Robust Ecosystem Demography (RED): Emergent simplicity of tree size distributions.

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Abstract

Understanding how the terrestrial biomass will respond to perturbations is currently a large source of uncertainty within ESMs. Cohort-based demographic models have been a recent development of DGVMs that can improve the representation of size-dependent interactions between the environment and species normally seen in individual-based models while removing stochastic characteristics within global runs. RED partitions the population of a PFT into size classes, of an appropriate variable (biomass, basal diameter) across the physiological range. Using a biomass/basal-diameter spaced advection equation that accounts for size-dependent scaling of the structural growth and mortality across the classes, we are able to model how the population evolves over time. By assuming a power scaling size-growth relationship with constant mortality, RED derives a quasi-Weibull distribution for the forest steady state. When compared to forest inventory data the solution provides a realistic fit. By applying a boundary condition limiting seedlings to open space, RED can derive solutions for the total vegetation fraction, biomass, and other variables by only knowing two parameters - the background ratio of mortality and growth and the fraction of NPP going into seedling production. From this, we have shown that RED can obtain realistic global outputs for biomass densities and evaluatory metrics.The analytical solutions derived from the foundational equations and assumptions of RED suggests an inherent simplicity of the forest structure, with low competition between trees, strong competition for seedlings, and size-independent mortality. Divergence from the analytical solution could indicate a historic disturbance. As RED allows for the representation of asymmetrical mortality and growth, disturbances in which size is important can be dynamically simulated. The theory and model allows for potential insights into how ecosystems will respond to future increases in CO2 and disturbances.

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Robust Ecosystem Demography (RED):

Emergent simplicity of tree size distributions.

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Introduction

Dynamic Global Vegetation Models (DGVMs) produce a wide-range in projections by the end of the 21st-century (Sitch et al., 2008). This leads to significant uncertainties in future land carbon storage and climate change (Friedlingstein et al., 2014), especially when land-use change is included (Brovkin et al., 2013). The responses of DGVMs differ because of deficiencies in the treatment of key processes, such as the distribution of tree sizes in forests.

Detailed models of forest demography are gradually being introduced into many DGVMs (Fisher et al., 2018), following on from pioneering work by (Friend et al., 1993) and (Moorcroft et al., 2001). These models typically resolve both different tree sizes and also different patch ages, which poses challenges for the implementation of these models within Earth System Models. Here we present a simplified forest demography model (RED – Robust Ecosystem Demography) which updates just the probability distribution of tree-sizes, and for which we can derive analytical equilibrium solutions (Moore et al., 2018).

Demographic Theory

The master equation for RED is a Fokker-Planck equation which defines how the number density of trees in each mass class $n(m,t)$ varies with growth-rate $g(m,t)$ and mortality $\gamma(m,t)$:

$$\frac{\partial}{\partial t}n(m,t) + \frac{\partial}{\partial m}[n(m,t)\cdot g(m,t)] = -\gamma(m,t)\cdot n(m,t) \quad (1)$$

Dynamically this allows for time varying mortality rates and growth rates across size, and by analogy age, enabling representation of disturbances such as droughts or fires. RED assumes a power-law scaling of the growth rate of individuals with with the mass (Niklas and Spatz, 2004):

$$g(m) = g_0\left(\frac{m}{m_0}\right)^{\phi} \quad (2)$$

Equilibrium analytical size distribution solutions can also be obtained for power-law growth and size independent mortality, $\gamma(m,t)\to\gamma$ (Muller-Landau et al., 2006; Moore et al., 2018)

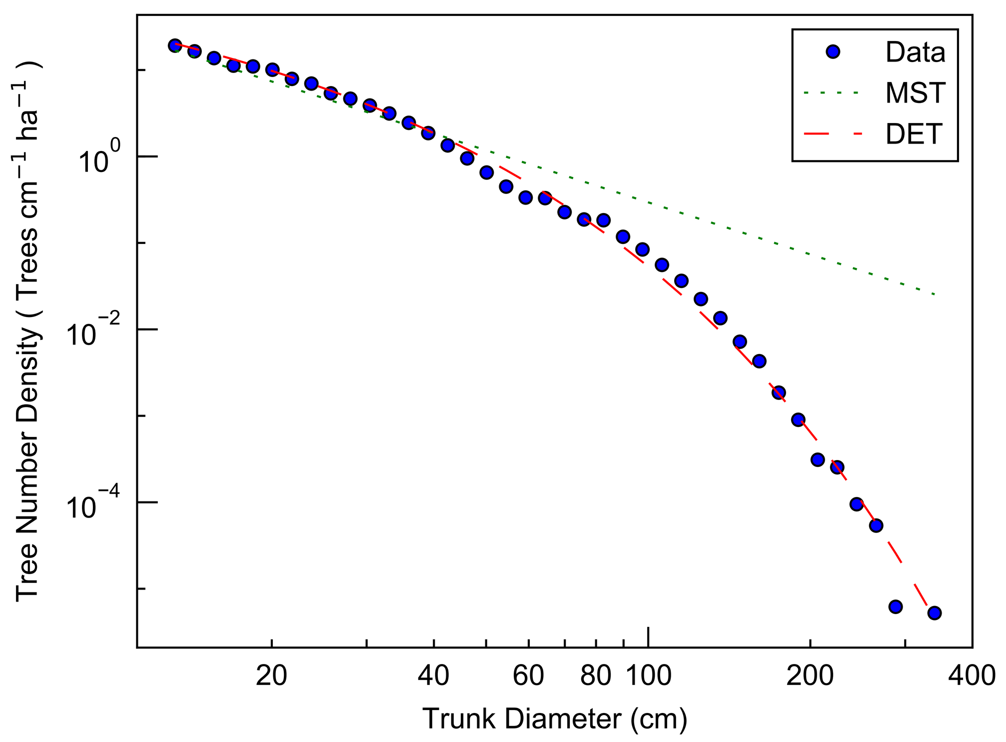

Figure 1: Shows the fitted Demographic Equilibrium Theory (DET) (Moore et al., 2018) of the US forest inventory data presented in terms of basal diameter against Metabolic Scaling Theory (MST) (Enquist et al., 2009).

RED Dynamics and Competition

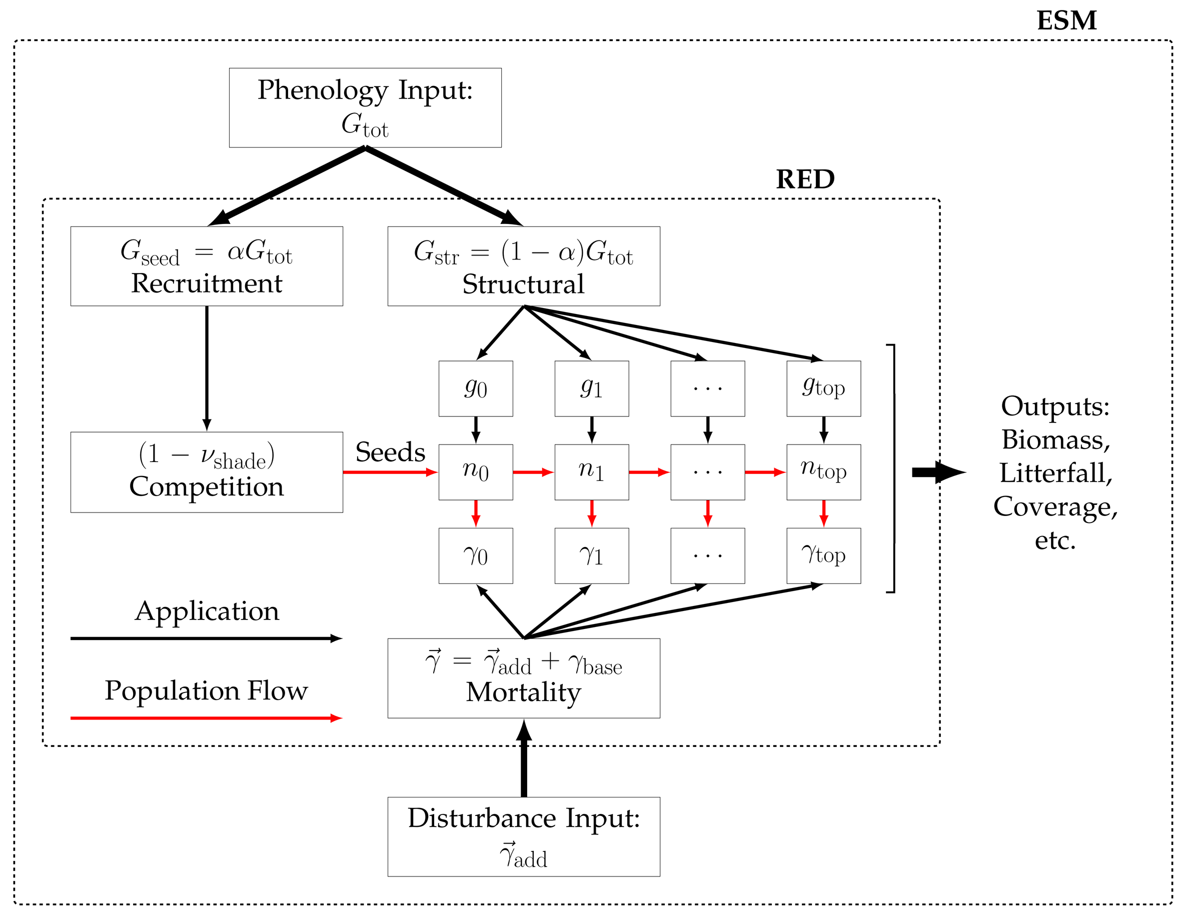

Figure 2: Schematic of RED coupled into an ESM. RED takes the total growth rate from the phenology input (G_{tot}) which is then split between seedling growth (G_{seed}) and structural growth (G_{str}) via a constant fraction (α). The seed flux is limited by the available free space ($1-\nu_{shade}$). Mortality rates from disturbance based models ($\vec{\gamma}_{add}$) are added on to an assumed baseline mortality (γ_{base}) at each mass class.

Plant Functional Types (PFTs) compete using a hierarchical regime with seeds only growing in the open (Figure 3) limiting the flux coming into the lowest mass class (Figure 2).

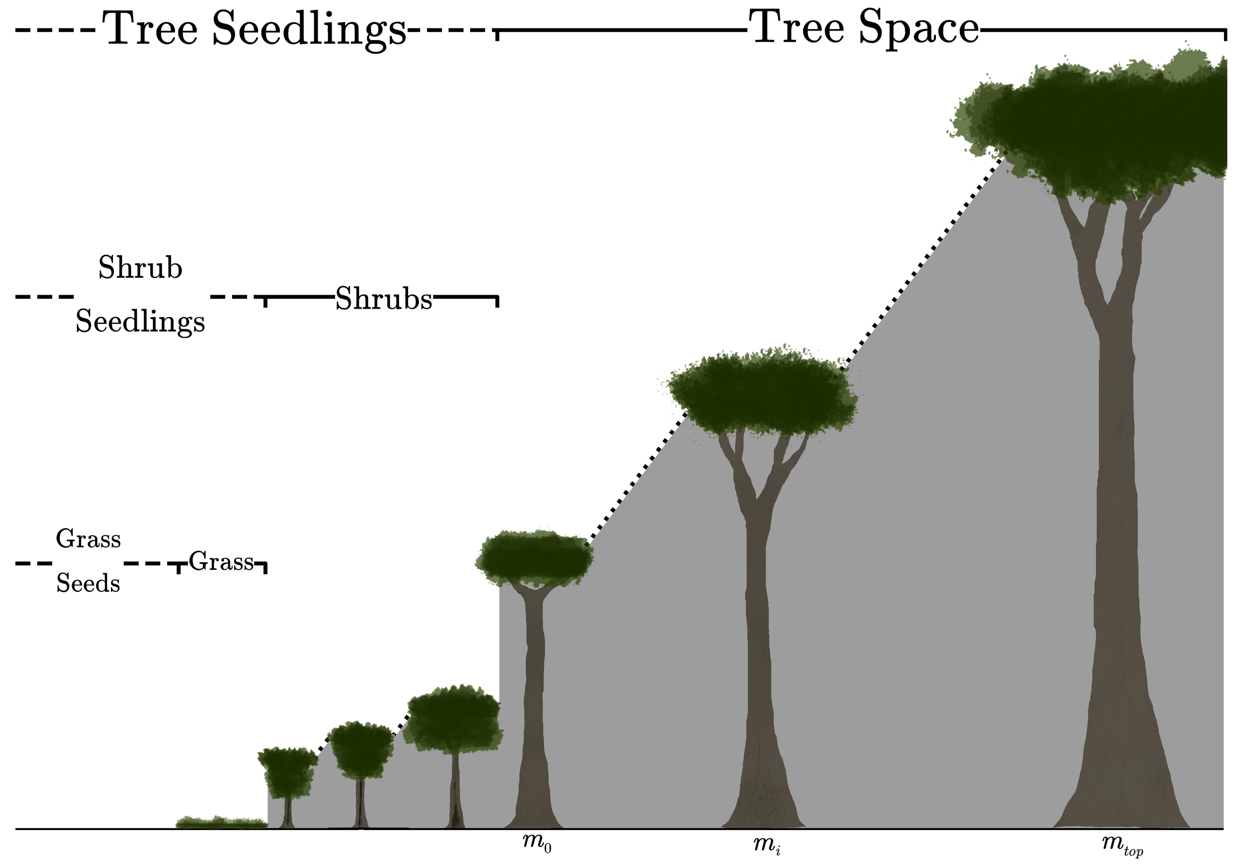

Figure 3: The competitive regime within RED. Tree PFTs have first choice of space, while Shrubs are sub-dominant. Followed by Grasses which only posses one mass class.

Comparison to Observed Vegetation

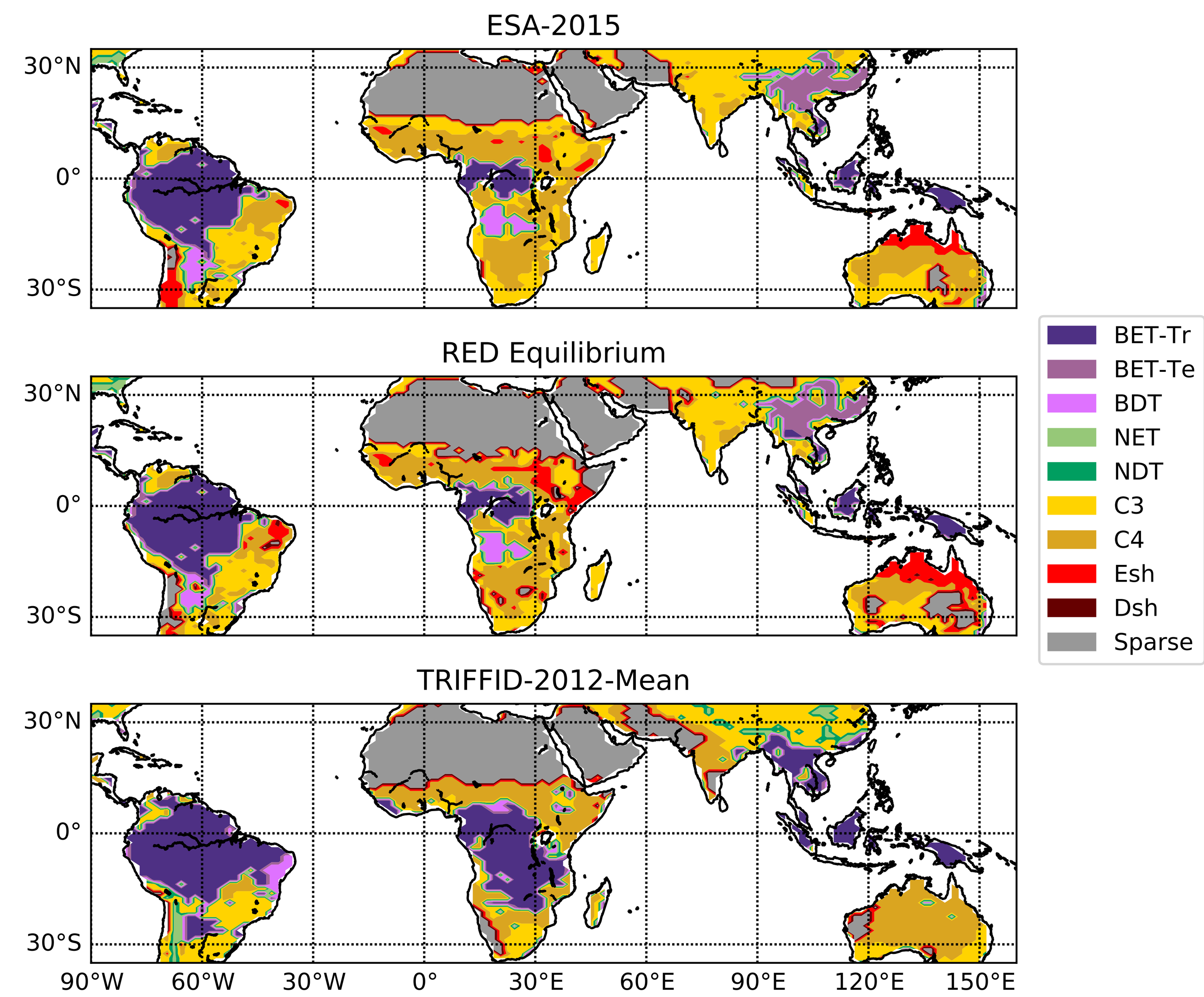

Figure 4: ESA - 2015 coverage map (Poulter et al., 2015) proscribed to the JULES PFTs and using JULES growth rates (NPP - Litterfall) for 2012 driving the RED equilibrium state.

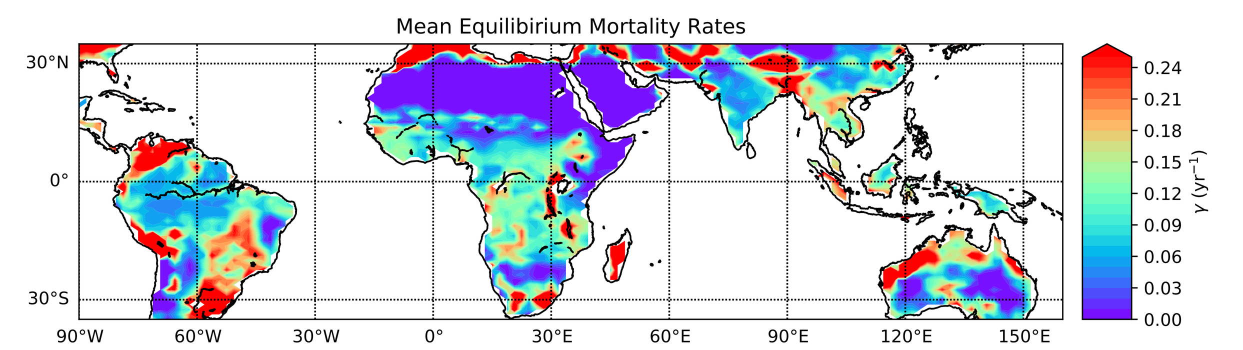

Figure 5: The rate of disturbance given by the equilibrium relationships using the ESA-2015 coverage and the mean JULES growth rates from 2012. What rate of Mortality is needed to fit the coverage map.

Conclusions

- **RED uses a Fokker-Planck equation to simulate the distribution of tree-sizes in forests.**
- **The US forest inventory size distribution is captured with the demographic theory in the equilibrium state.**
- **Driven only by a few parameters, the analytical equilibrium solutions allow RED to avoid the 'spin-up' seen in other models.**
- **RED can estimate a implicit disturbance rates based on average coverage and growth.**

Acknowledgements

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Further Reading

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):084019