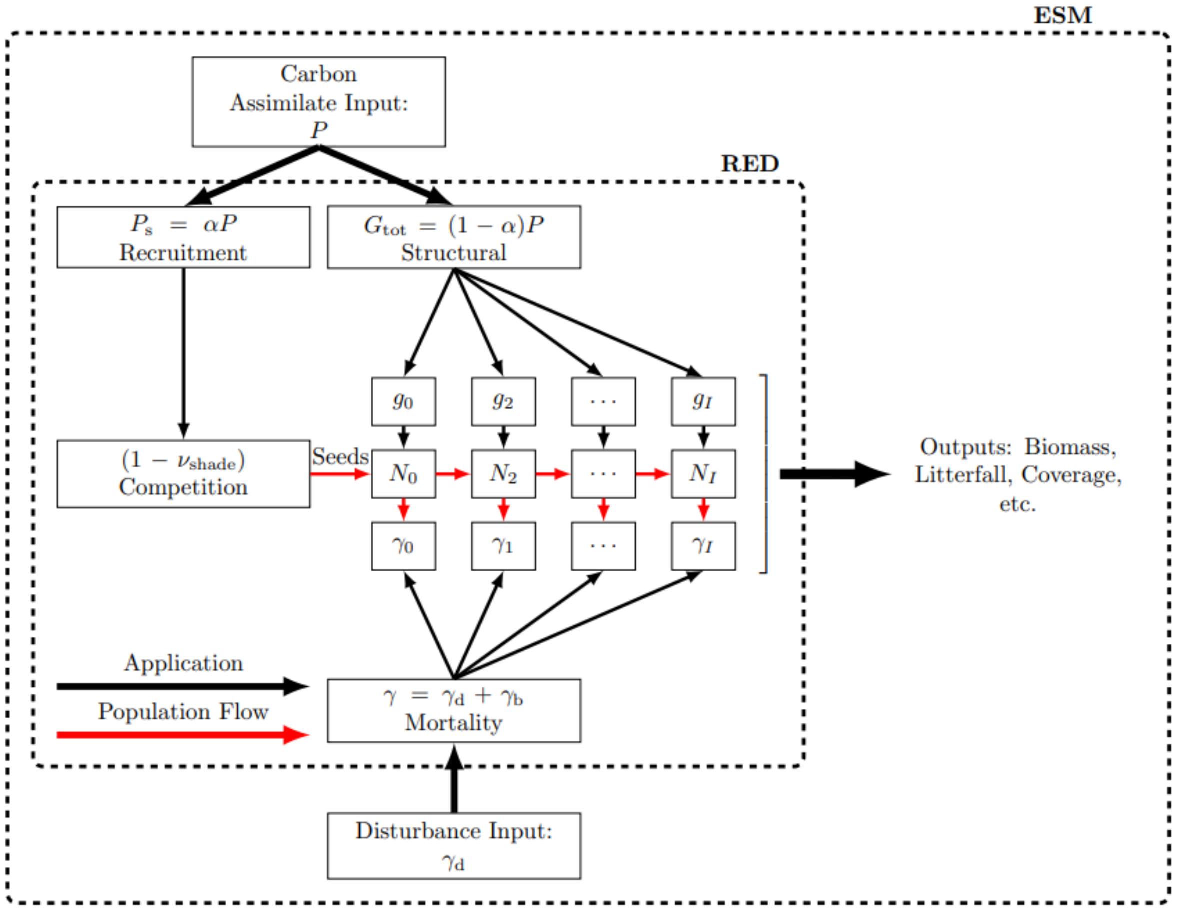
Model Set-up

RED requires the total grid-box assimilate, P , and any mortality arising from disturbance, γ_d , to update the demographic profile of the grid-box.

The numerical model uses 10 geometric mass classes.

The reseed fraction for trees is assumed to be $\alpha = 0.1$, for shrubs & grasses $\alpha = 0.25$.

(A full list of model parameters is given in the model paper)



Equilibrium Inversion (1)

At equilibrium the population recruited must equal the total lost due to mortality. From this we find that the equilibrium cover for PFT (k), ν_{eq}, must be:

$$\nu_{\mathrm{eq}} = 1 - \left(\frac{1-\alpha}{\alpha}\right)\frac{\mu_0}{1 + \frac{3}{4\mu_0} + \frac{3}{8\mu_0^2} + \frac{3}{32\mu_0^3}} - \sum_{l \neq k} c_{lk} \cdot \nu_l$$

It is possible to invert the equation and tune μ_0, assuming α to be consistent with observed coverage. We demonstrate this with ESA LC_CCI dataset for the 9 JULES PFTs.

$$\mu_0 = \frac{\gamma g_0}{m_0}$$

Additionally, given knowledge of g_0, we are able to rearrange μ_0 for the required mortality to match the observed coverage. We use model outputs for annual assimilate from UKESM for the 9 JULES PFTs.

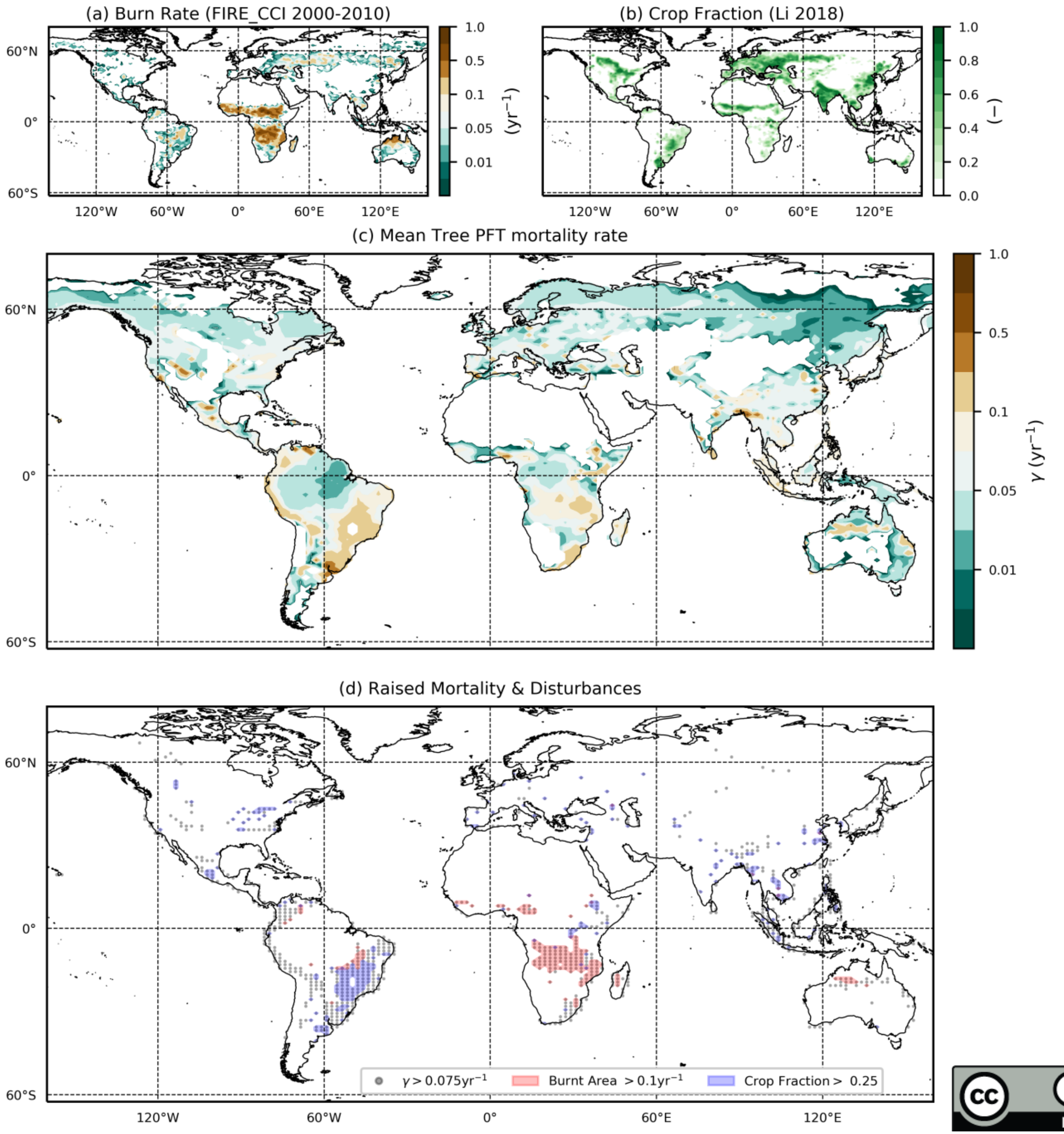
In the next slides we demonstrate some potential uses for this approach.

Poulter, Ben, et al. "Plant functional type classification for earth system models: results from the European Space Agency's Land Cover Climate Change Initiative." *Geoscientific Model Development* 8 (2015): 2315-2328.
Harper, Anna B., et al. "Vegetation distribution and terrestrial carbon cycle in a carbon cycle configuration of JULES4. 6 with new plant functional types." (2018).

Spatial Mortality:

By finding the mortality required to match both the ESA LC_CCI coverage and the UKESM assimilate rates for PFTs it is possible to construct a spatial map of mortality.

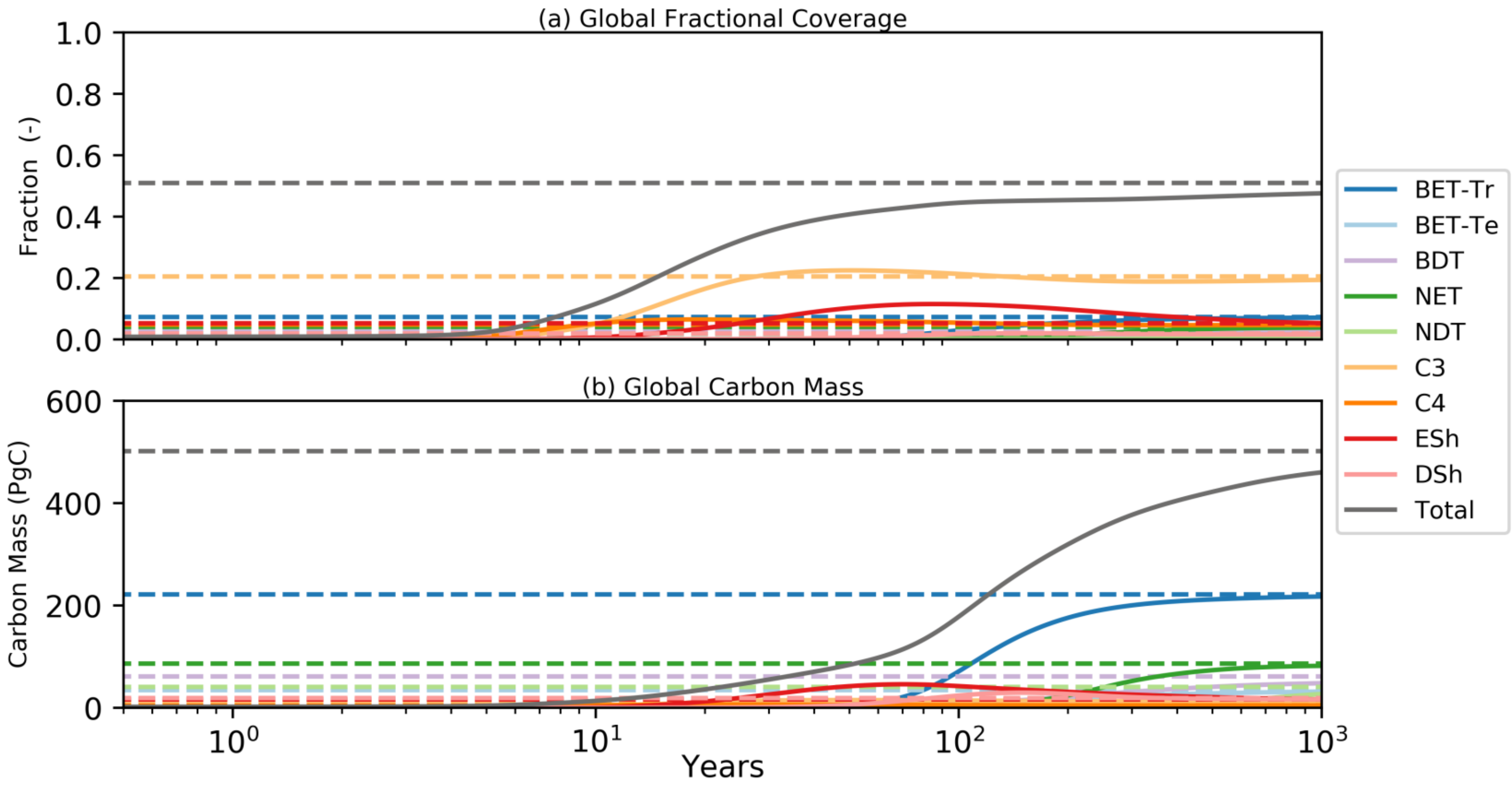
RED’s closed form solution to DET, through the constraints of recruitment and competition, provides an implicit approach for inverting rates arising from disturbances and land-use. There is alignment with surveyed burn areas and crop fractions (top panels a & b).



Chuvieco, E., et al. "Global burned area mapping from european satellites: the ESA fire_CCI project." Advances in Remote Sensing and GIS applications in Forest Fire Management From local to global assessments (2012): 237.

Li, Wei, et al. "Gross and net land cover changes in the main plant functional types derived from the annual ESA CCI land cover maps (1992–2015)." (2018).

Skipping spin-up



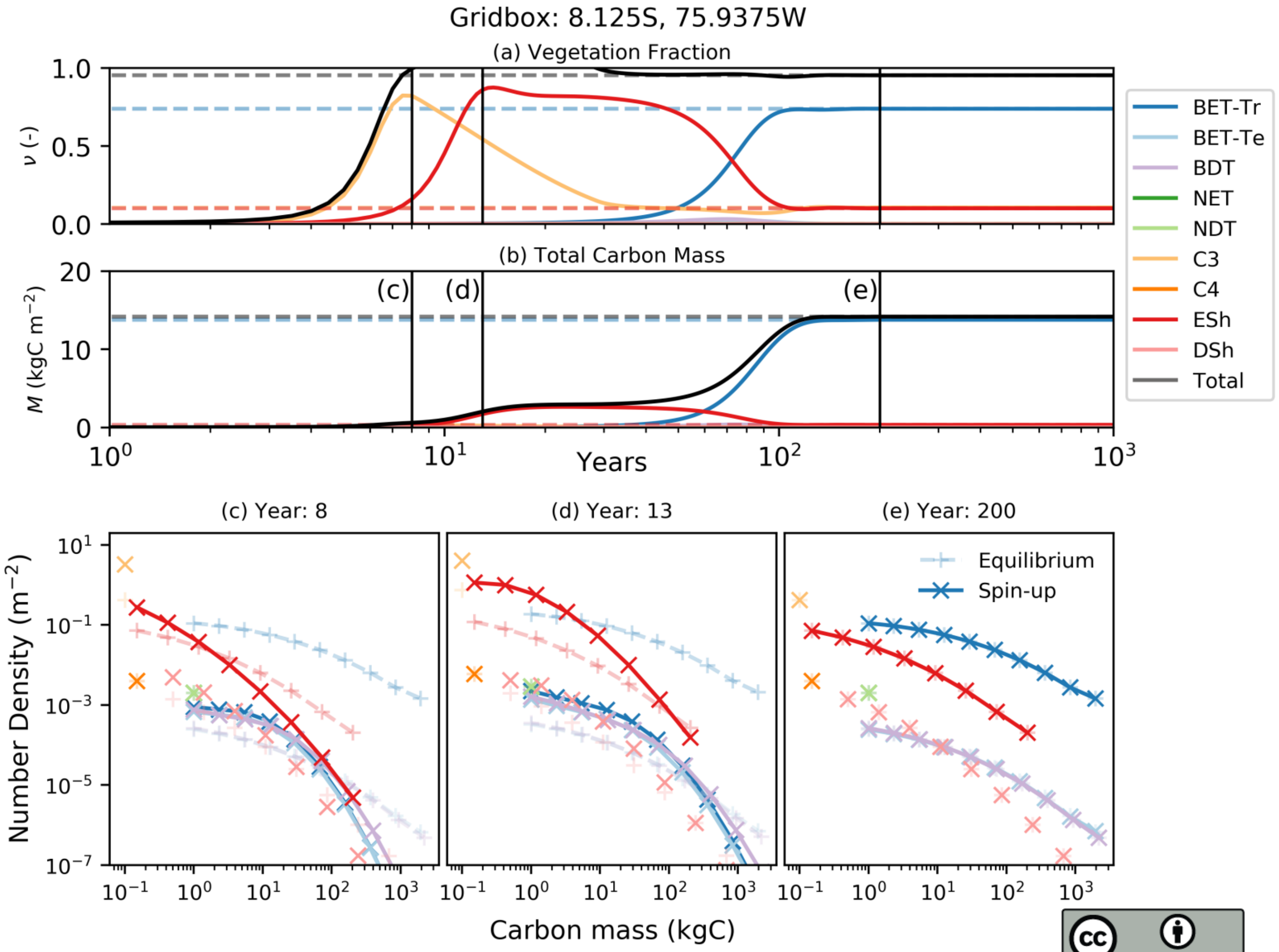
Two dynamical runs – first one (solid lines) starts from the fitted equilibrium. Second one (dotted lines) grows vegetation from bare soil. Both runs use the same constant UKESM growth.

Looking inside a grid-box:

Picking a tropical grid-box, the figure to the right illustrates the gap-dynamics of the competitive regime. Firstly C3 grass fills the grid-box, being replaced by Evergreen Shrubs and finally Broadleaf Evergreen Tropical trees. Below panels show the flow of population through the size-structure.

The solid and dotted lines again indicate two runs starting from the fitted equilibrium and bare soil.

In future developments RED will be able to take additional disturbance/mortality inputs across the carbon mass such as from fire or drought.



Conclusions

- We present a new Dynamic Global Vegetation Model – the Robust Ecosystem Demography (RED) model where the population of a Plant Functional Type is partitioned into mass classes. This allows for physiological and allometric relationship with size to be explicitly represented. Competition is done on the recruited seedlings – establishment can only occur in non-shaded 'free' space determined by the occupation of PFTs.
- The analytical equilibrium allows for easy parameterisation of key terms and for the model to be initialised without spin-up. We demonstrate the potential for the closed-form to diagnose novel mortality rates from demographic principles.
- RED is currently being coupled into the UK land surface scheme (JULES) in the future we hope to run transient simulations along with other developments on fire (INFERNO) and drought (SOX & SUGAR) with the aim of better understanding of ecosystem resliance.

Best, M. J., et al. "The Joint UK Land Environment Simulator (JULES), model description–Part 1: energy and water fluxes." *Geoscientific Model Development* 4.1 (2011): 677-699.
Burton, Chantelle, et al. "Representation of fire, land-use change and vegetation dynamics in the Joint UK Land Environment Simulator vn4. 9 (JULES)." *Geoscientific Model Development* 12.1 (2019): 179-193.
Eller, Cleiton B., et al. "Stomatal optimisation based on xylem hydraulics (SOX) improves land surface model simulation of vegetation responses to climate." *New Phytologist* (2020).
Jones, Simon, et al. "The Impact of a Simple Representation of Non-Structural Carbohydrates on the Simulated Response of Tropical Forests to Drought." *Biogeosciences Discussions* (2019): 1-26.