On the importance of modeling carbon and nitrogen

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Outline

- Modeling the carbon cycle: The GCM -> ESM evolution
- What predictions do ESMs make, and which of these do we actually trust?
- Addendum: carbon isotopes in Earth and CLM

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A highly biased and terrestrial-centric timeline of the GCM – ESM evolution

"GCM era" 1990 — 2000 "ESM era" — now

1991: Tans, Fung, & Takahashi: terrestrial carbon sink is large, start of the "missing sink" era.

Follow-on papers: Ciais et al, 1995: ^{13}C Pacala et al., 2001: how to reconcile bottom-up and top-down estimates of C sinks?

1992: Bonan et al., 1996: Sellers et al.:

Physically-coupled climate ecosystem models

Biophysical effects of terrestrial ecosystems are large and need to be incorporated in climate projections

1995: VEMAP (offline MIP)

2000: first coupled-carbon-climate models.

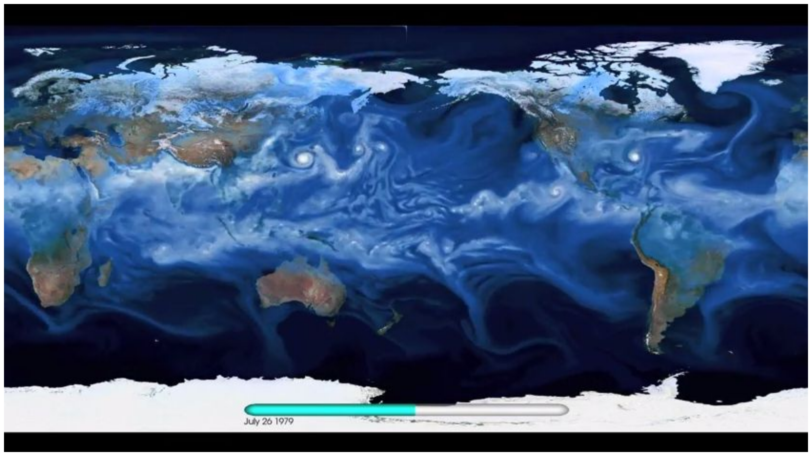
Carbon feedbacks are either enormous (Cox et al., 2000) or not (Friedlingstein et al., 2001)

2006: C^4MIP (Friedlingstein et al)
2009: Gregory et al
2013-: CMIP5 exps (many papers)

Theory developed for including carbon feedbacks into climate projections, "allowable emissions" but the models underlying the theory still completely uncertain

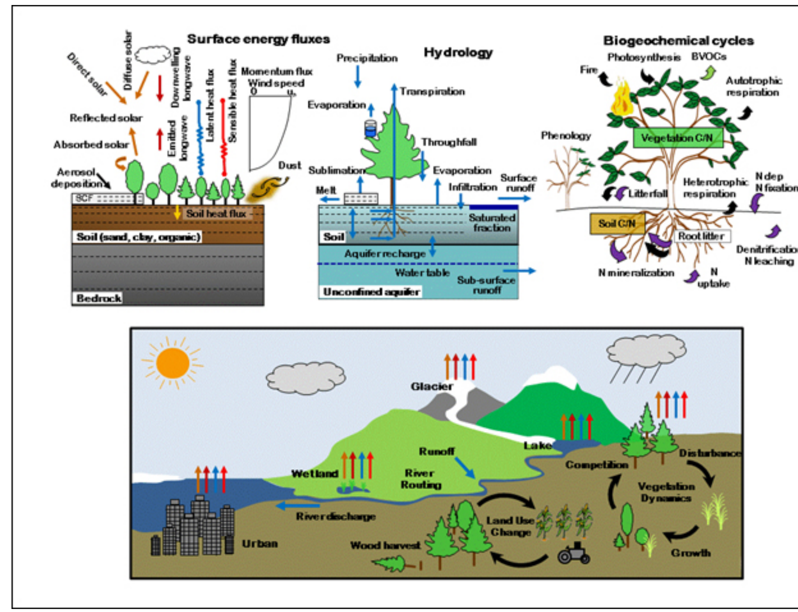
Modeling the Earth system

Atmosphere



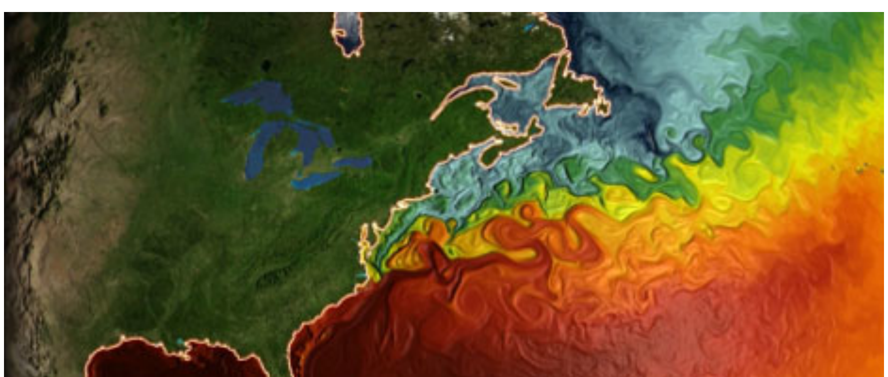
Water, energy, momentum, CO_2

Land



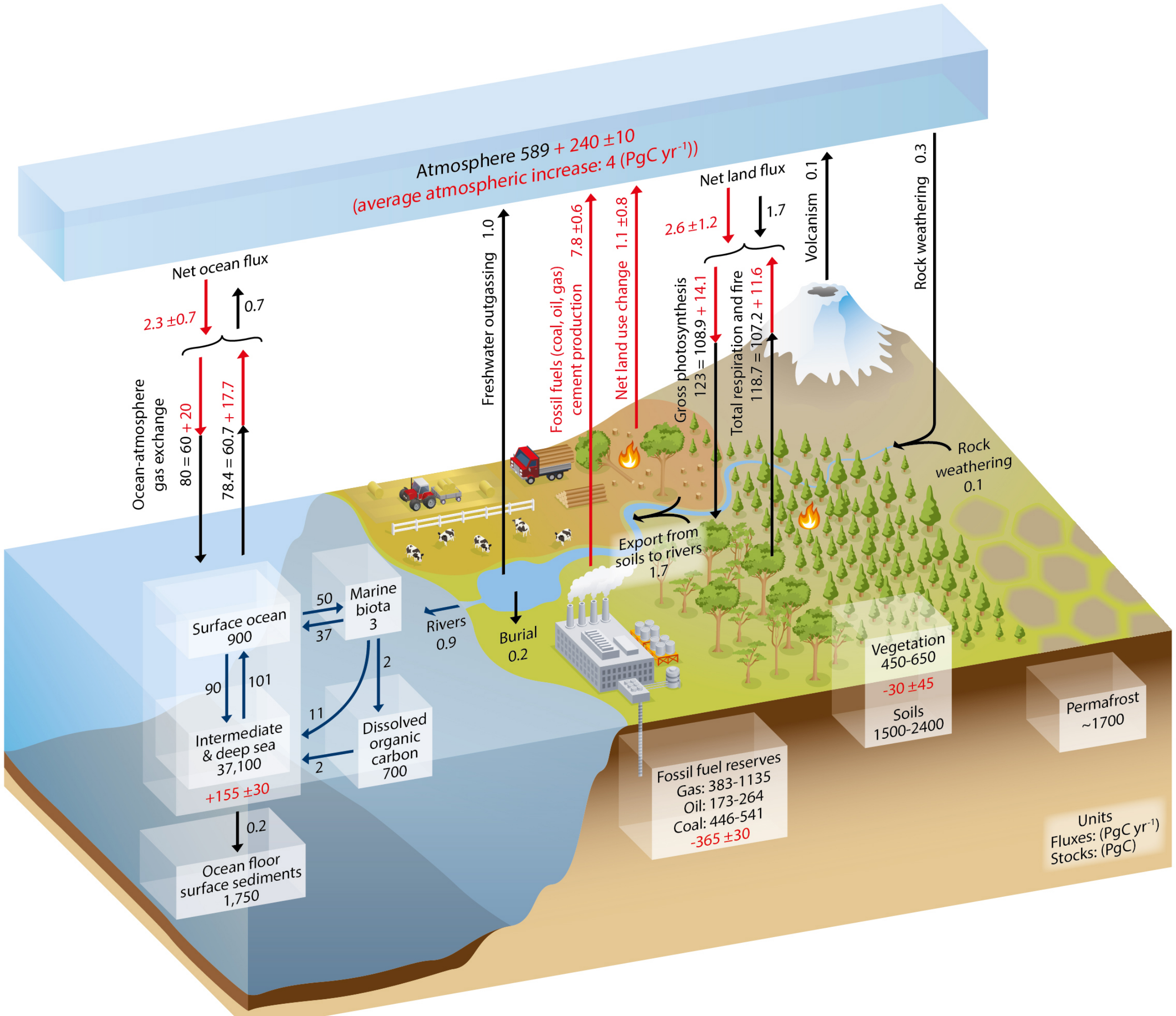
Water, energy, momentum, CO_2

Water



Ocean

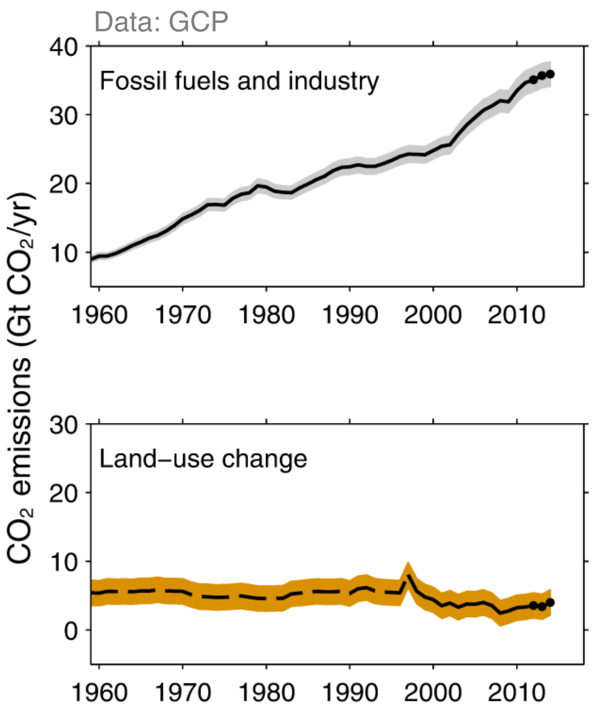
Stocks and flows of carbon in the Earth system

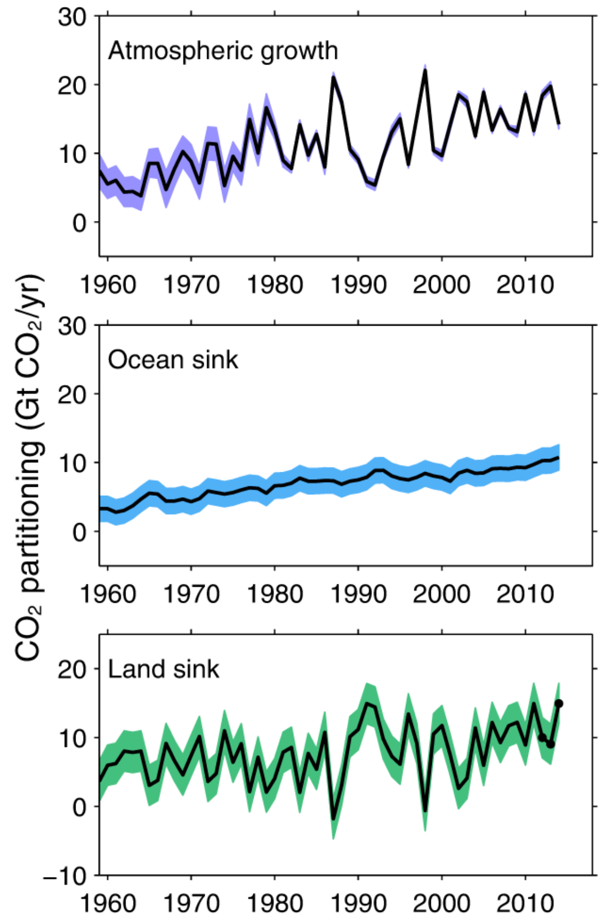


IPCC-AR5 (Ciais et al., 2013)

Changes in the budget over time

The sinks have continued to grow with increasing emissions, but climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere

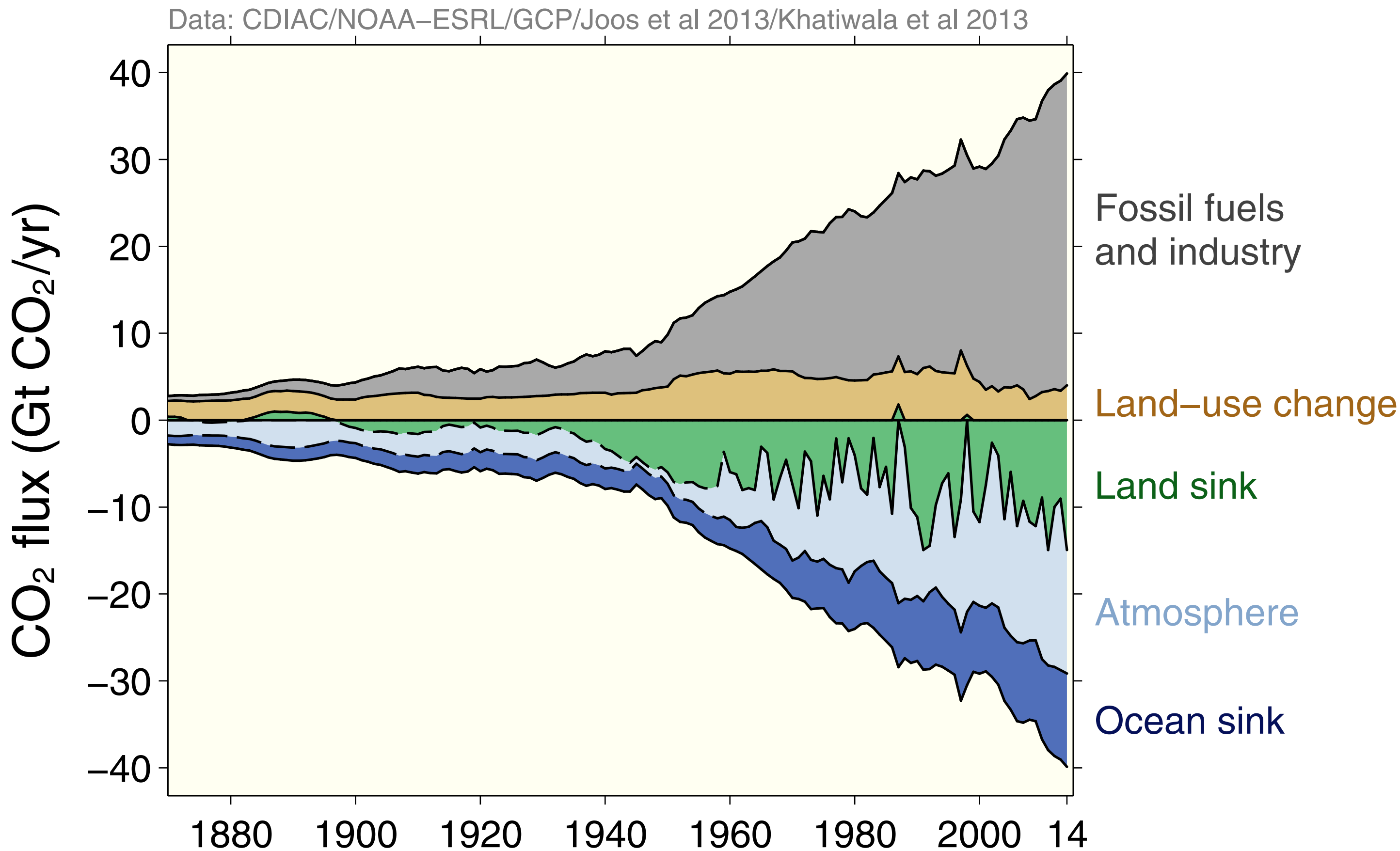




Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2015; Global Carbon Budget 2015

Global carbon budget

The carbon sources from fossil fuels, industry, and land use change emissions are balanced by the atmosphere and carbon sinks on land and in the ocean



Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2015; Global Carbon Budget 2015

Coupled carbon cycle – climate modeling intercomparison project (C^4MIP) protocol, CMIP5 version

	CO_2 input to radiation scheme	CO_2 input to carbon-cycle scheme	Reason
Fully coupled			Simulates the fully coupled system
'Biogeochemically' coupled 'esmFixClim'			Isolates the carbon-cycle response to CO_2 (β) for land and oceans
Radiatively coupled 'esmFdbk'			Isolates carbon-cycle response to climate change (γ) for land and for oceans

IPCC-AR5 (Ciais et al, 2013)

Offline analogues with CLM:

- "biophysical" CO_2 via namelist and stream files
- "radiative" CO_2 via forcing data

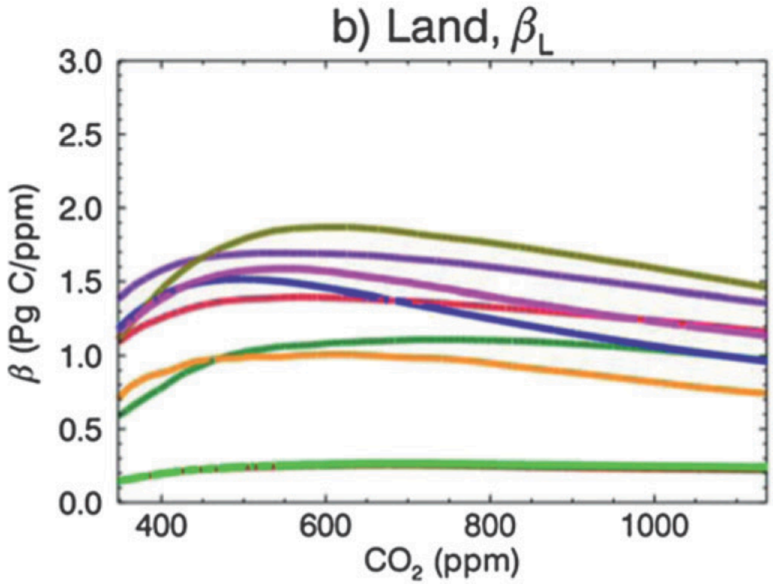
Theoretical framework:

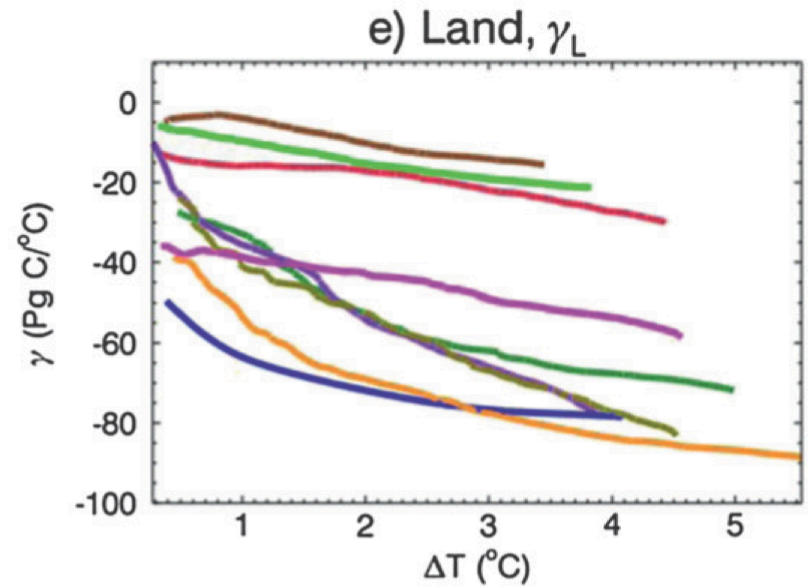
determine linear feedback terms γ, β

$$g = -\alpha(\gamma_L + \gamma_O)/(1 + \beta_L + \beta_O).$$

Transient climate sensitivity (K ppm^{-1})

Friedlingstein et al., 2006





Arora et al., 2013

Gregory et al., 2009,
Arneth et al, 2010:
Put biogeochemical feedbacks in same units as physical feedbacks

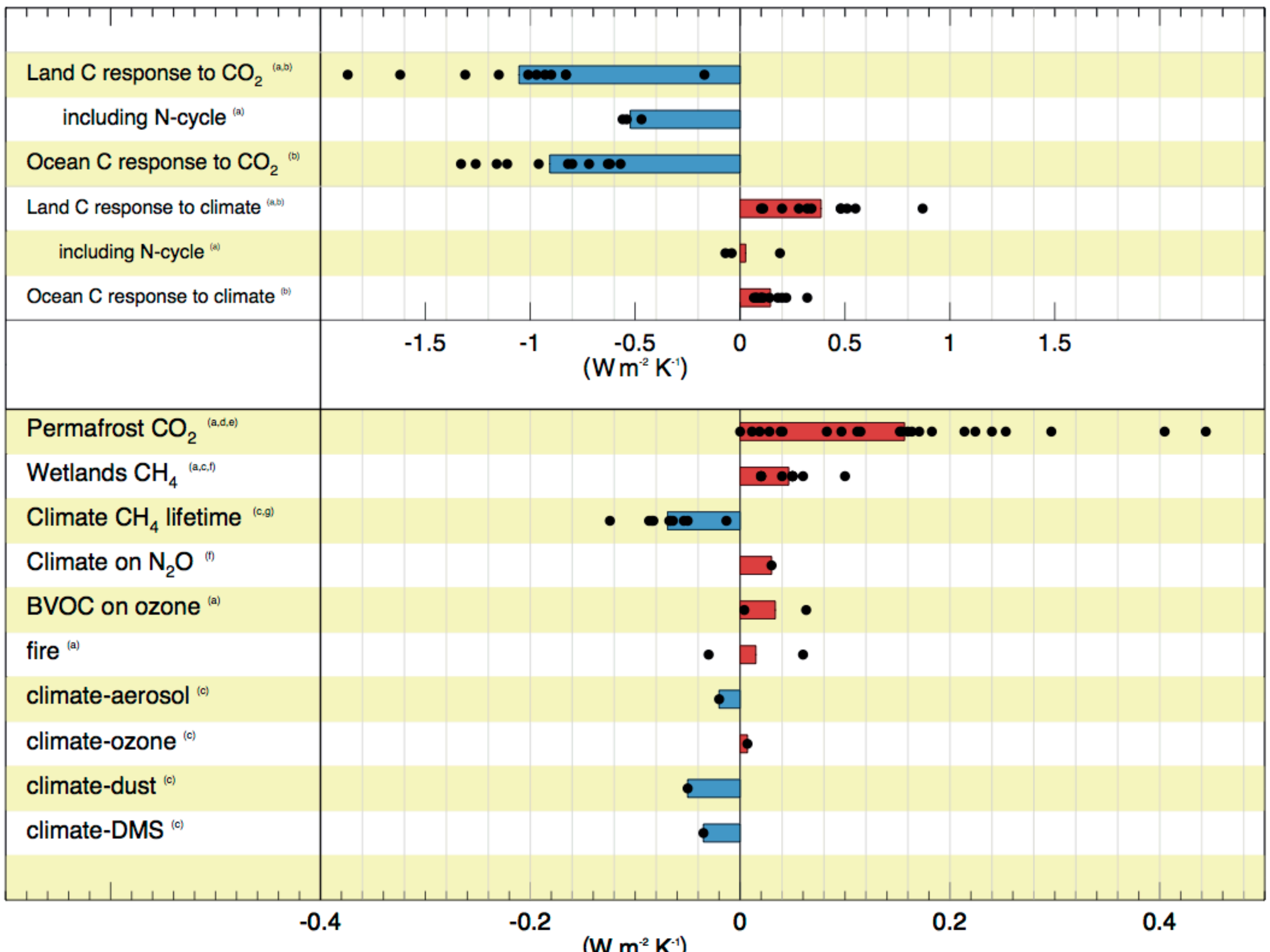
$$r_{\beta,CO2} = \rho \ \beta_{land,CO2}$$

Climate resistance (W m^{-2} K^{-1}) = $\Delta RF_{CO2}/\Delta T$

$$r_{\gamma,CO2} = \phi \ \gamma_{land,CO2}$$

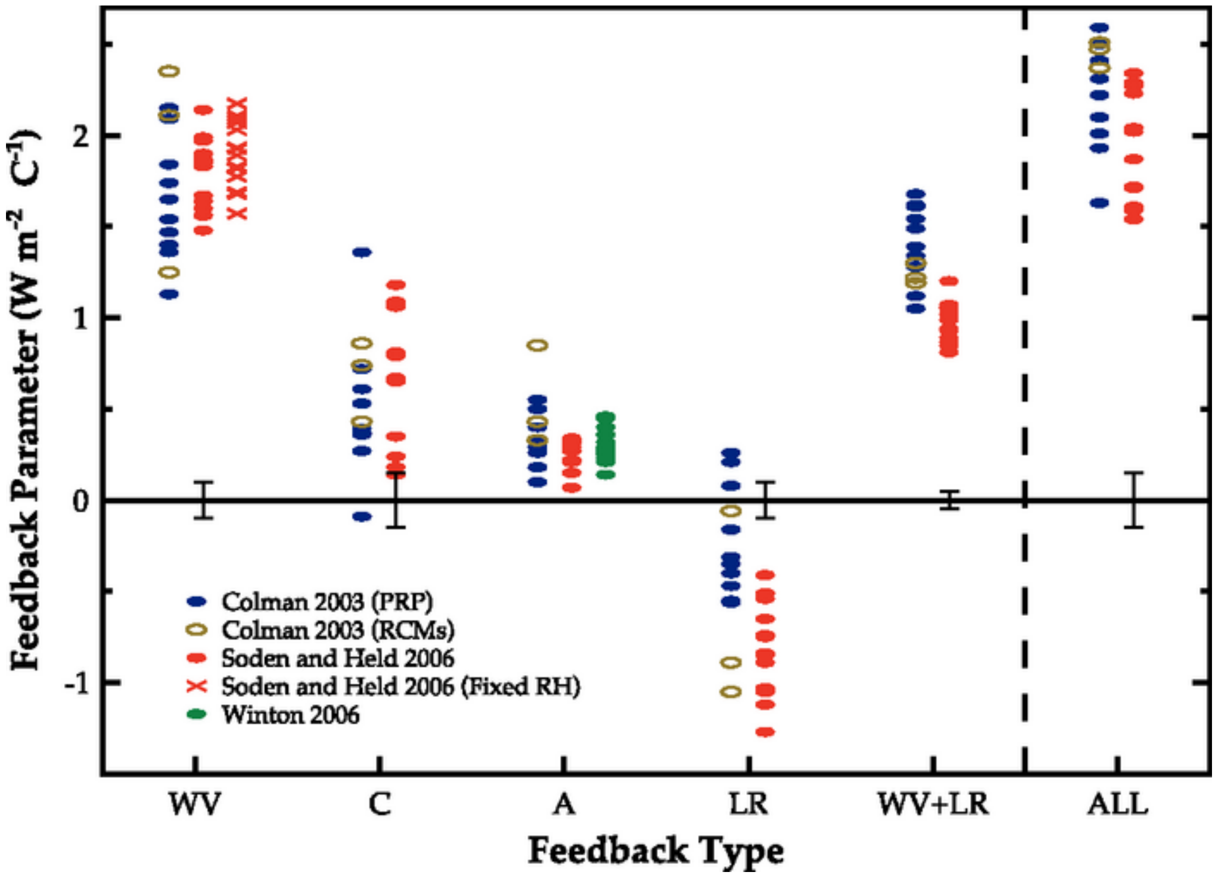
Linearized $\Delta RF/\Delta CO_2$ (W m^{-2} Pg C)

IPCC-AR5-WG1-Ch6 (Ciais et al., 2013)
Estimates of biogeochemical feedback parameters

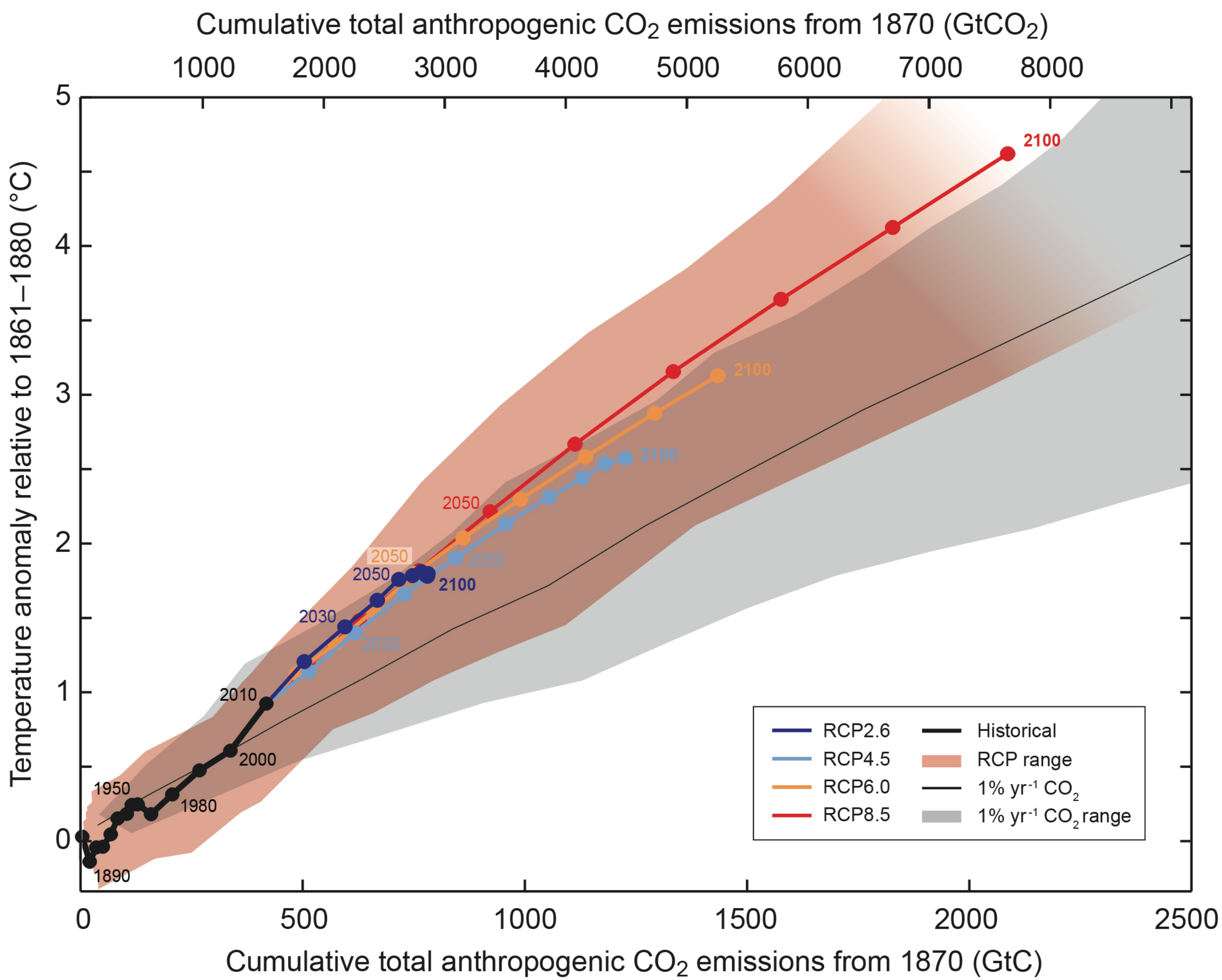


IPCC-AR5 (Ciais et al, 2013)

For comparison, IPCC-AR4 spread in physical feedbacks



“Allowable Emissions”, the total global amount of carbon we can burn and still allow Earth to remain below a given climate change, is sensitive to both the physics and biology in the Earth system



IPCC AR5 Summary for Policymakers

Outline

- Modeling the carbon cycle: The GCM -> ESM evolution
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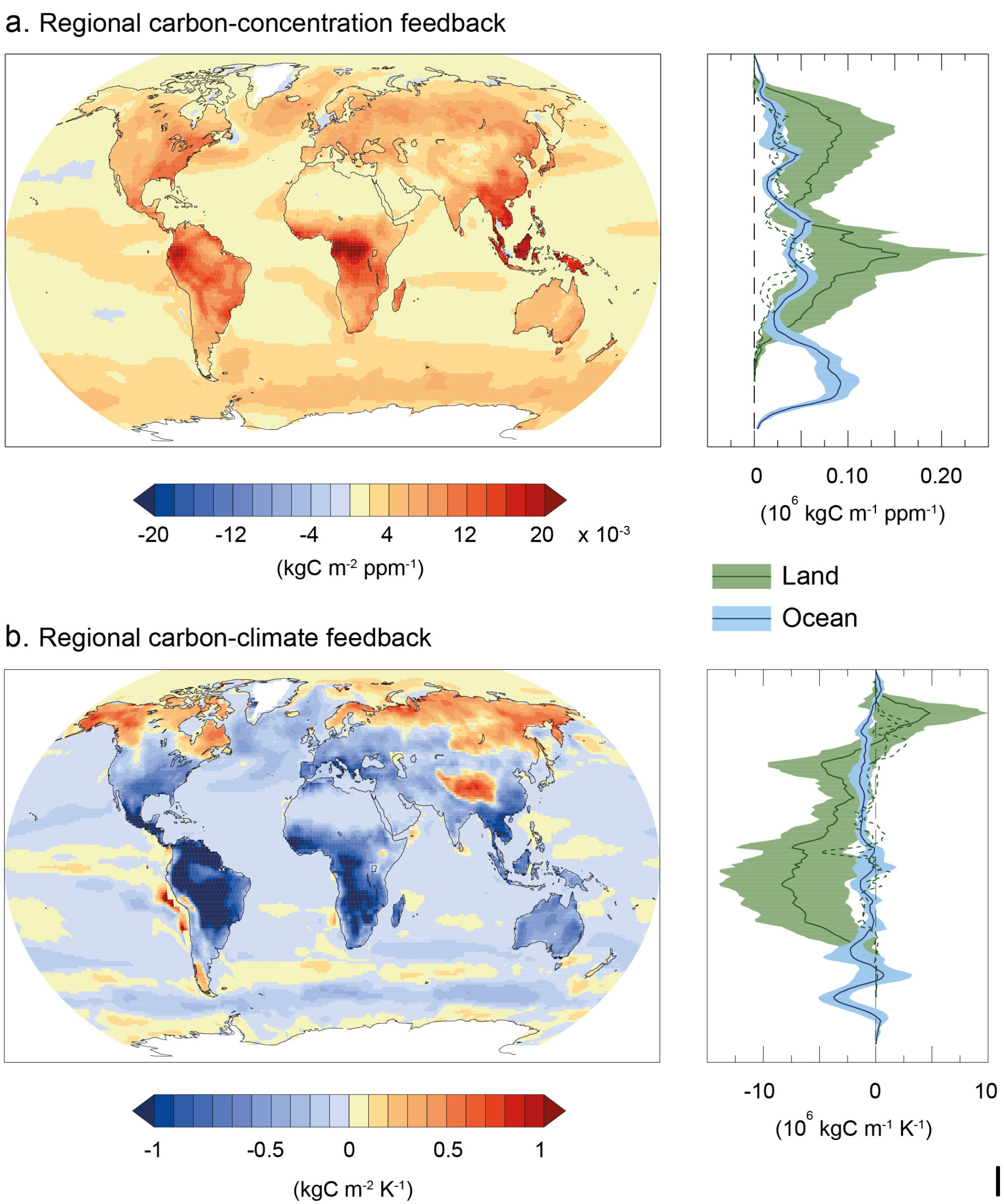
(at least) 2 types of uncertainty:

- Resolved uncertainty: That uncertainty which can be estimated using the spread in predictions between members of a MIP ensemble, parametric perturbation ensemble, etc.
- Unresolved uncertainty: Uncertainty that can't be estimated from looking at parametric or structural ensemble spreads, because it is based on shared assumptions.

CMIP5-generation ESM predictions



- CO_2 fertilization effect: strongest in the tropical forests, basically proportional to productivity
- CO_2 fertilization effect: stabilizing everywhere

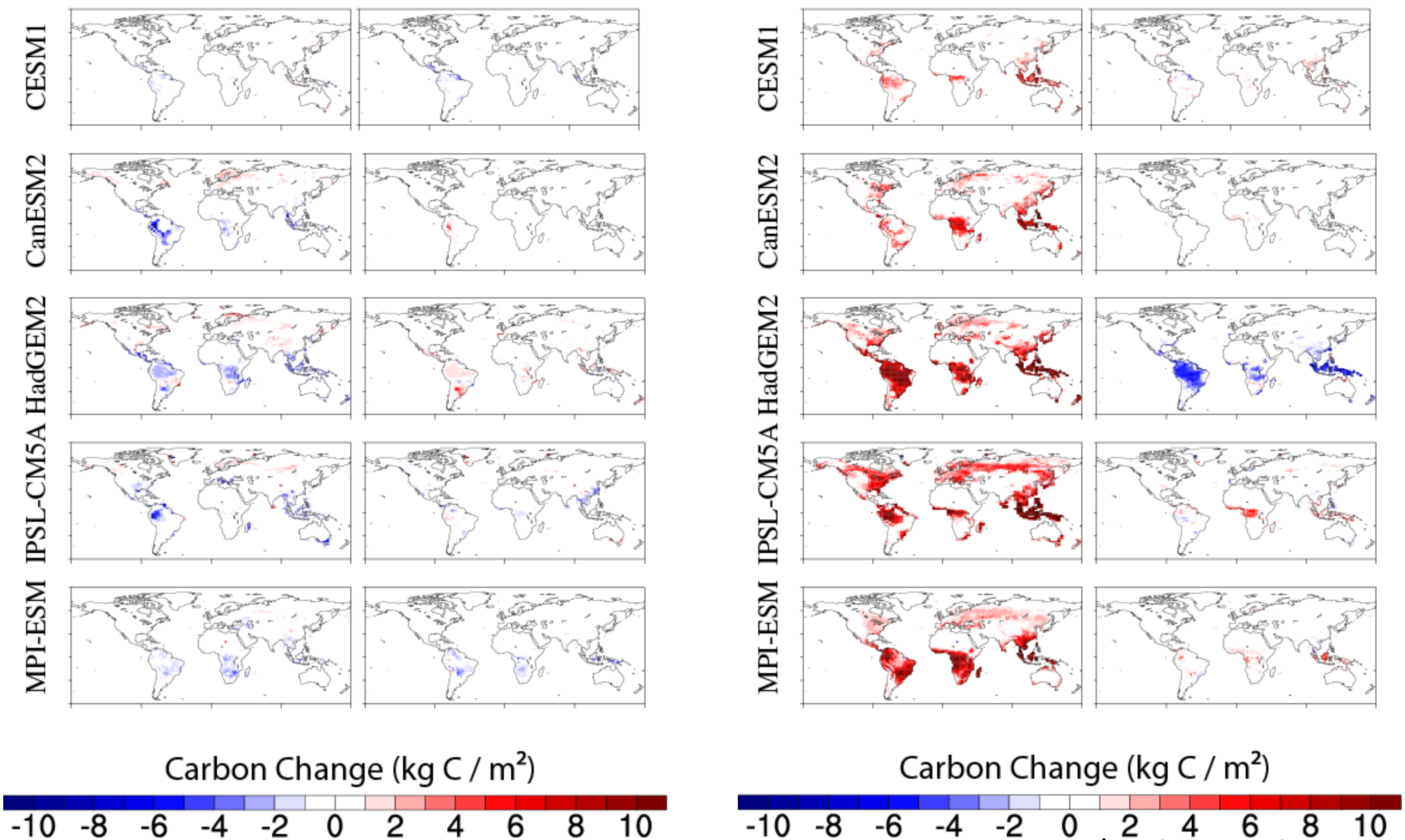
- Climate effect: stabilizing at high latitudes, destabilizing at low latitudes
- Climate effect also highest in tropical forests, weaker at high latitudes

IPCC-AR5 (Ciais et al, 2013)

What drives carbon feedbacks: inputs or outputs? 1: Vegetation

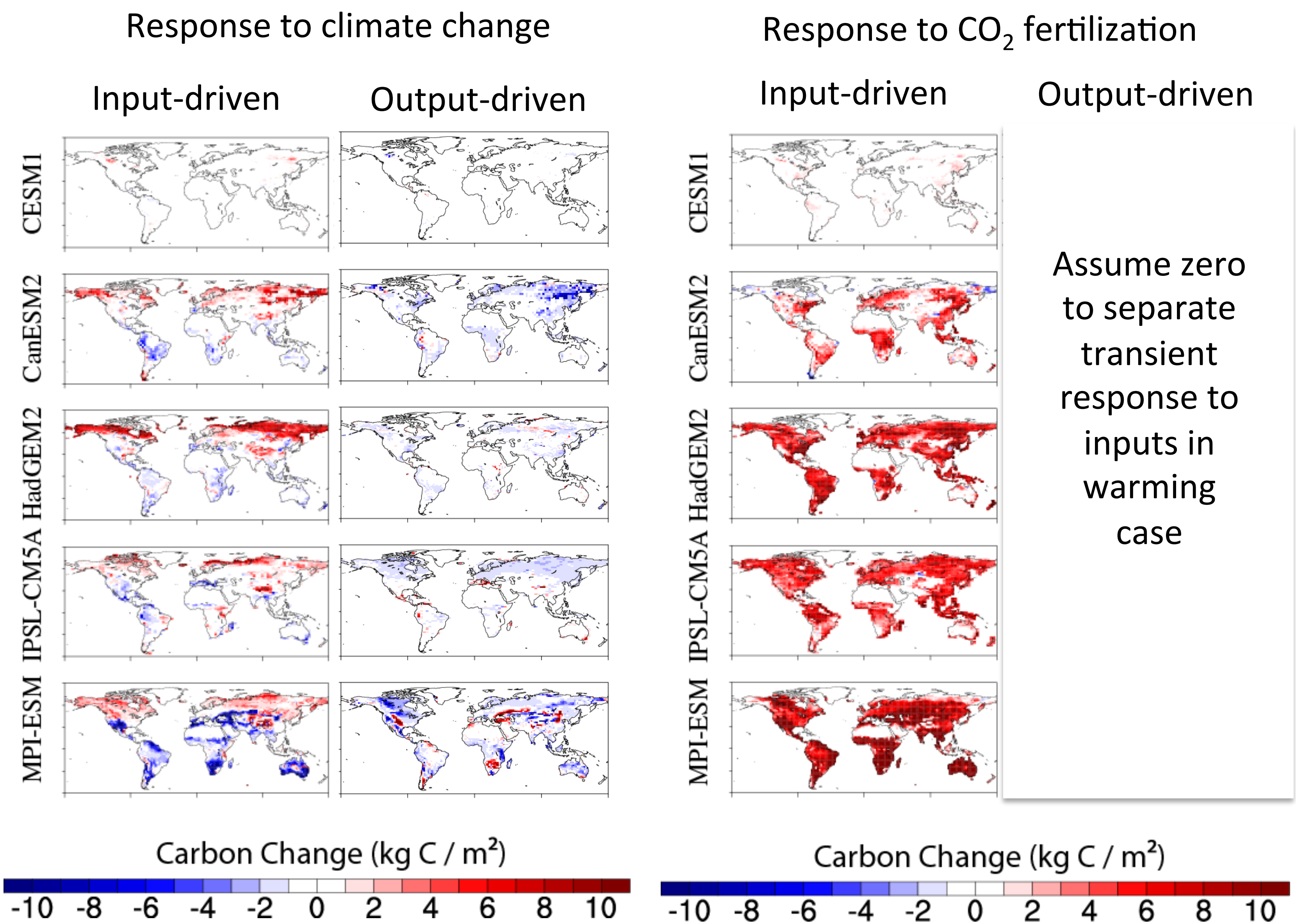
Response to climate change — Input-driven | Output-driven

Response to CO_2 fertilization — Input-driven | Output-driven



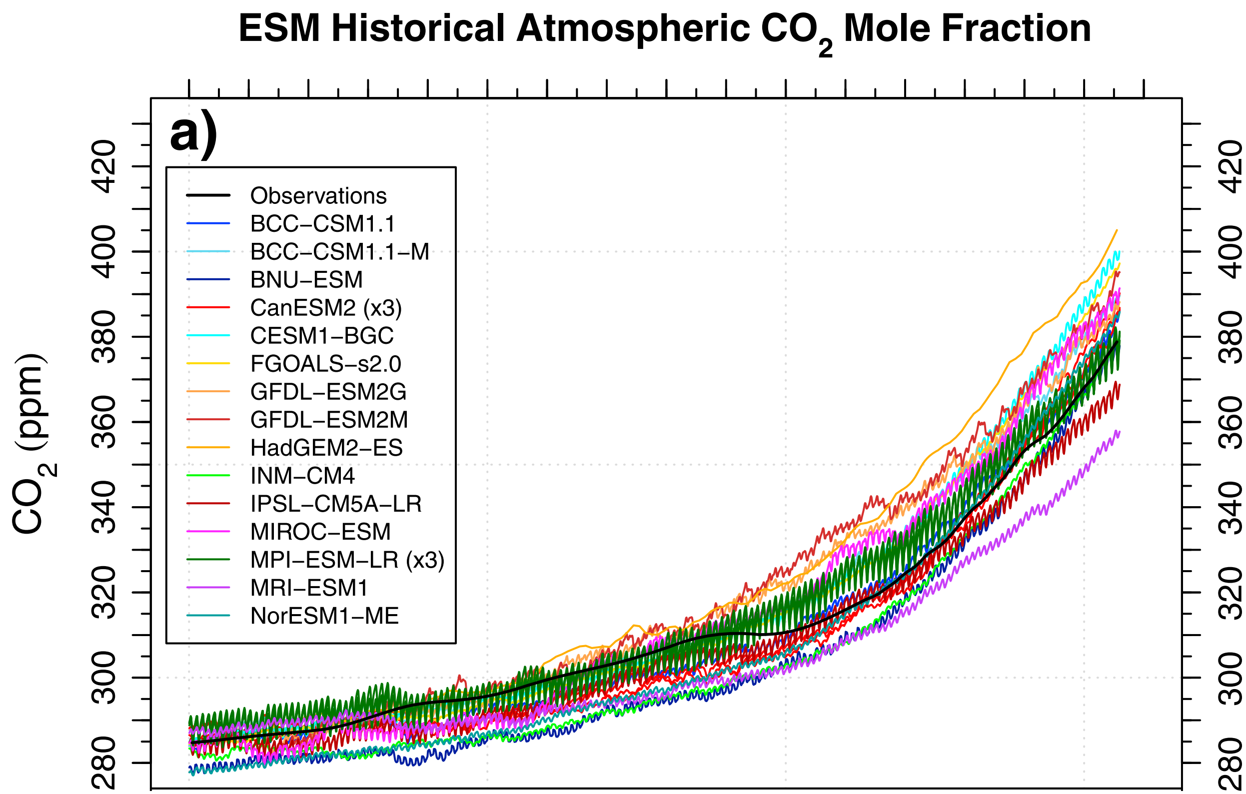
Koven et al., Biogeosciences, 2015

What drives carbon feedbacks: inputs or outputs? 2: Soils



Koven et al., Biogeosciences, 2015

Globally-intregated historical C cycle: models and obs

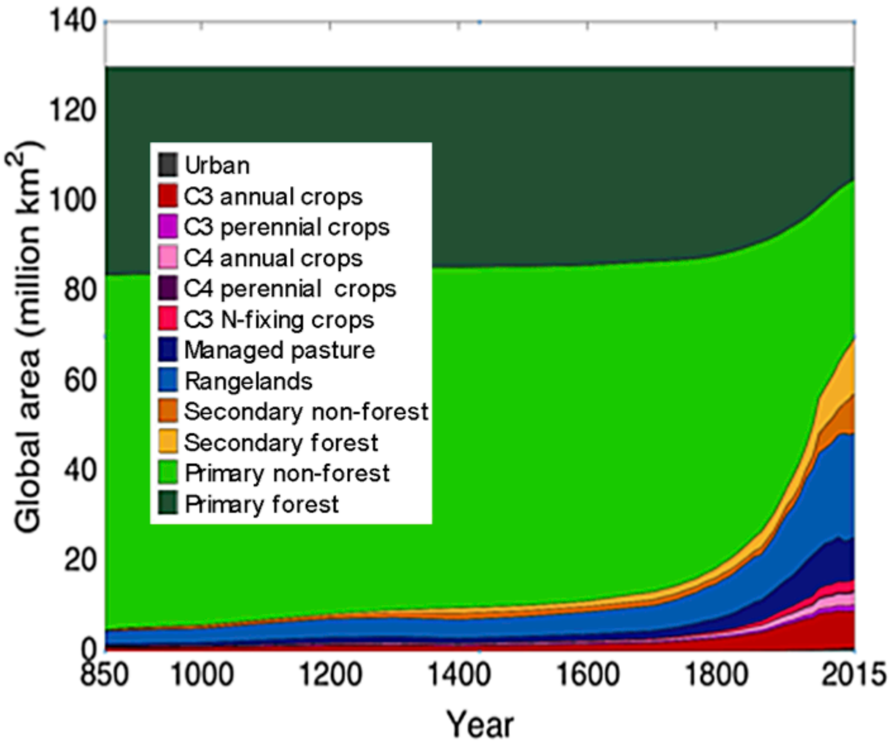


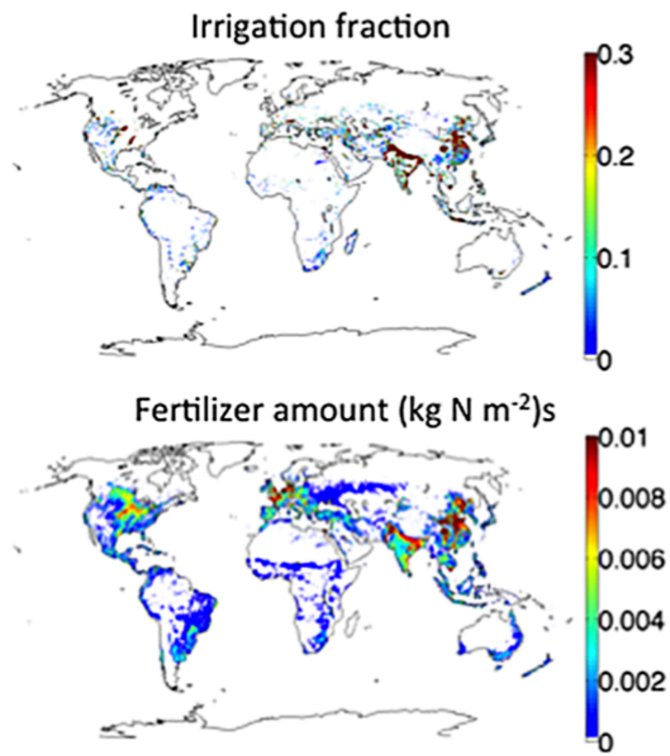
Wide range of CO2 prediction, but models tend to underestimate the combined carbon sinks

Amplitudes of carbon seasonal cycles all over the place

- Hoffman et al., 2014

Idealized feedback experiments ignore the large role played by land use





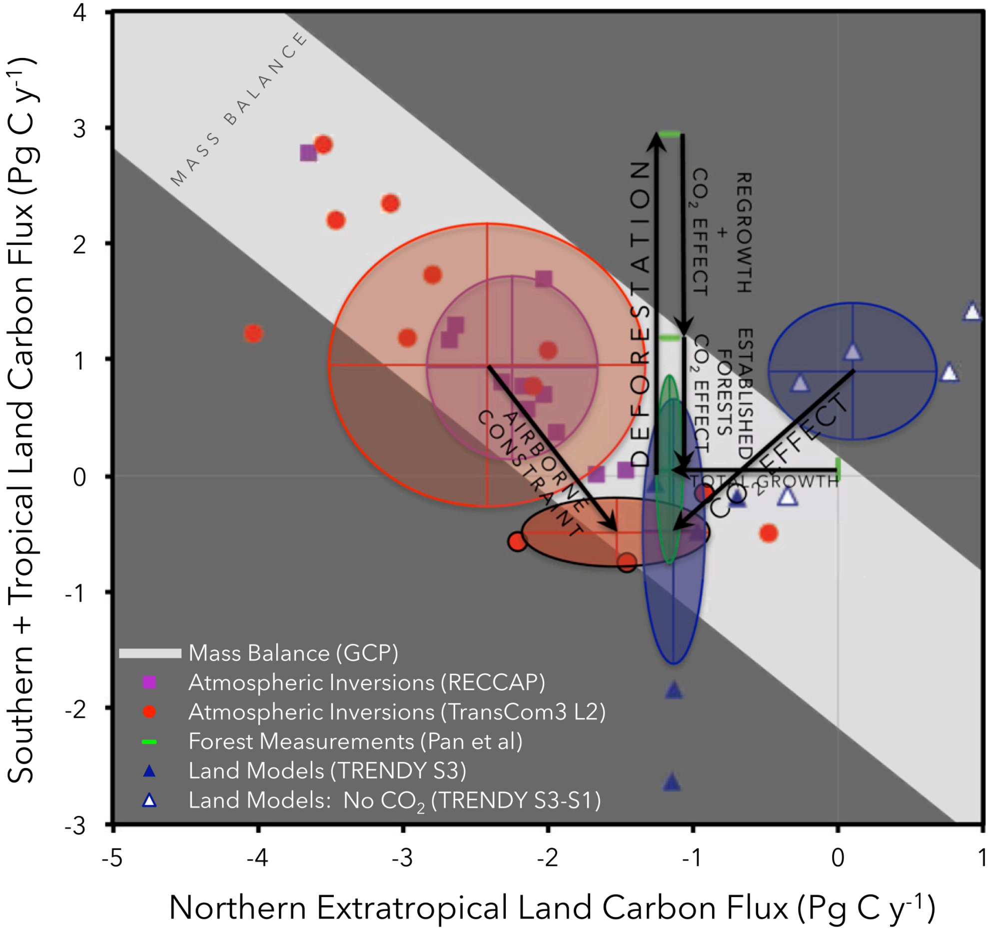
Lawrence et al., 2016

Nonetheless: a recap of the CMIP5-generation model predictions / hypotheses:

1. CO_2 fertilization strong: everywhere but especially in tropical forests
2. Change in biomass basically scales with change in NPP; weak nonlinear effects like self-thinning
3. Change in soil basically scales with change in NPP; no nonlinear soil effects to changing inputs
4. Carbon losses due to warming mainly due to change in NPP: strong losses in NPP in the tropics because of increased VPD
5. Weak feedback due to respiration from warming soils
6. Weak or negligible feedback from vegetation mortality

But: which, if any, of these are correct?

H1: CO_2 fertilization strong: everywhere but especially in tropical forests



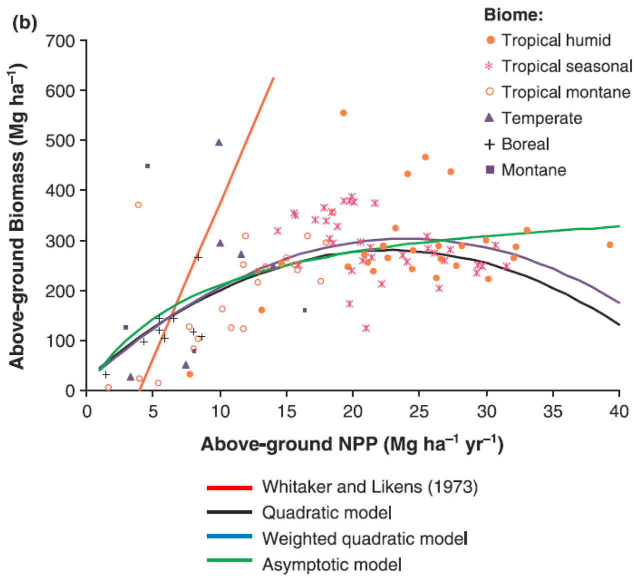
Schimel et al., 2015

Evidence for: rough agreement between atmospheric inversions, forest measurements, and models. Circumstantial but multi-faceted.

Evidence against: models missing key processes like N and P limitations that ought to reduce growth rates (although the models with nutrients tend to overestimate the stoichiometric fixednesss of ecosystems). Fingerprints of fertilization in, e.g., tree rings not obvious.

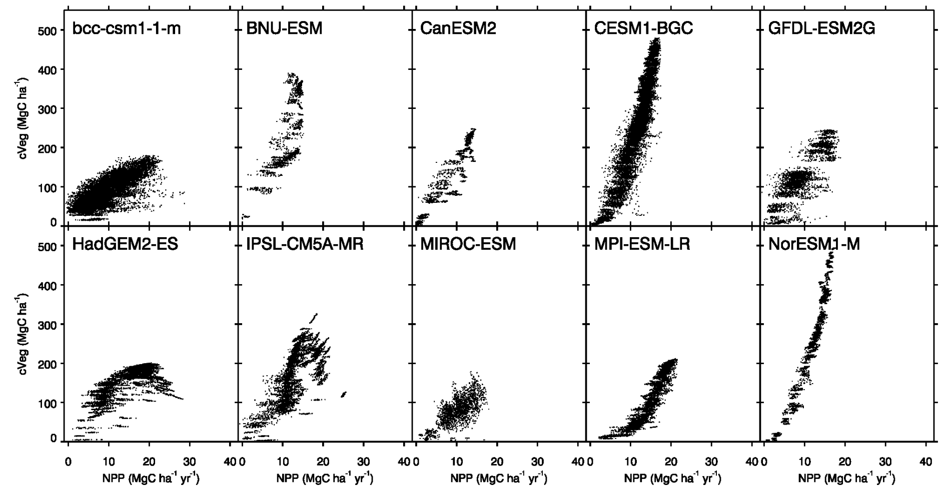
H2: Change in biomass basically scales with change in NPP; weak nonlinear effects like self-thinning

Observations



Keeling and Phillips, 2007

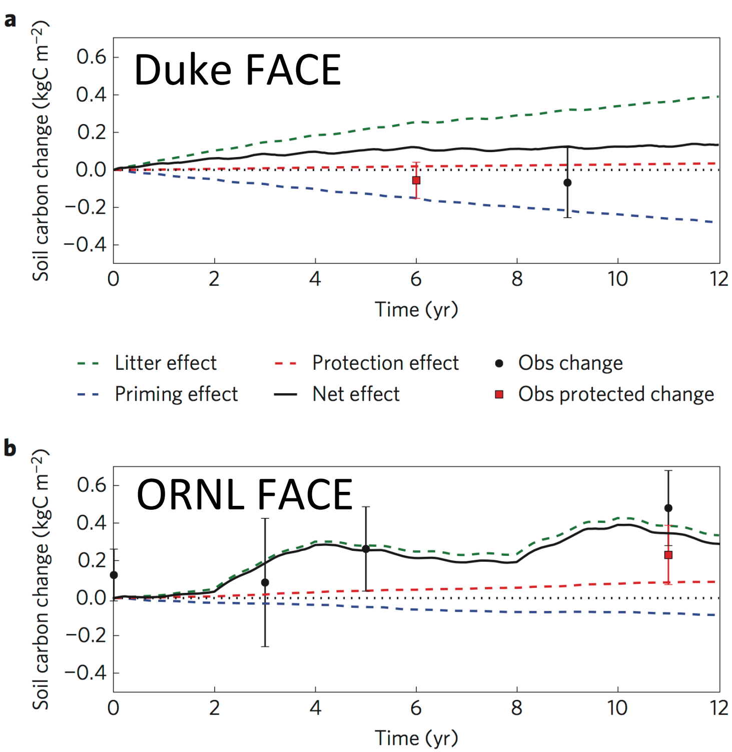
CMIP5 ESMs



Negron-Juarez et al., *2015*

Space-for-time substitution suggests this is wrong. Biomass does not scale linearly with productivity because high-growth forests are also high-mortality forests. Unclear if this also applied to transient case, but need to represent individual and stand-level dynamics in ESMs.

H3: Change in soil basically scales with change in NPP; no nonlinear soil effects to changing inputs

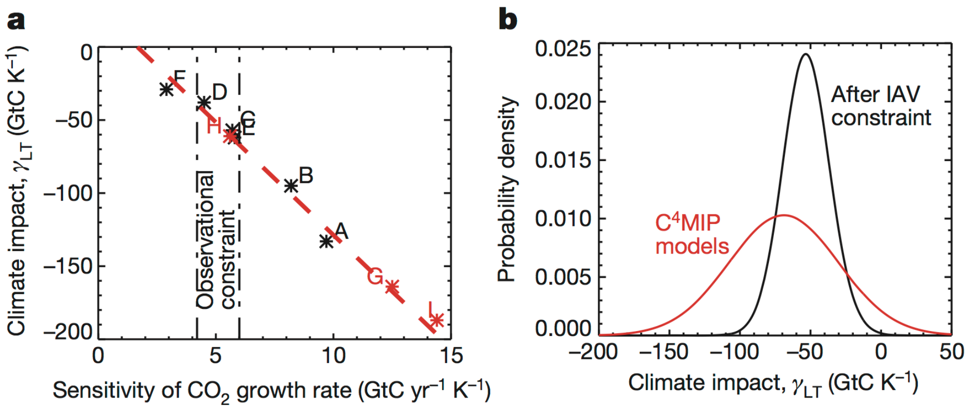


Sulman et al., 2014

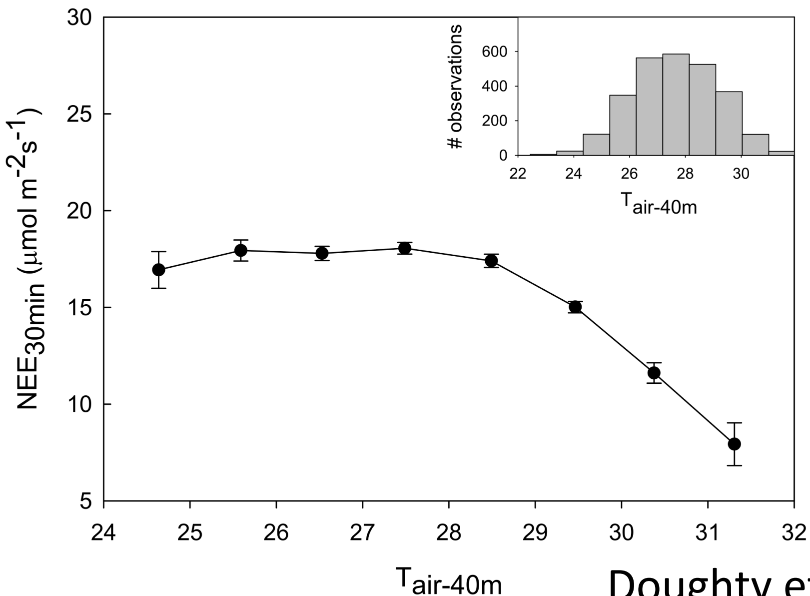
Evidence for: space-for-time substitution does show higher C with higher NPP; transient responses to increased and decreased inputs in agricultural soils; e.g. long-term fallow.

Evidence against: FACE experiments more compatible with a more complex model of enhanced decomposition via microbial priming working against mineral stabilization processes.

H4: Carbon losses due to warming mainly due to change in NPP: strong losses in NPP in the tropics because of increased VPD



Cox et al., 2014

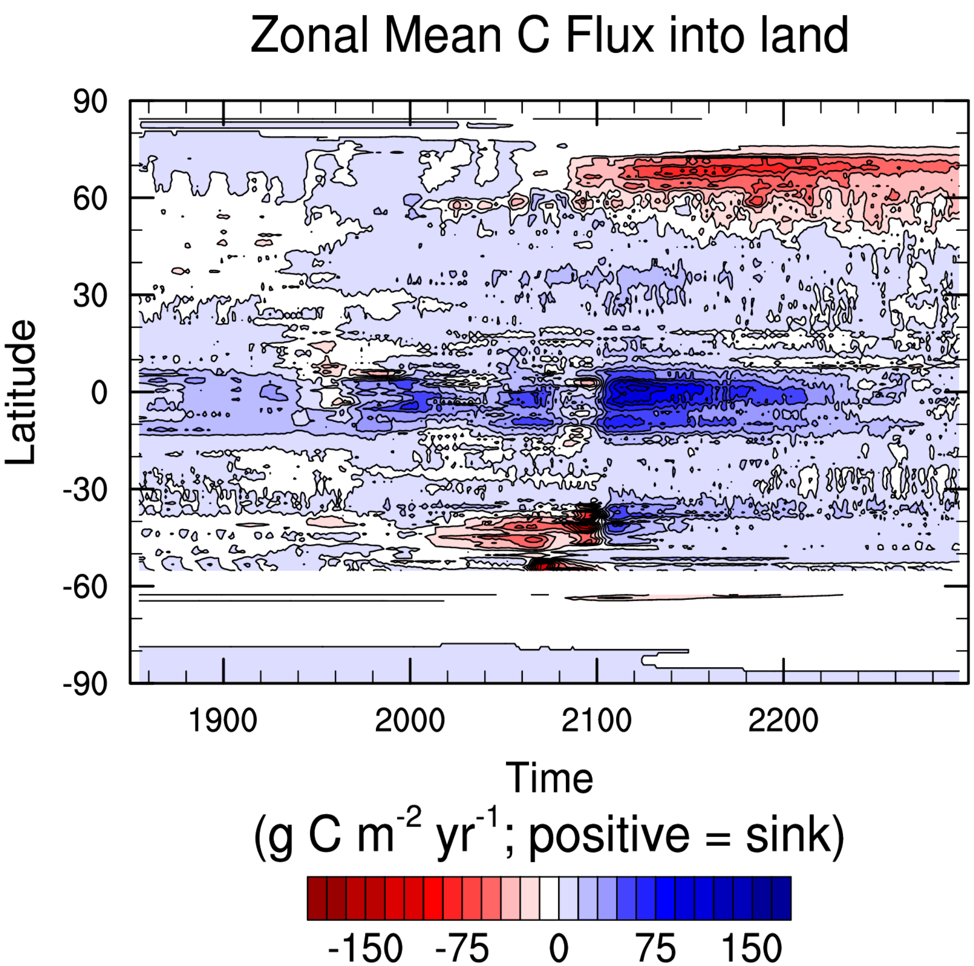


Doughty et al., 2008

Evidence for: Interannual variability constraint (but see Keppel-Aleks 2015); high-frequency leaf-level and canopy-level flux measurements.

Evidence against: tropical forests hugely diverse, which current models don't represent. Quite possible that long-term and short-term dynamics diverge as a result of community-level processes.

H5: Weak feedback due to respiration from warming soils

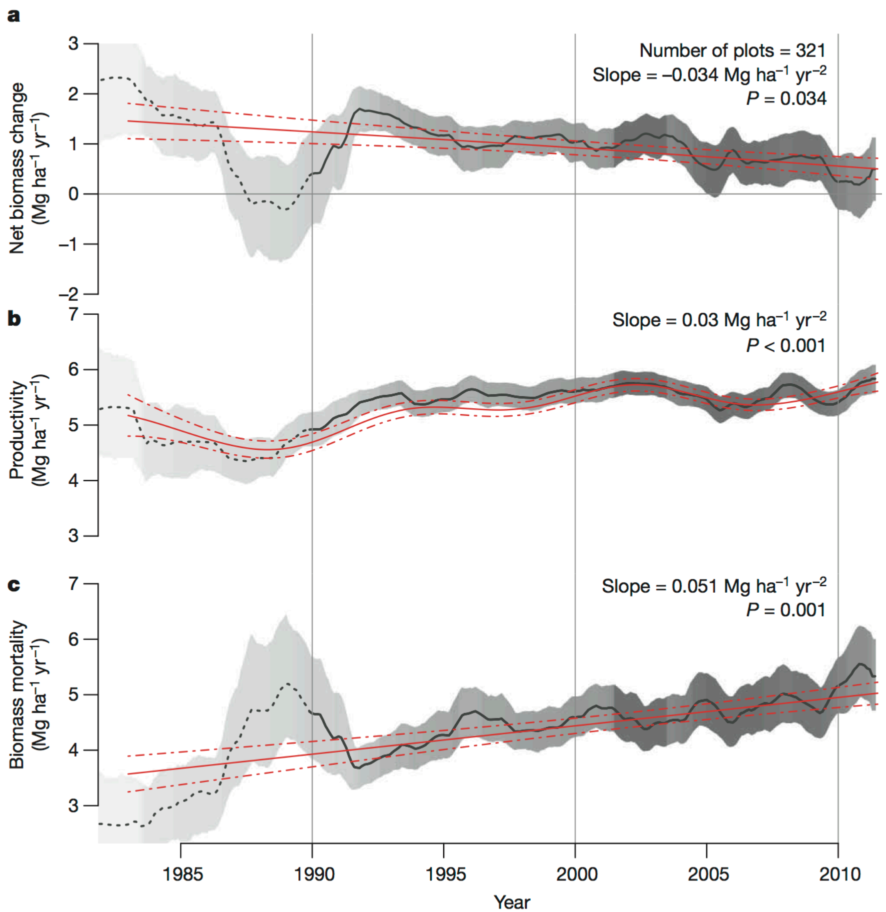


Koven et al., *PNAS*, 2015

Evidence for: On one hand, warming experiments such as that at Harvard Forest show a relatively fast equilibration that suggests microbes may acclimate quickly to warming with little carbon loss.

Evidence against: none of the models used in CMIP5 included any representation of carbon in permafrost, which is the single largest pool in the terrestrial system. Including such a pool qualitatively changes the prediction to large but slow losses from high latitude soils.

H6: Weak or negligible feedback from vegetation mortality



Brienen et al., 2015

Evidence for: None really, most of the models simply don't include the process

Evidence against: observations of increasing mortality in Amazon, western US, elsewhere. But, is this due to environmental stress, or merely increased self-thinning due to CO_2 fertilization?

A recap of the CMIP5-generation model predictions / hypotheses:

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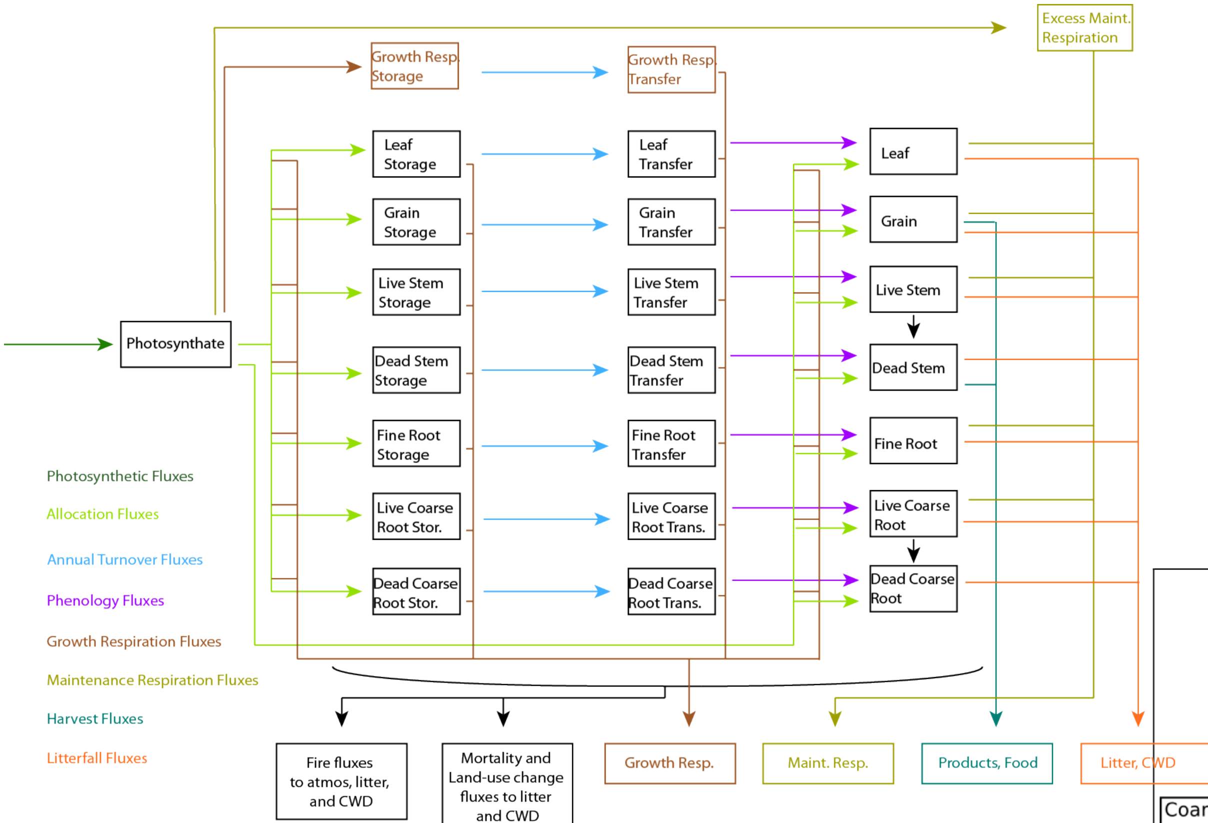
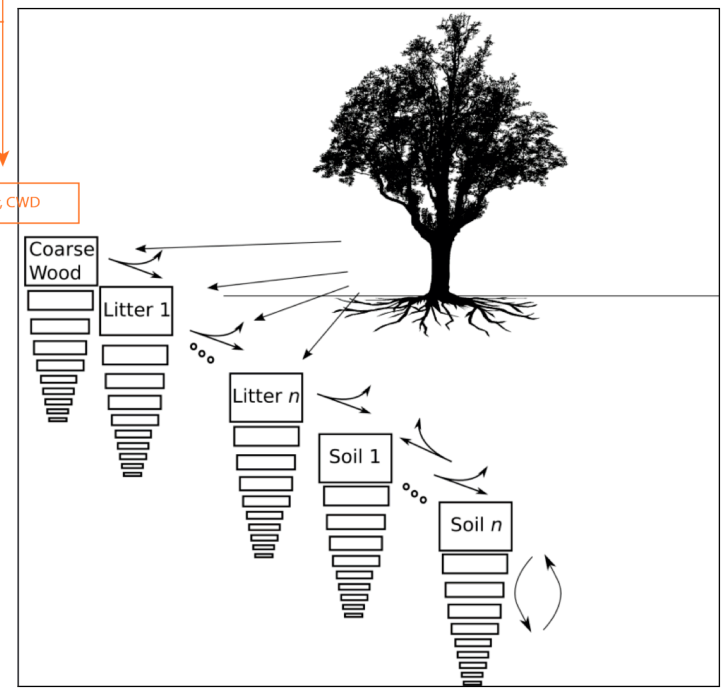
C isotopes as observable diagnostics of model behaviors

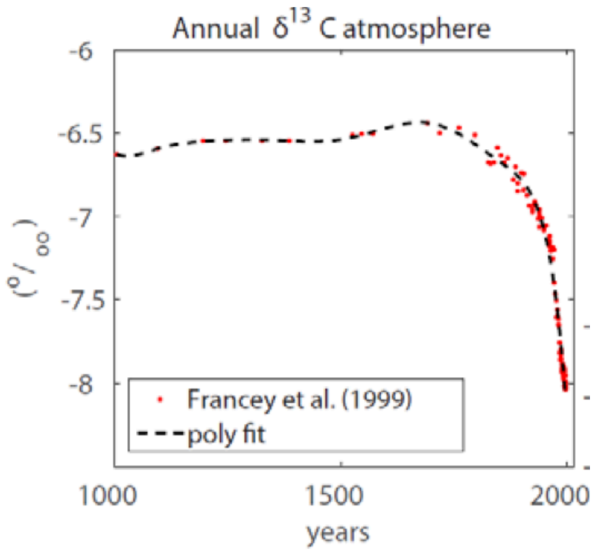




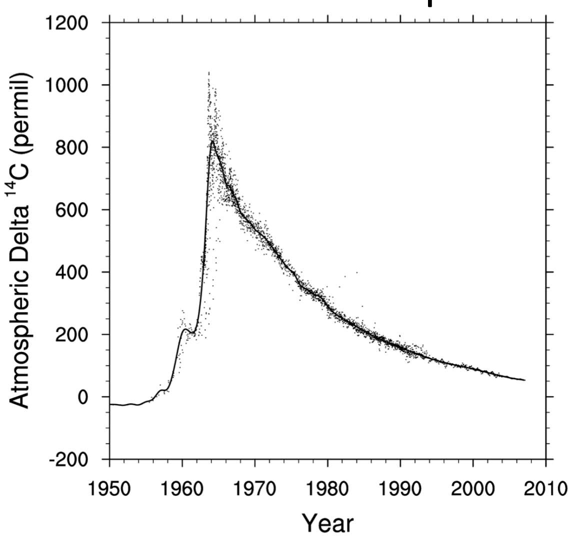
CLM4.5 and CLM5 include ability to enable 2nd and/or 3rd instance of entire C cycle, including all pools and fluxes, for isotope calculations. These have no effect on the overall behavior of the model but may be useful to diagnose and benchmark model.

4 basic use cases for C isotopes in CLM

1: Dole Effect



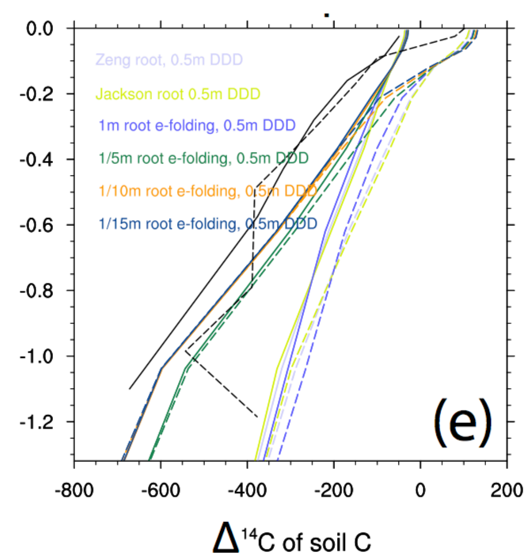
2: ^{14}C bomb spike



3: ^{13}C photosynthetic fractionation

$$\alpha_{psn} = 1 + \frac{4.4 + 22.6\,\frac{c_i^*}{c_a}}{1000}$$

4: ^{14}C natural abundance



To use isotopes in CLM:

- Enable them via the namelist flags: use_c14, use_c13
- Ensure that transient isotopic forcing data is present and looks like it should. The bomb spike file should auto-load by default but the 13C Dole effect file is (I don't think) default.
- Spin up with isotopes on and proceed. Radioactive decay of ^{14}C is also accelerated during AD spinup, so as to allow rapid equilibration of old ^{14}C pools (see Koven et al, Biogeosciences, 2013 for details).

A few things to be aware of with respect to isotopes in CLM

- No post-photosynthetic fractionation (though his could be added easily enough)
- Nighttime autotrophic respiration currently uses credit-card rather than debit-card accounting. This is unfortunately necessary at present, but it messes with the isotopic signature of Ra. (see Duarte et al., *in prep*)
- CLM4.5 and prior used a 2-step N downregulation of GPP, which made the GPP flux inconsistent with the Ci/Ca and transpiration fluxes. This leads to weird isotopic issues (see Raczka et al., Biogeosciences 2016) but *should* be corrected in CLM5, which uses a foliar limitation paradigm.
- No photosynthetic fractionation applied to ^{14}C. This is by design to simplify the math such that $\Delta^{14}C = \partial^{14}C$. But don't try to double-correct the ^{14}C when converting into Δ units.