

Future Biosphere Models for ESMs:

*Elegance, Pragmatism,
and Emergent Constraints*

Peter Cox

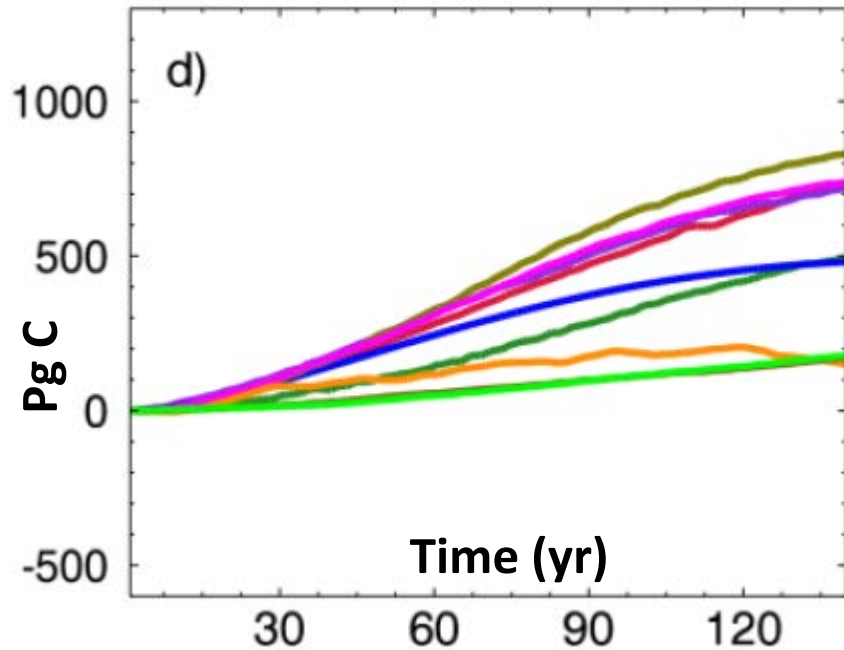
Jon Moore, Arthur Argles, Nina Raoult
University of Exeter

The Land Surface in Climate Models

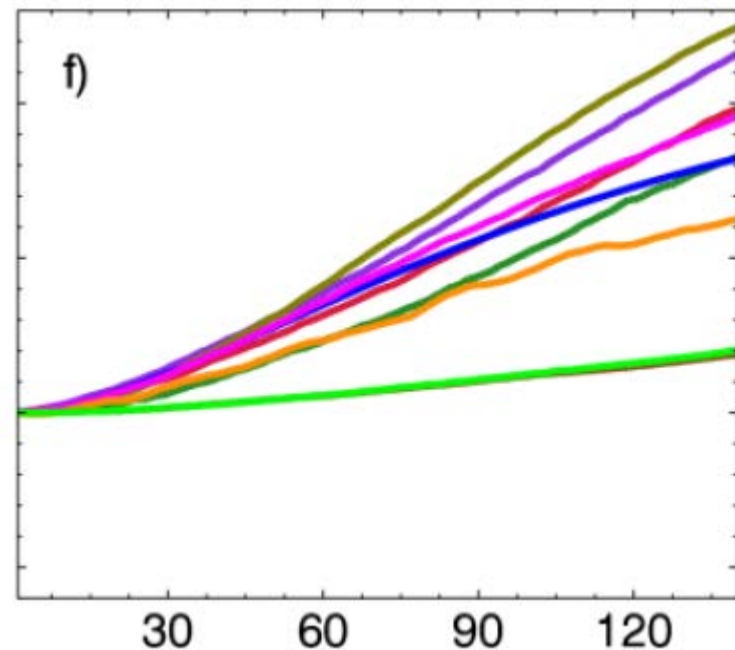
- Up to 1990s seen as a *'necessary evil'* – providing the lower boundary condition for atmospheric models.
- **Importance of the land-surface has increased dramatically as climate models have become Earth System Models.**
- **Land carbon cycle now amongst the most significant uncertainties in climate projections.**

Uncertainties in Climate-Land Carbon Feedbacks (1% per year increase in CO₂)

Coupled

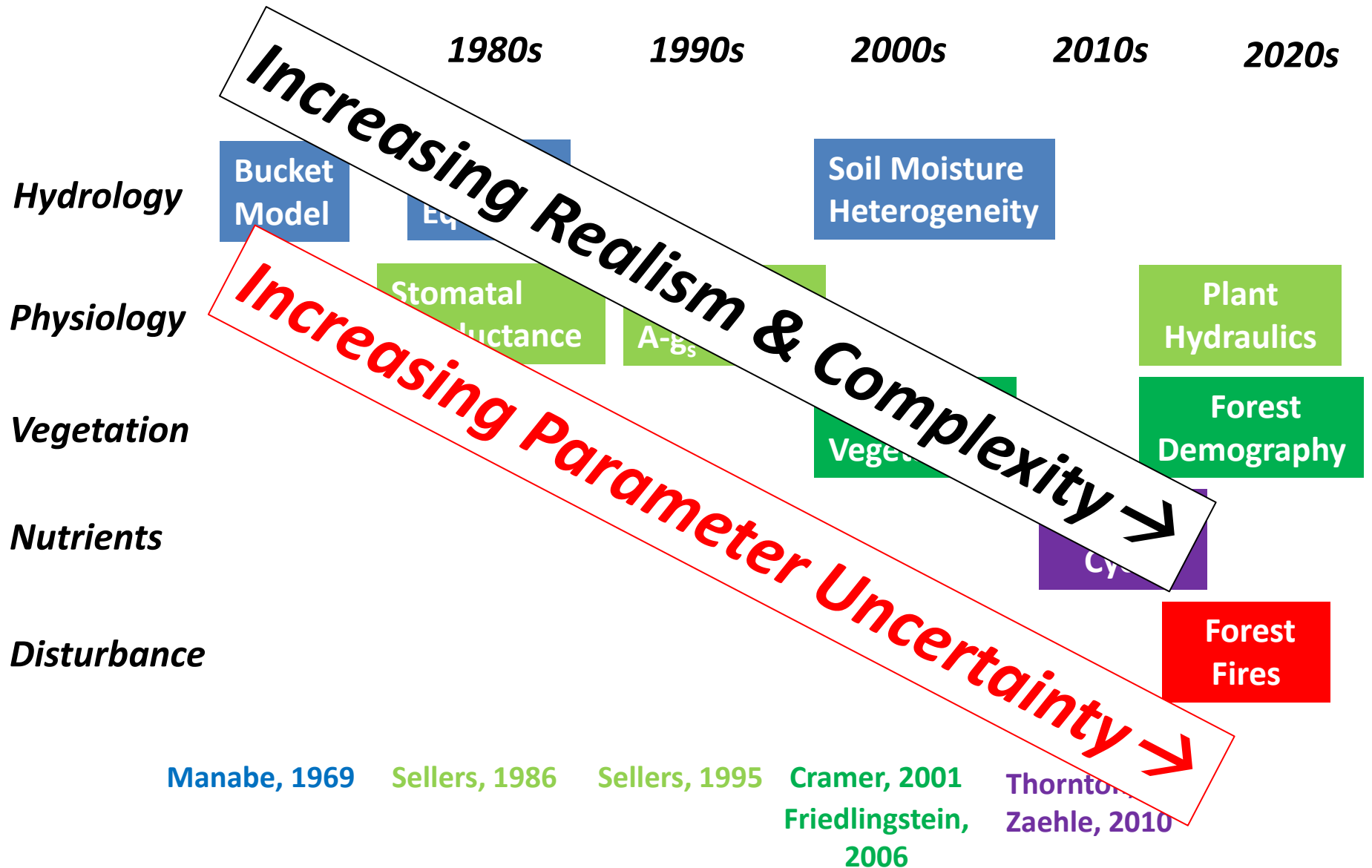


Uncoupled



- | | | |
|---------------------|------------------------|-----------------------|
| — CCCma - CanESM2 | — UVic - UVic ESCM 2.9 | — JAMSTEC - MIROC-ESM |
| — UKMO - HadGEM2-ES | — MPI - MPI-ESM-LR | — NCC - NorESM-ME |
| — BCC - BCC-CSM1-1 | — IPSL - IPSL-CM5A-LR | — NCAR - CESM1-BGC |

Evolution of LSMs



Keys to Reducing Uncertainties in Land Surface Models

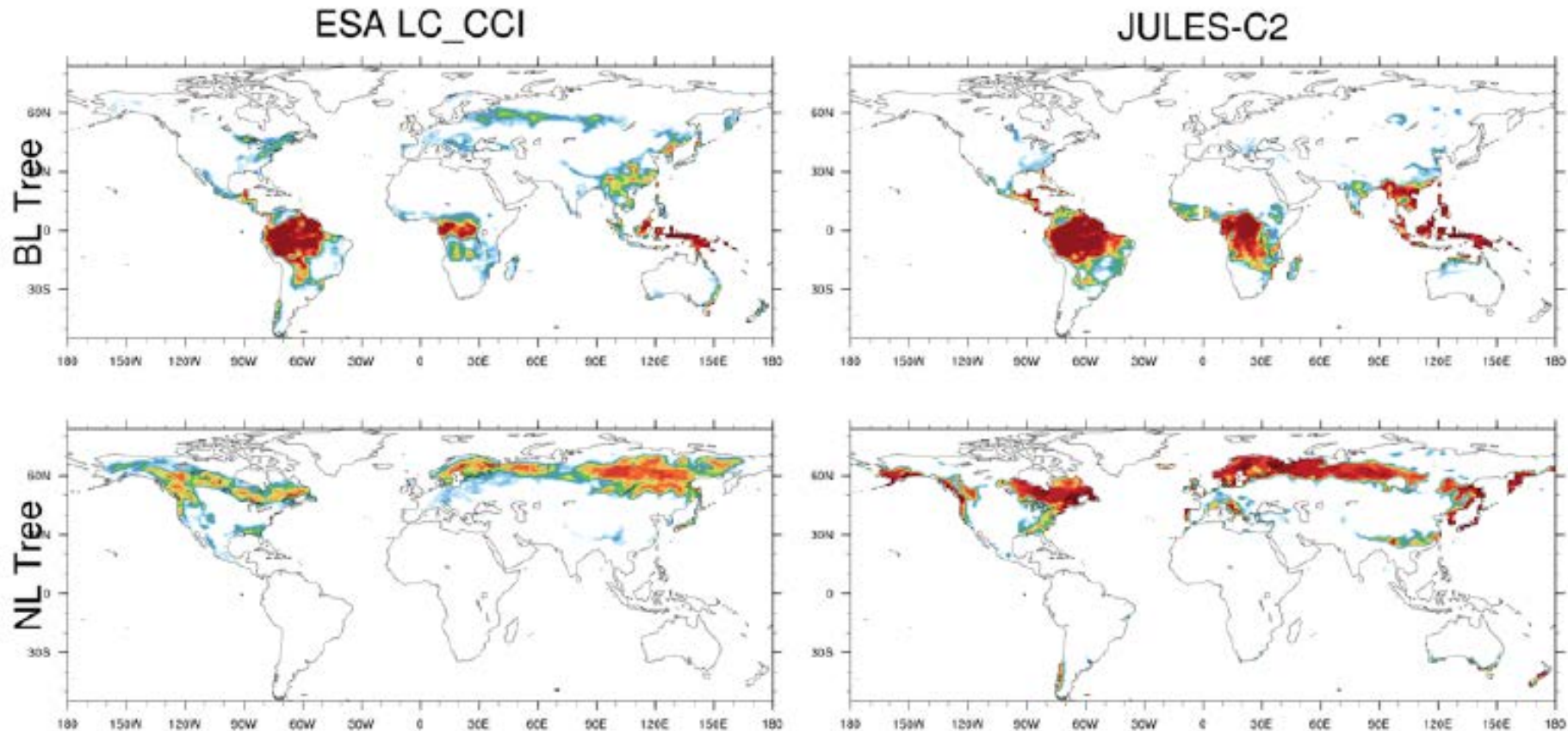
- ✓ **Better process representation**
- **Parameter sparse models
(e.g. Vegetation Demography).**

Latest TRIFFID Dynamic Global Vegetation Model

(Harper et al., 2016, and *in press*)

Observations

Model



TRIFFID is better than ever, but we need a new type of model to simulate impacts of land-management and disturbance on the land carbon store.....

Robust Ecosystem Demography (RED)

- A simplified version of the ED Model (Moorcroft *et al.*, 2001, Fisher *et al.*, 2010).
- A model designed to update tree mass distributions (for each PFT) based on growth and mortality rates as a function of tree mass, M .
- Essentially a continuity equation for tree number density $n(M,t)$, with a sink term due to tree mortality and source term due to seedling production.
- Implicitly assumes that age-dependencies of growth or mortality can be approximated by mass-dependencies.

RED : Governing Equation

$$\frac{\partial n(M, t)}{\partial t} + \frac{\partial}{\partial M} \{n(M, t) g(M, t)\} = - \mu(M, t) n(M, t)$$

Growth-rate of Tree of mass M Mortality-rate of Tree of mass M

- We assume that growth rate depends on tree-mass as a power-law:

$$g = g_0 \left\{ \frac{m}{m_0} \right\}^b$$

We follow Niklas and Spatz (2004) in assuming that $b=3/4$.

- We also assume that mortality rate is independent of mass.

Allows comparison to data on individual tree sizes....

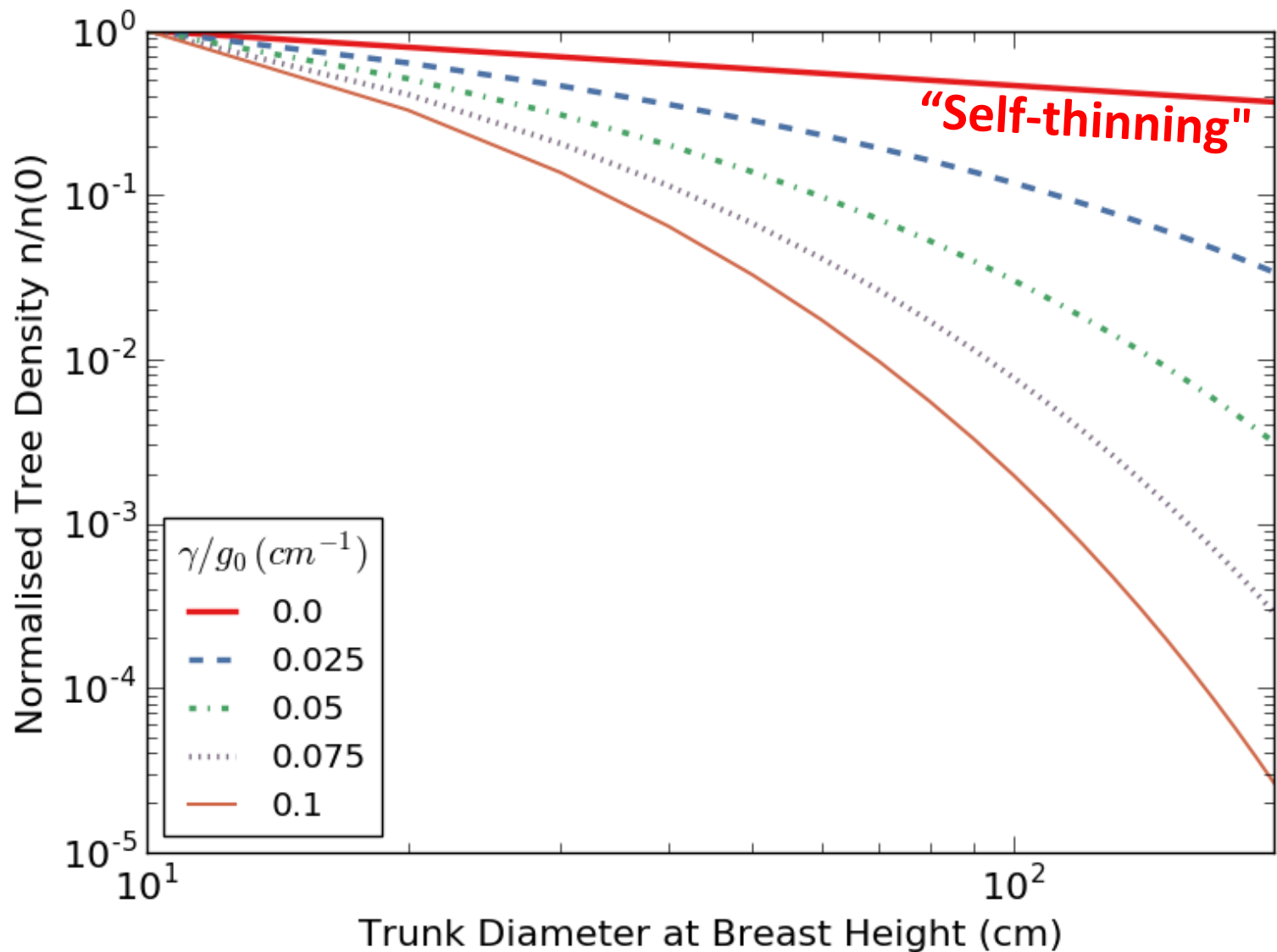
Steady-state solution for Finite Mortality

- If mortality rate is non-negligible, but the other simplifications still apply, the steady state solution becomes:

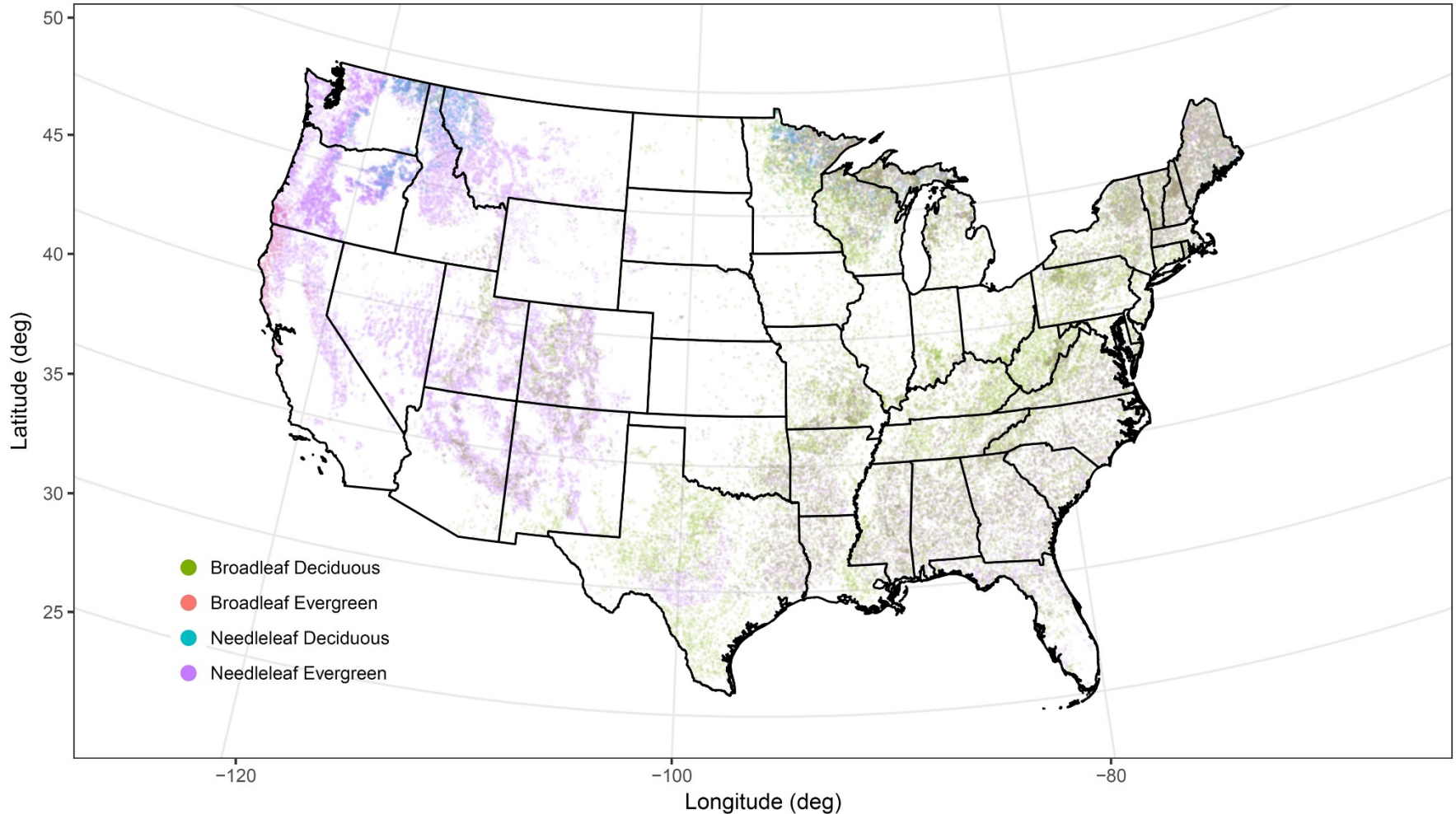
$$\frac{n}{n_0} = \left(\frac{m}{m_0}\right)^{-b} \exp \left\{ \frac{\gamma m_0}{g_0(1-b)} \left[1 - \left(\frac{m}{m_0}\right)^{1-b} \right] \right\}$$

- We can also work in terms of *Trunk Diameter, D* , for more direct comparability with forest inventory data.

Steady-state RED solutions for Varying Mortality Rates

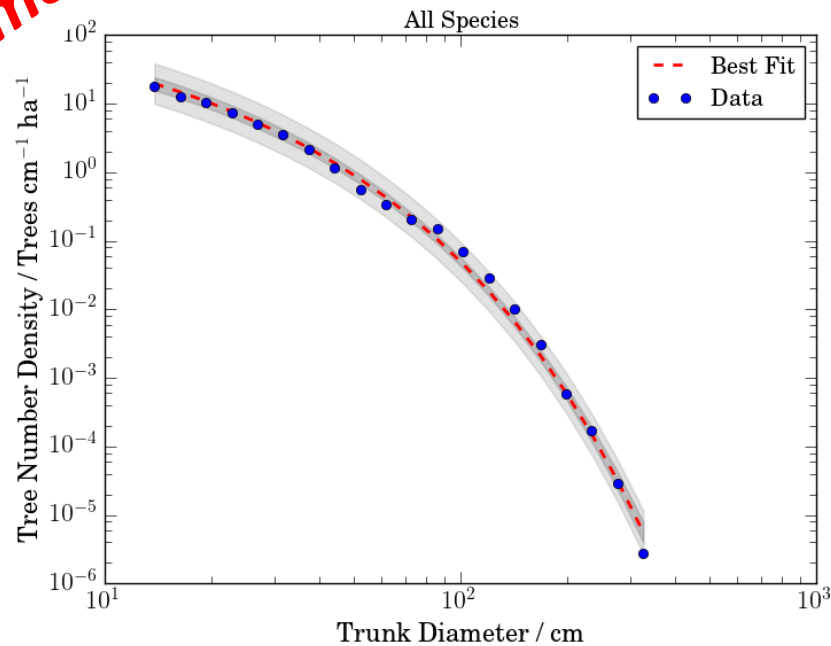
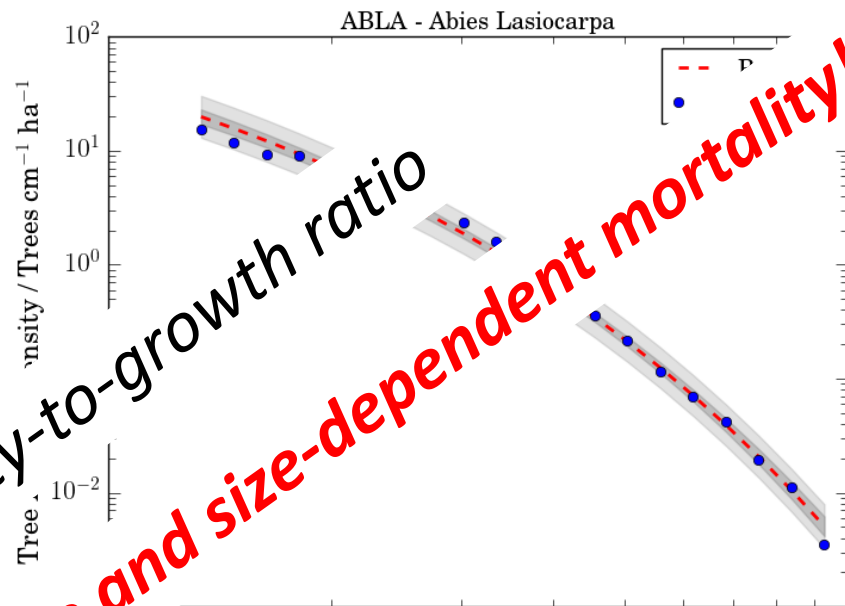
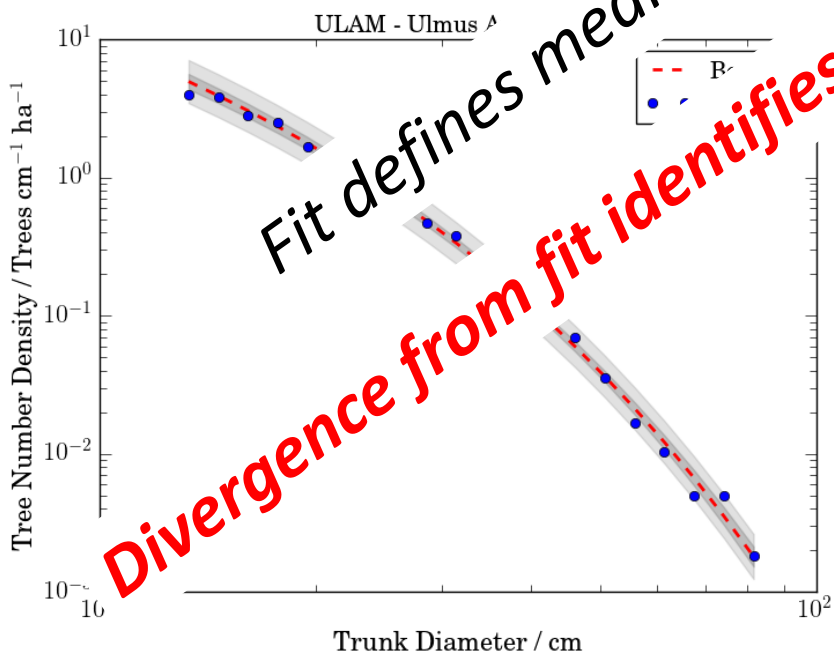


Evaluation for N. America (USDA Forest Inventory Data)

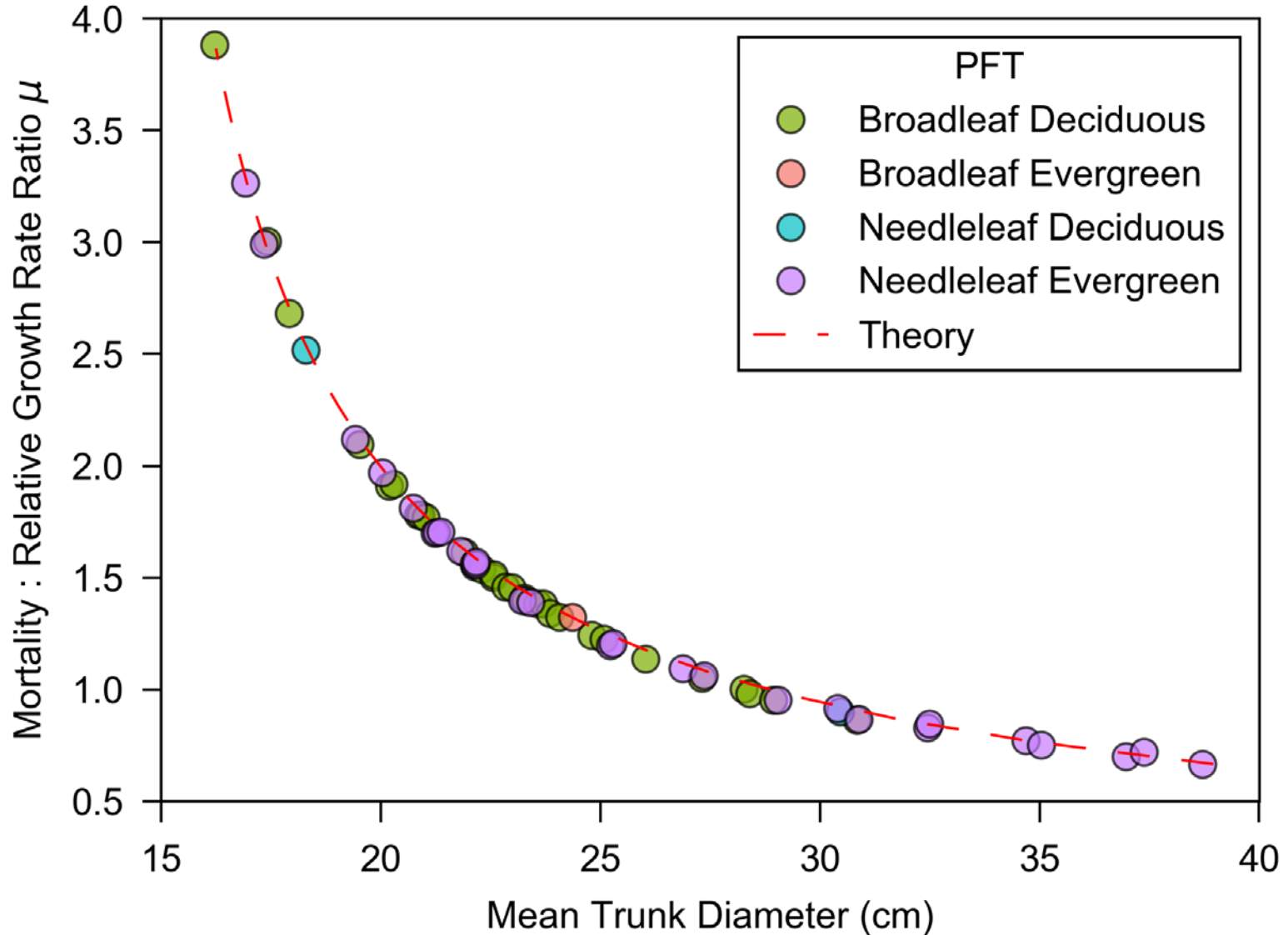


Trunk diameters for 1.6 million trees, of 61 species (Zhu et al., 2012)

Example RED Model-USDA Data Comparisons



Mean Trunk Diameter against Mortality to Growth Ratio



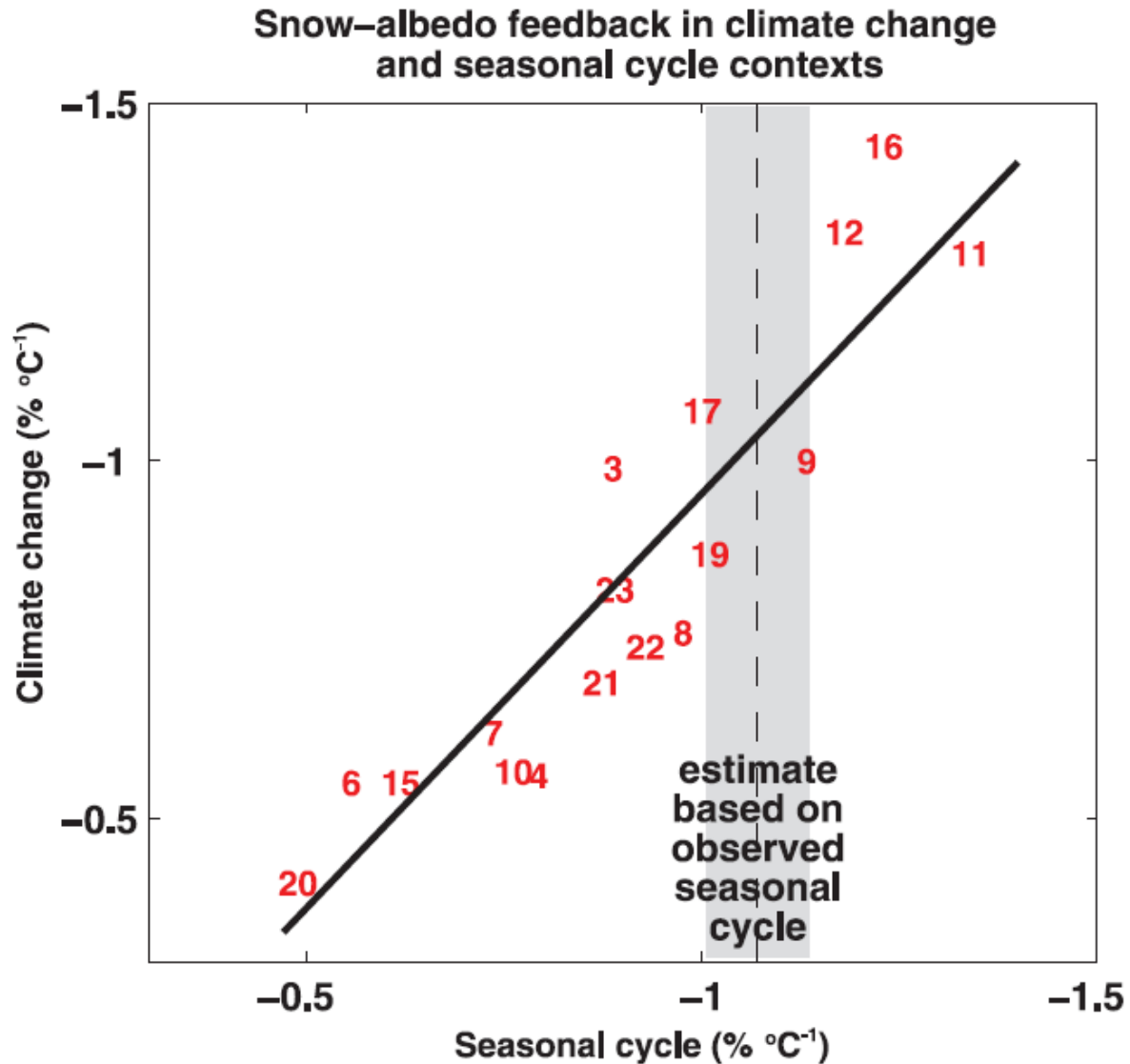
Keys to Reducing Uncertainties in Land Surface Models

- ✓ **Better process representation**
- **Parameter sparse models
(e.g. Vegetation Demography).**
- **Observational constraints
(e.g. Emergent Constraints)**

Emergent Constraints:

Using Earth System Models
to identify the relationships between
observable contemporary variations
and future sensitivity

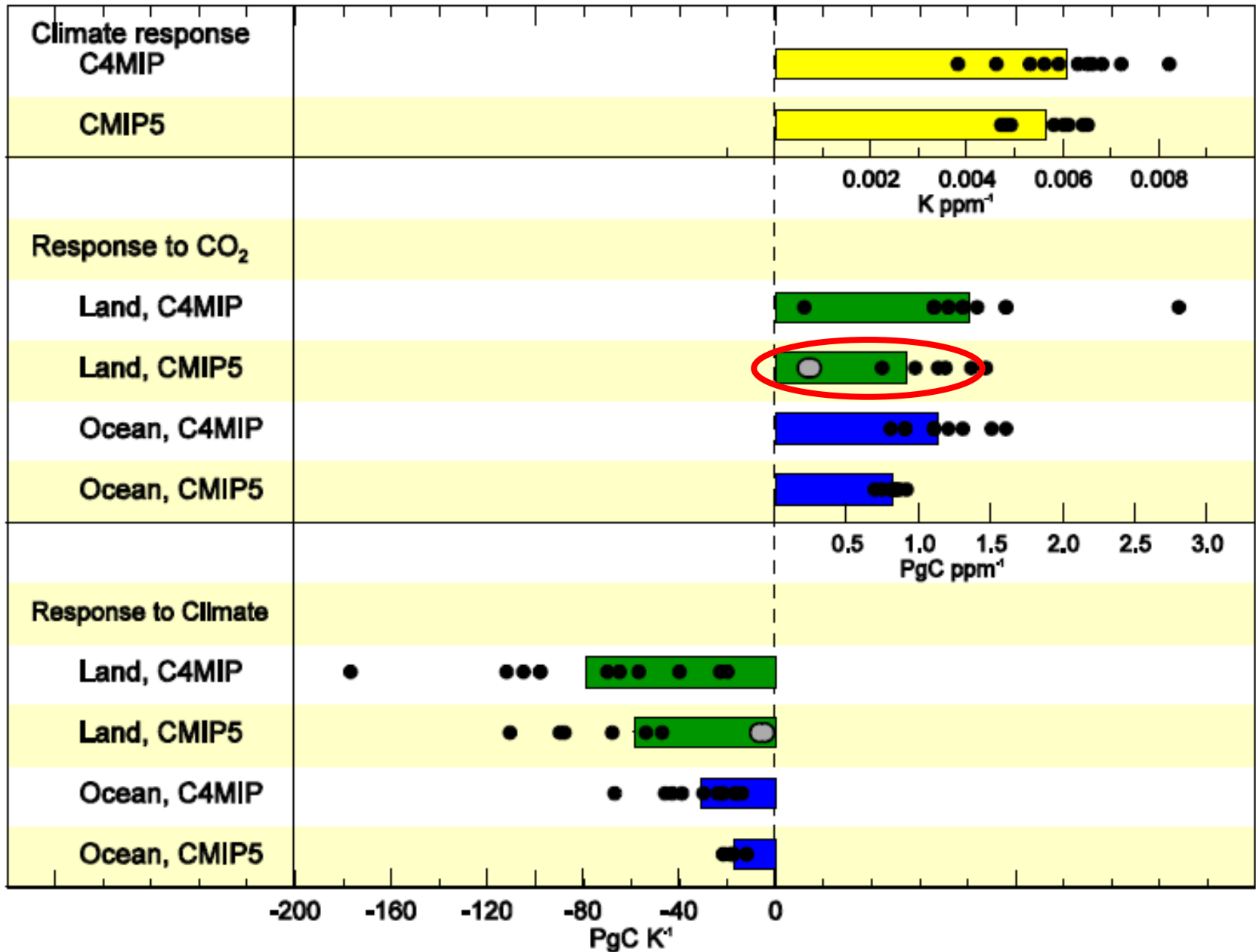
Archetypal Example of an *Emergent Constraint*



**An Emergent Constraint on
CO₂ Fertilization of Photosynthesis,
*from trends in the
CO₂ seasonal cycle***

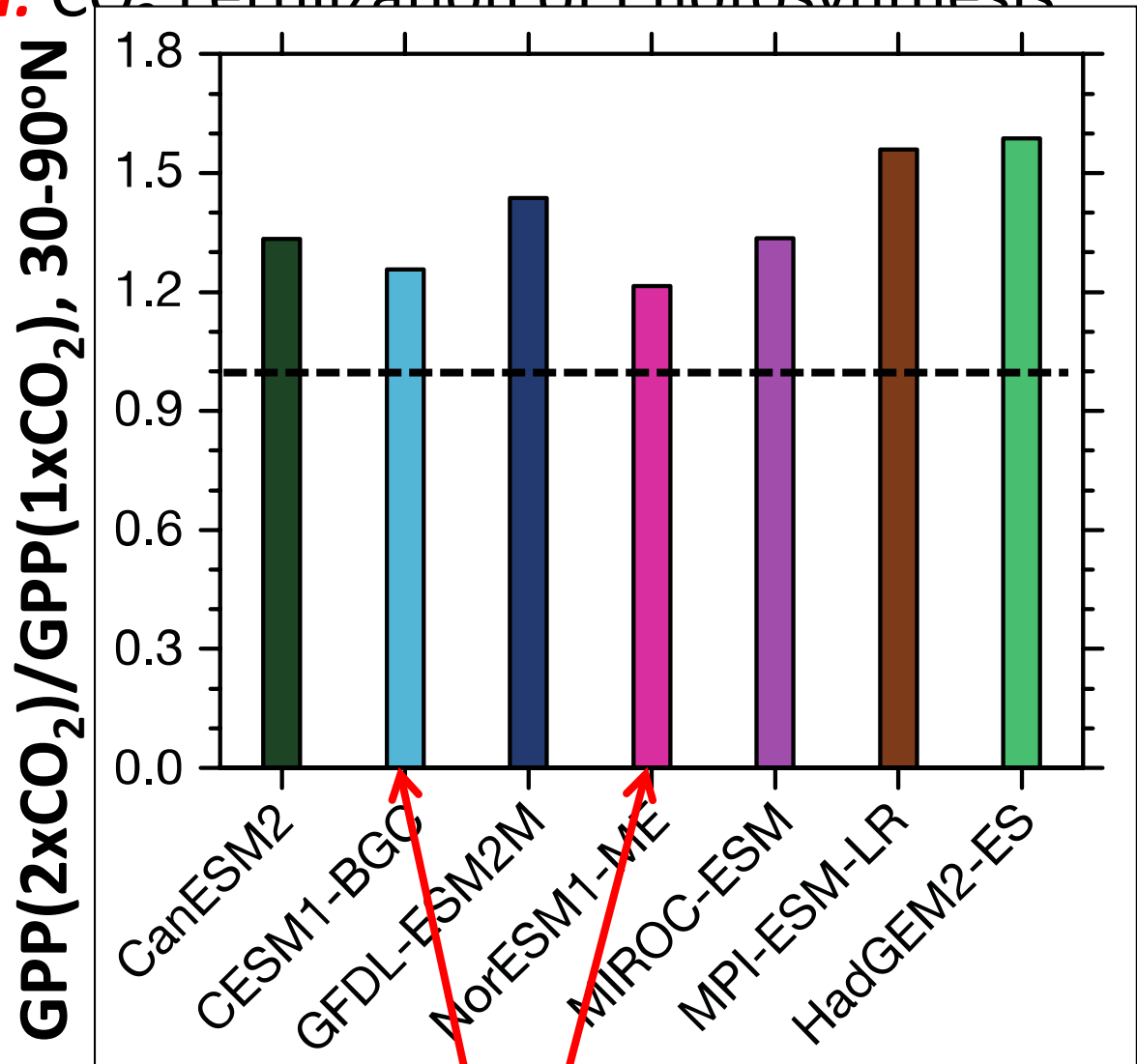
Wenzel *et al.*, *Nature*, 2016

Uncertainties on Carbon Cycle Feedbacks



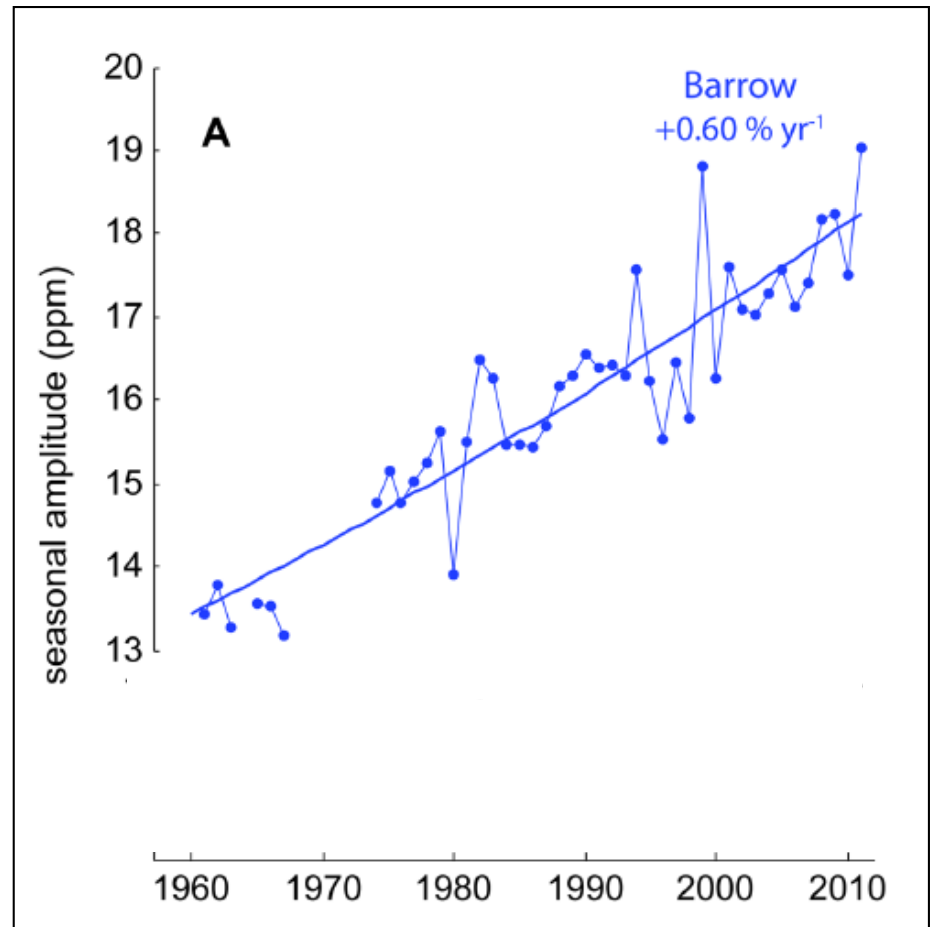
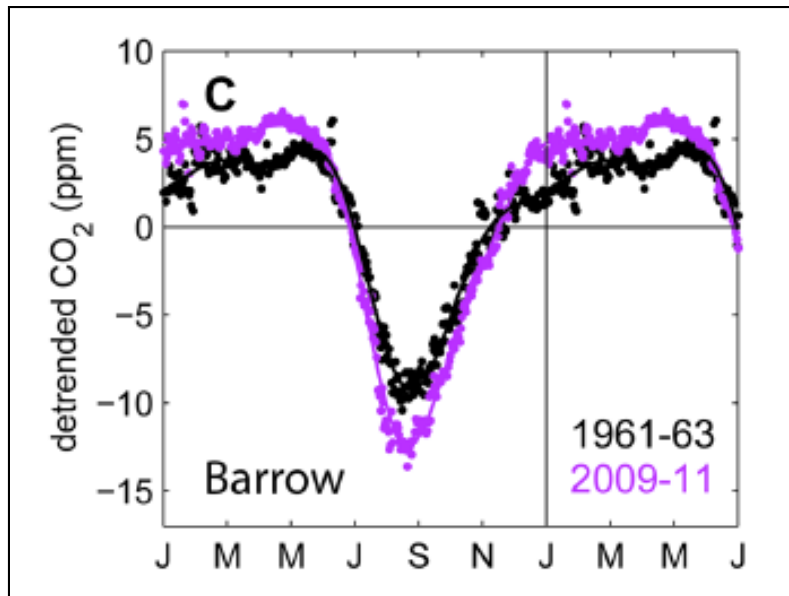
The Unknown: CO₂ Fertilization of Photosynthesis

*20% to 60%
projected increase
of GPP due to
doubling CO₂*



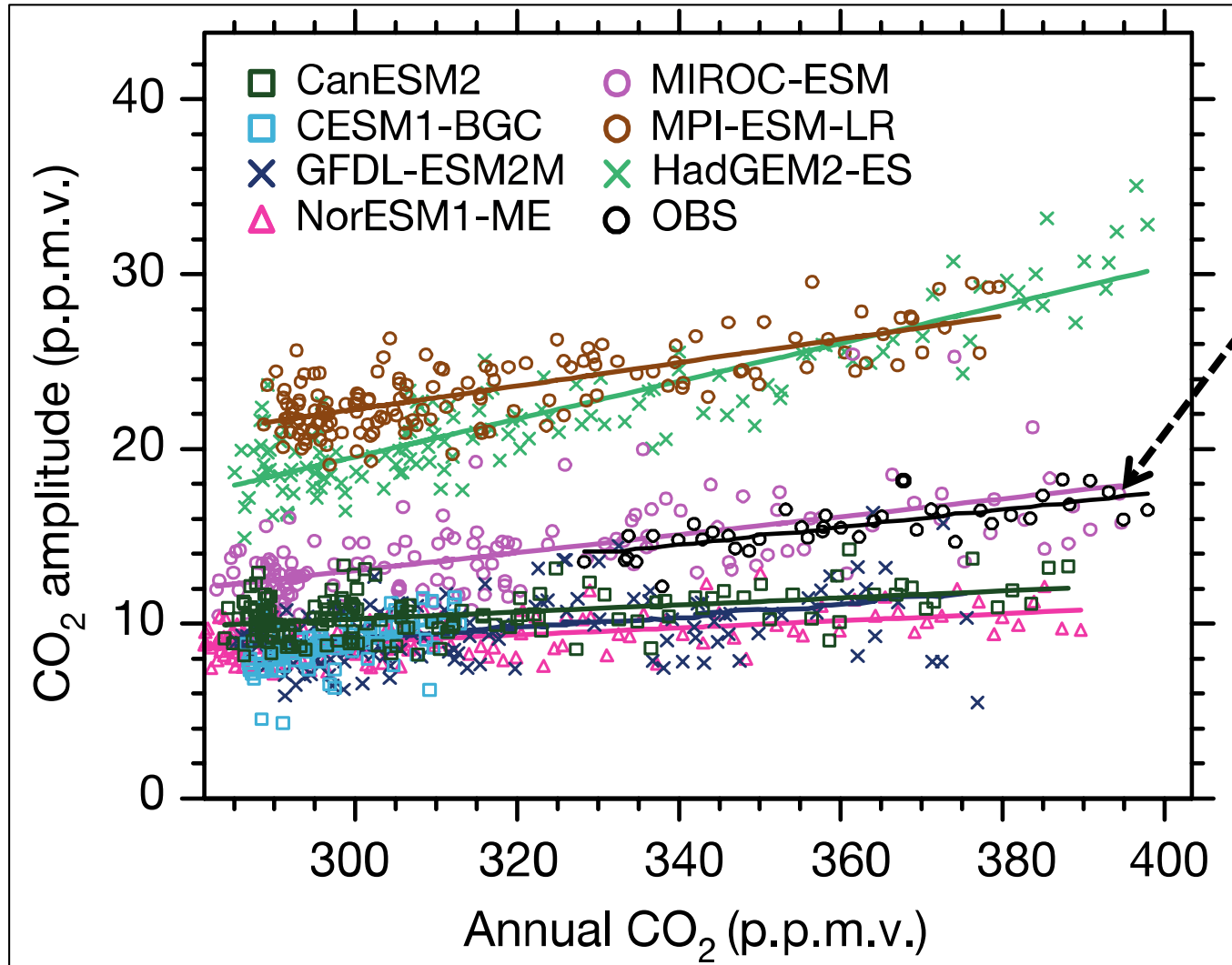
Models with N limitations

The Observations: Increasing Seasonal Amplitude of Atmospheric CO₂



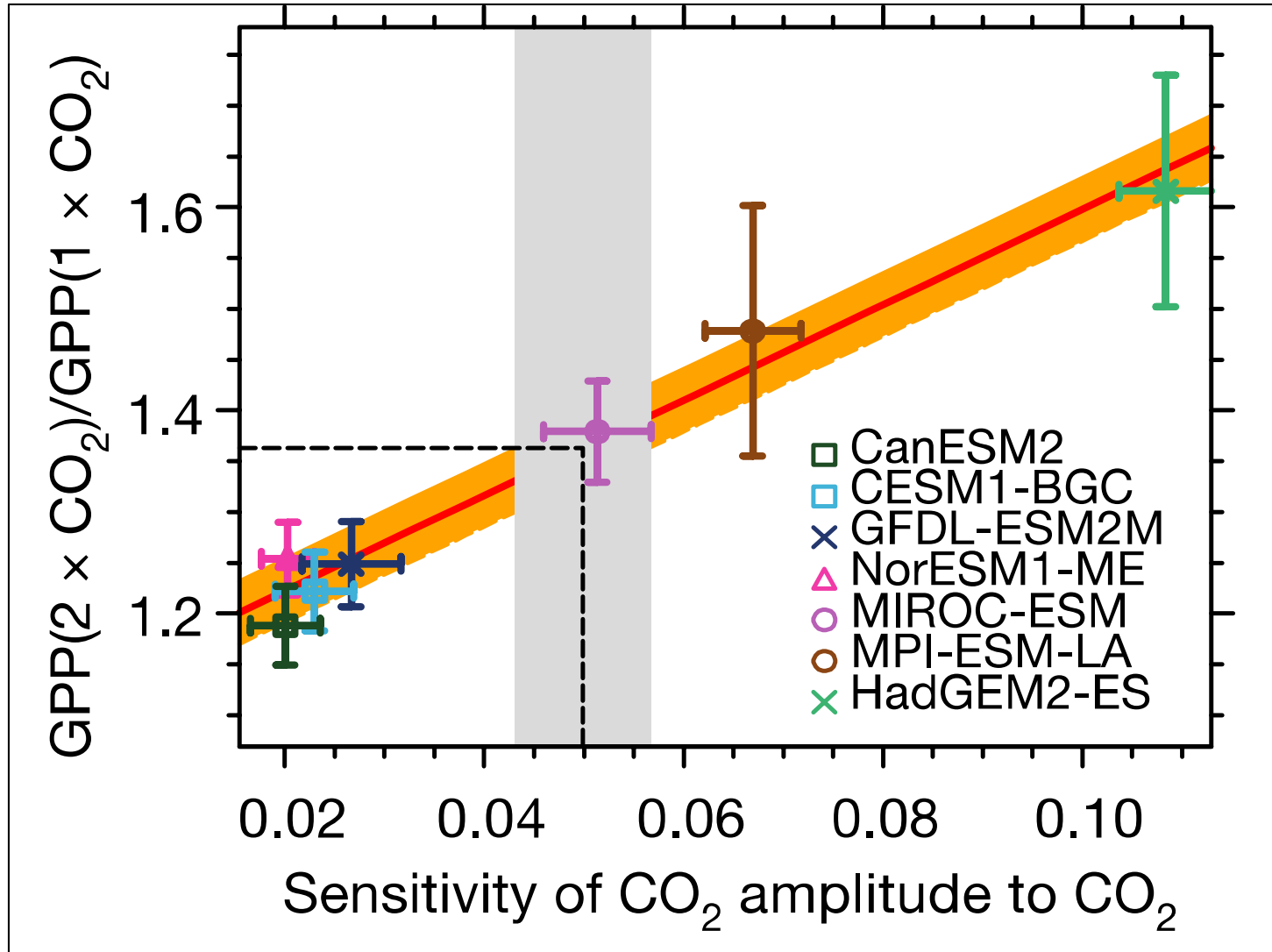
Comparing Models to Data:

BRW CO₂ Amplitude against Annual Mean CO₂

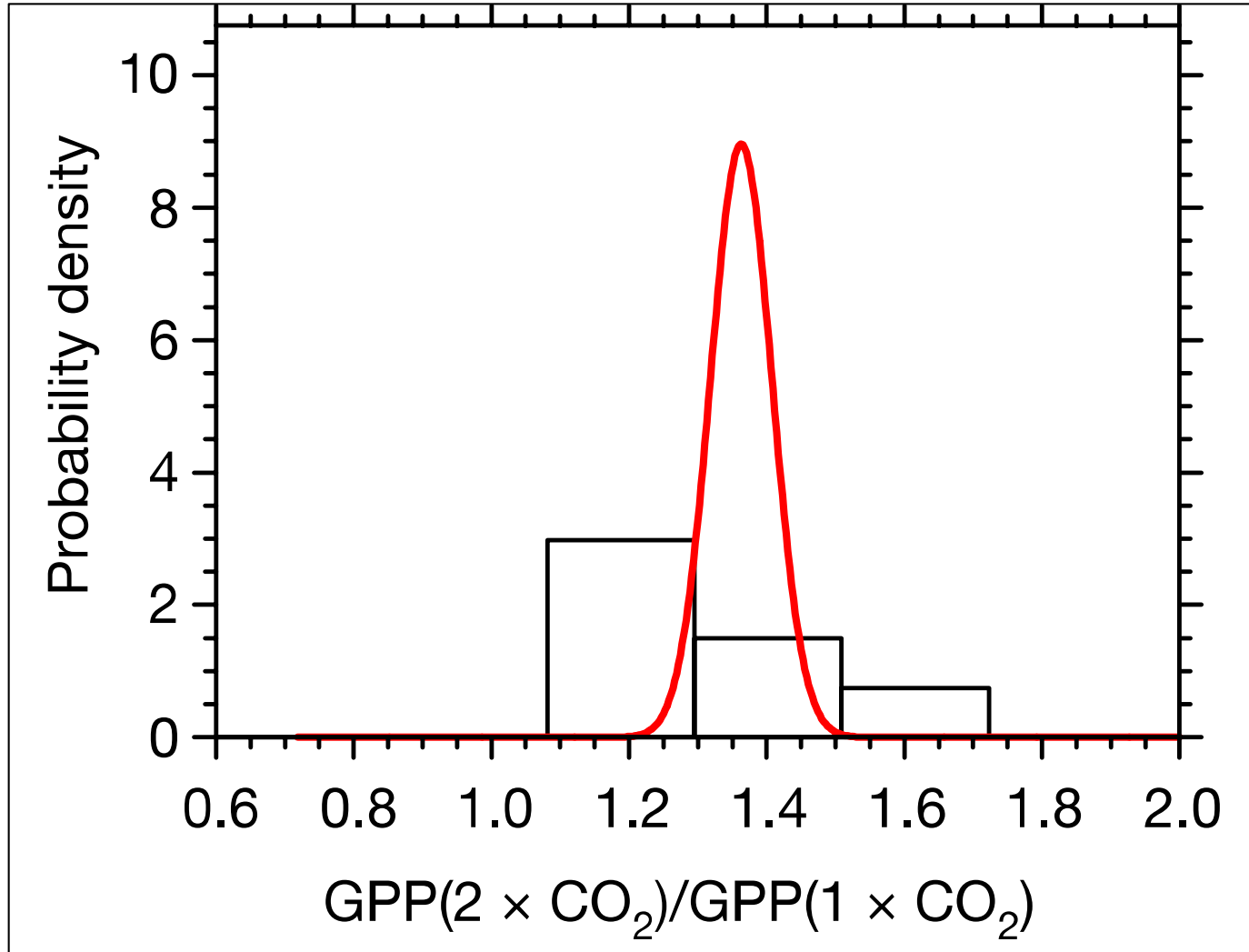


Observations

The Emergent Relationship



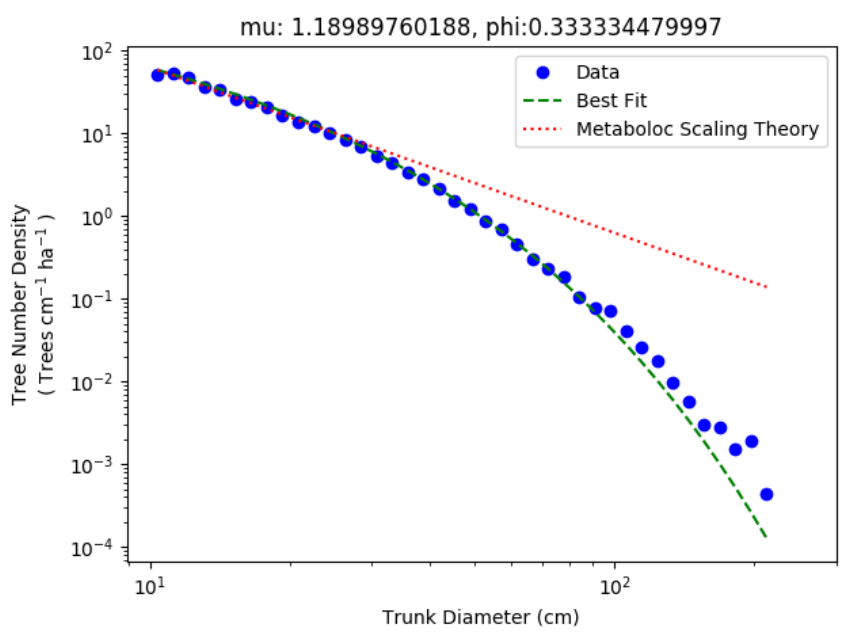
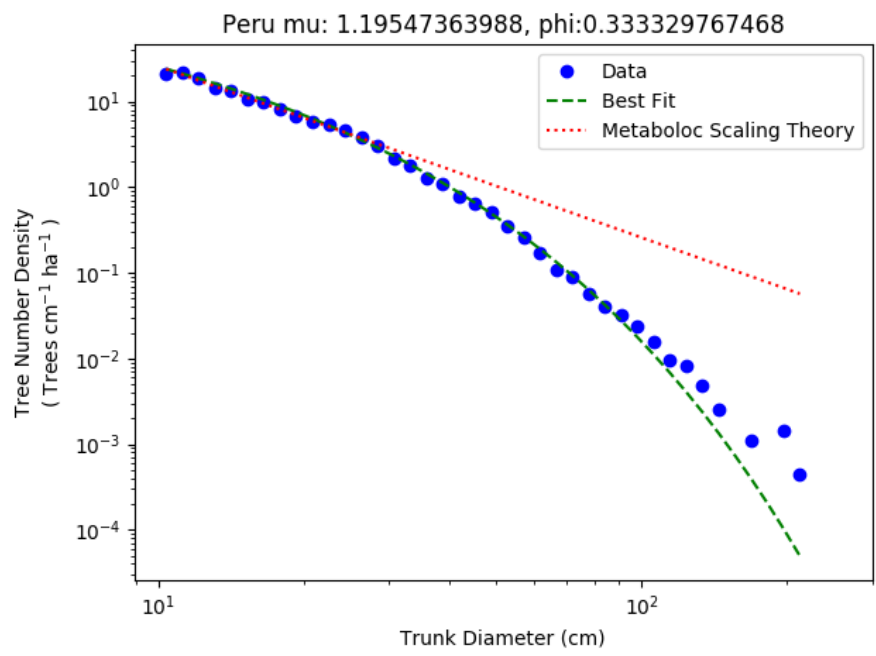
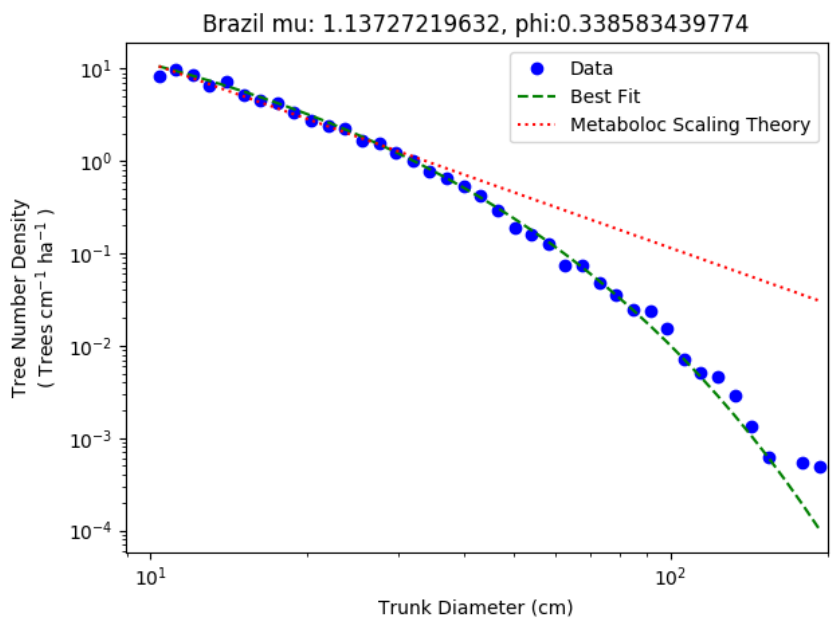
The Emergent Constraint: PDF of CO₂ Fertilization



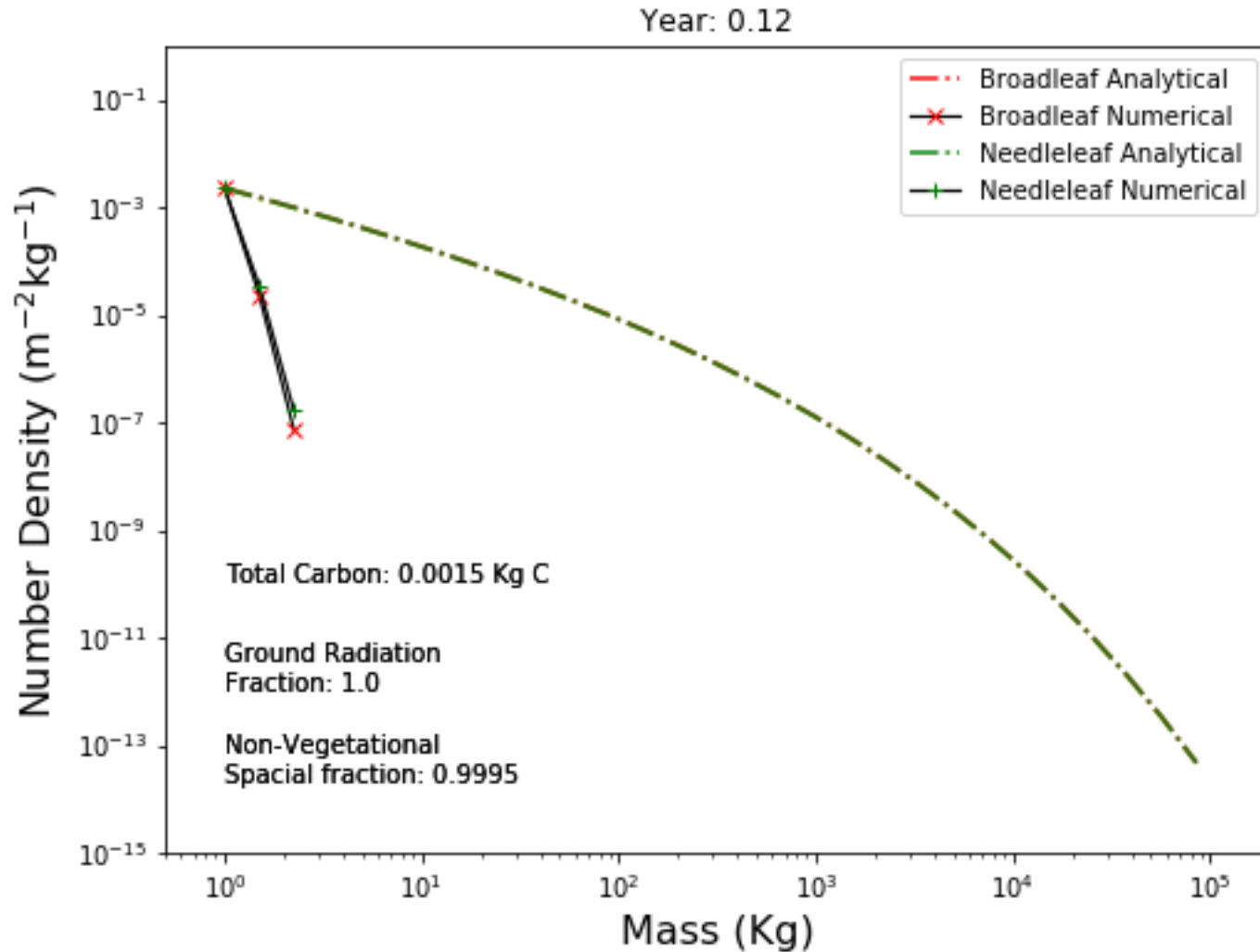
Conclusions

- **Land carbon cycle now amongst the most significant components of ESMs.**
- **Improving LSMs requires improved process representation, without increasing parameter uncertainty.**
- **We need more parameter sparse models and tighter constraints from observations.**
- **Emergent Constraints promise top-down constraints on land-surface sensitivities that can be used to inform model evaluation and development.**

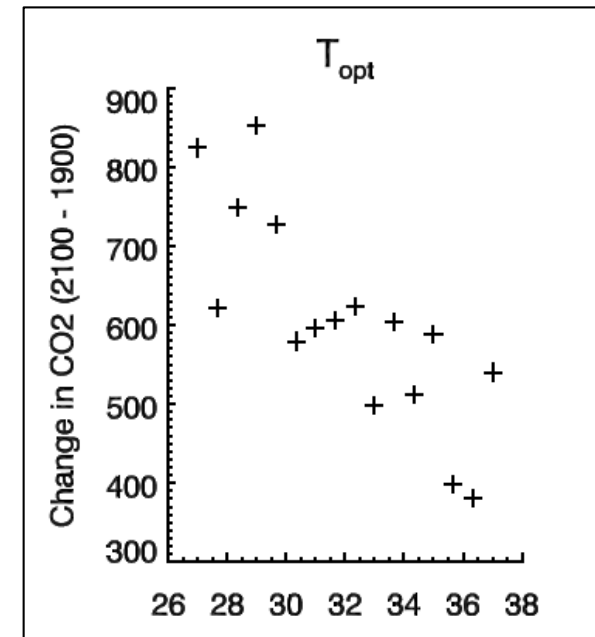
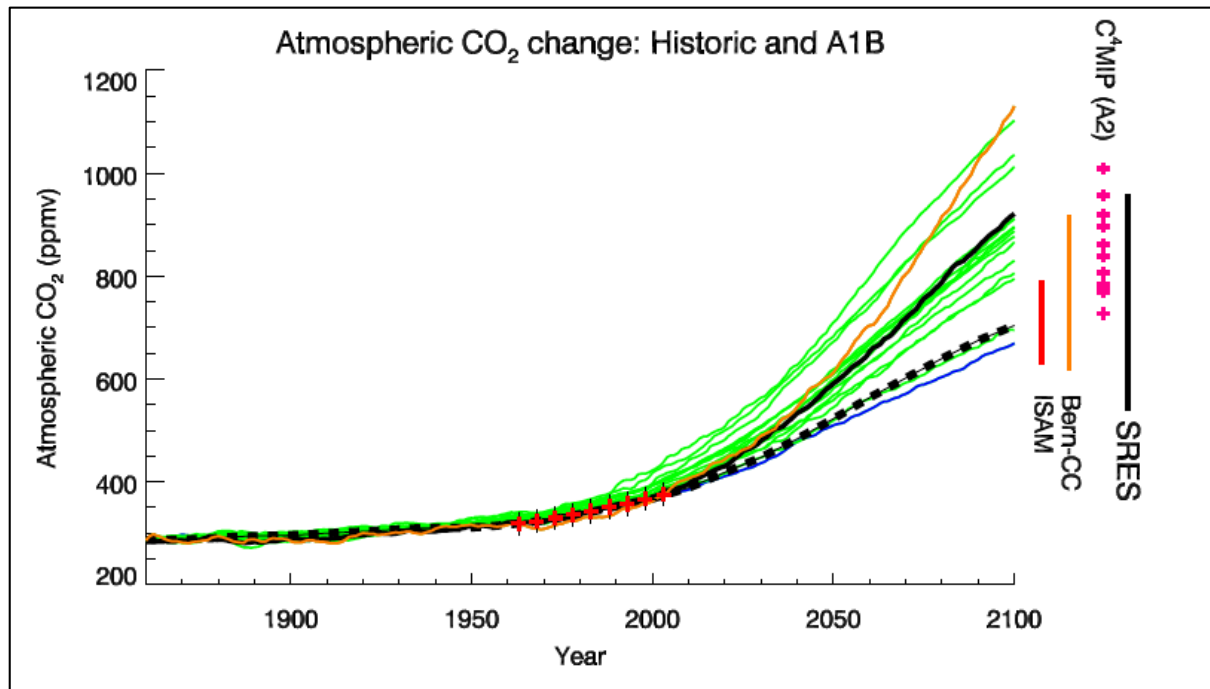
Evaluations of RED equilibria for Brazil, Peru and all RAINFOR data



Dynamical Solutions with RED



Climate Change Uncertainties & Land Carbon Cycle



Constraints on T_{opt} from Assimilation of Fluxnet → Constraints on Future CO_2

