Land carbon sink uncertainty in mitigation scenarios: Towards an emissions-driven coupled perturbed parameter mini-ensemble with CESM

David Lawrence, Linnia Hawkins, Charlie Koven, Rosie Fisher, Peter Lawrence, Abby Swann, Daniel Kennedy, Katie Dagon, Forrest Hoffman, Nate Collier, Keith Lindsay, and others

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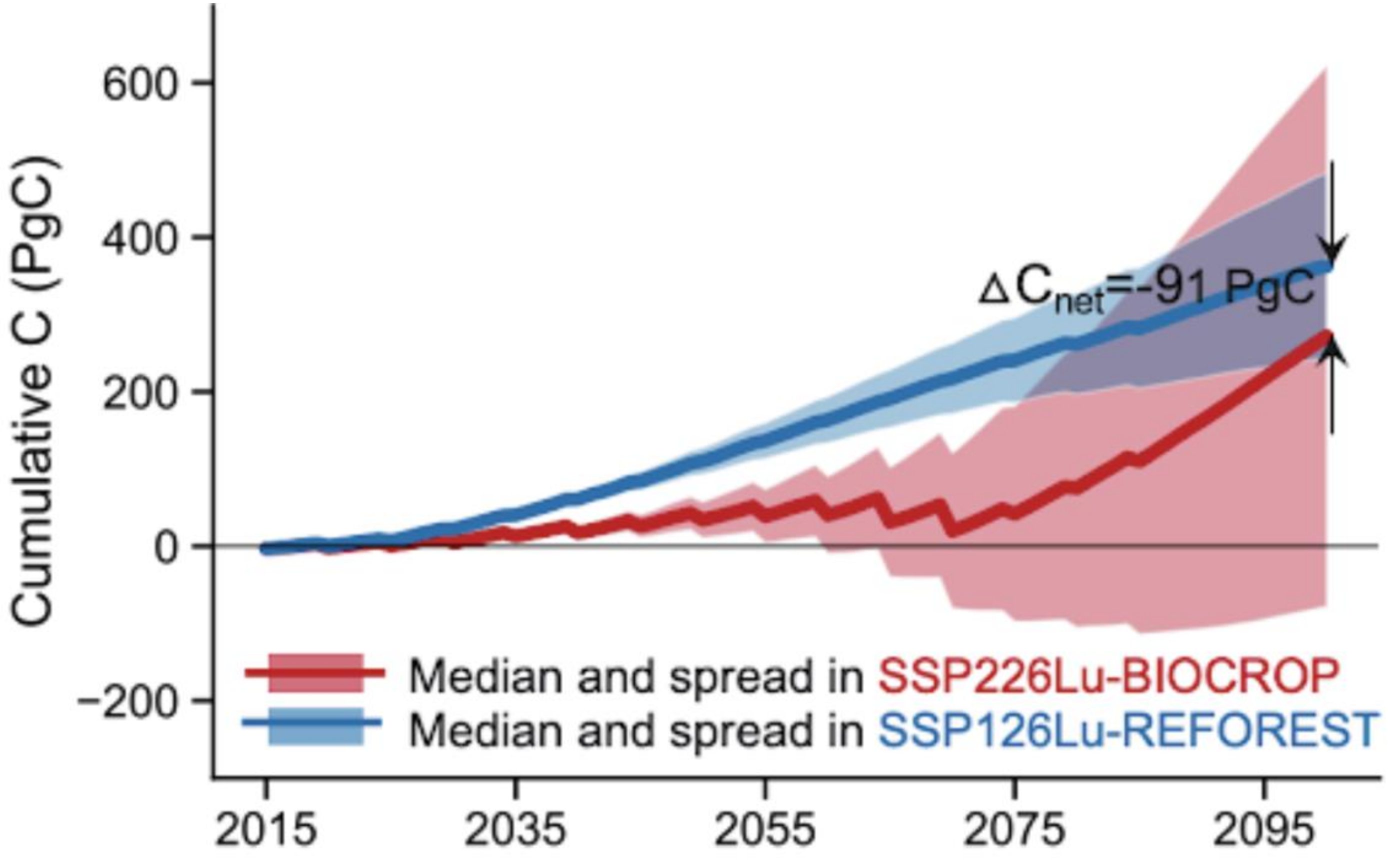
Image: Joel Vodell

- Land-based mitigation strategies (e.g., reforestation, BECCS) are likely required to achieve 1.5º C or 2º C climate targets
- Potential to mitigate approximately 10–15 $GtCO_2eq\ yr^{-1}$ by 2050, about 20%–30% of the mitigation needed to achieve the 1.5°C temperature target (Roe et al., 2019)

But, many open questions, e.g.:

- Will the natural terrestrial carbon sink (which is very uncertain anyway) persist?
- Parametric and structural uncertainty?
- Where we can effectively plant trees to store carbon?
- Will BECCS will work without interfering with food production?
- What are climate feedbacks?

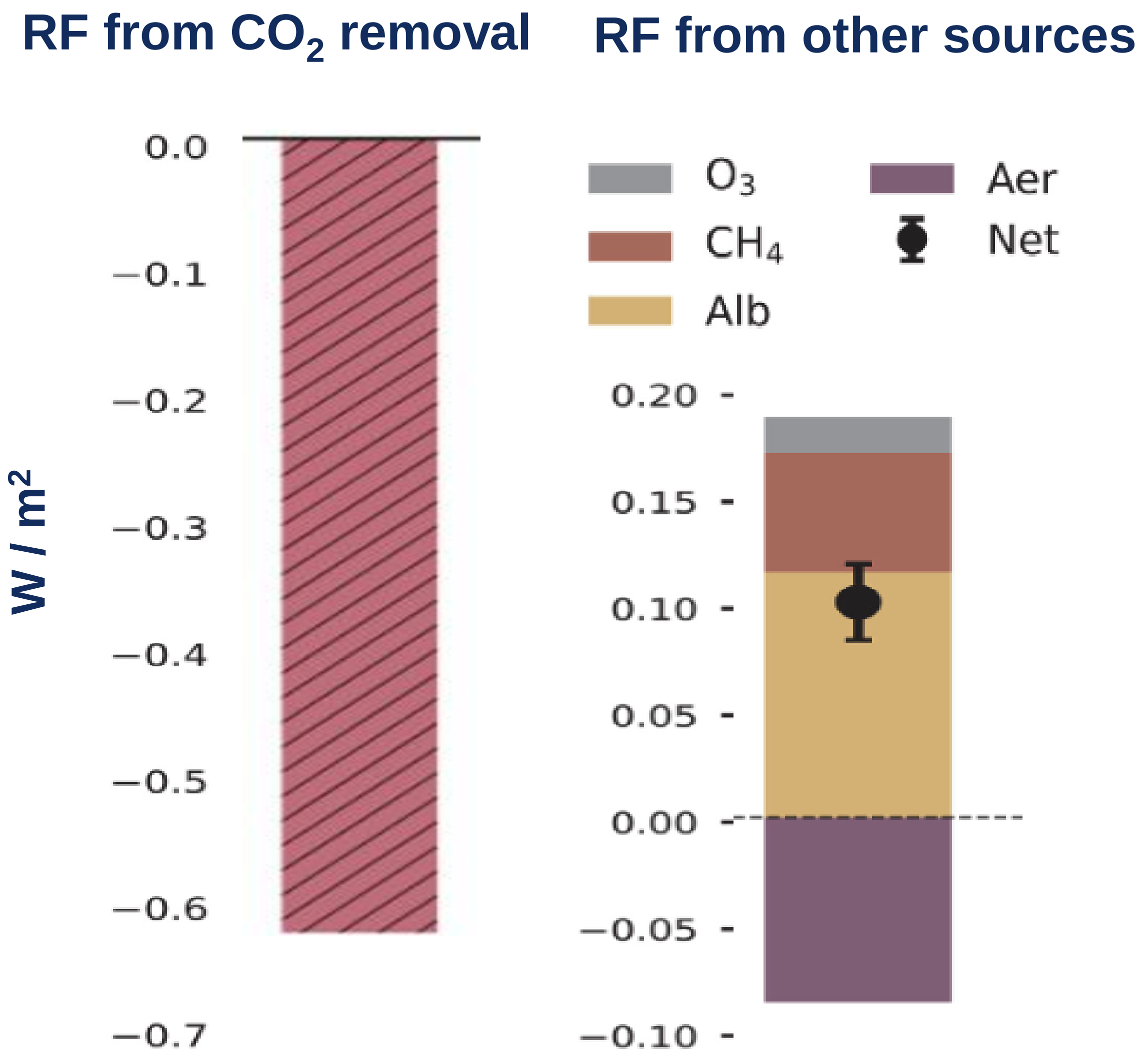
Effective land C sink, including BECCS



The high spread with BECCS reflects uncertainties in future biomass yield, energy conversion technology, and CCS effectiveness

Cheng et al., PNAS (2024)

Earth System response to reforestation is complex



Full understanding of impacts of reforestation requires ESM

In CESM2 experiments, the direct radiative forcing (RF) from CO_2 removal is offset by changes in albedo and BVOC emissions and their impact on ozone, methane, and aerosol burdens

Science

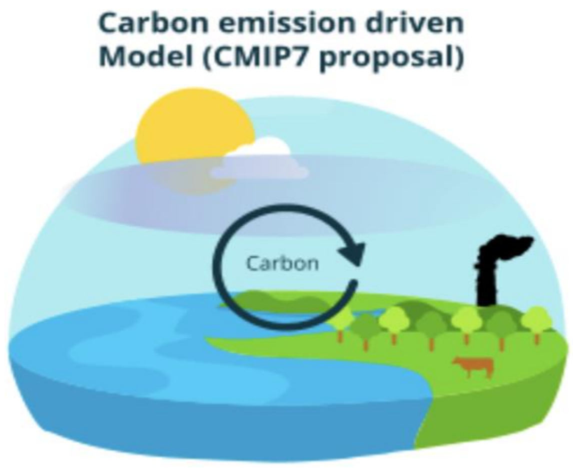
Chemistry-albedo feedbacks offset up to a third of forestation's CO_2 removal benefits

JAMES WEBER, JAMES A. KING, NATHAN LUKE ABRAHAM, DANIEL P. GROSVENOR, CHRISTOPHER J. SMITH, YOUNGSUB MATTHEW SHIN, PETER LAWRENCE, STEPHANIE ROE, DAVID J. BEERLING, AND MARIA VAL MARTIN Authors Info & Affiliations

Building a CESM2 (and CESM3) configuration for carbon mitigation research

More comprehensive representation of processes and feedbacks relevant for mitigation scenarios

- **Emissions-driven**
- **Interactive fire and fire emissions**
- **Interactive BVOC emissions**
- **Treatment of BECCS**
  - Switchgrass, miscanthus crops (Cheng et al., 2019)
  - *New biomass energy crop product pools (1-yr slash and 1000-yr storage)*
  - *BECCS technology trend coefficient*
  - *Remove negative BECCS emissions from CO_2 emissions files*



Sanderson et al, in review

Image: BC Wildfire Service/Handout

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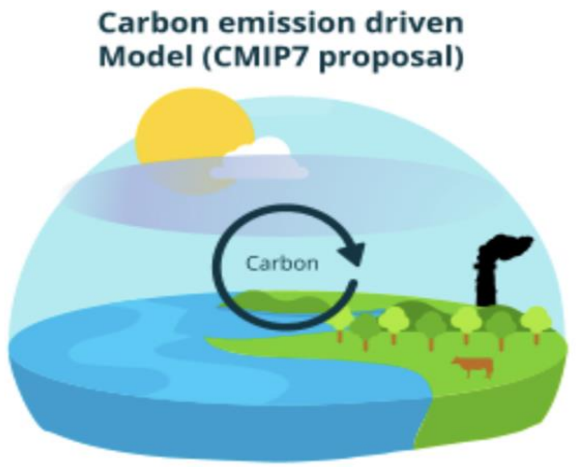

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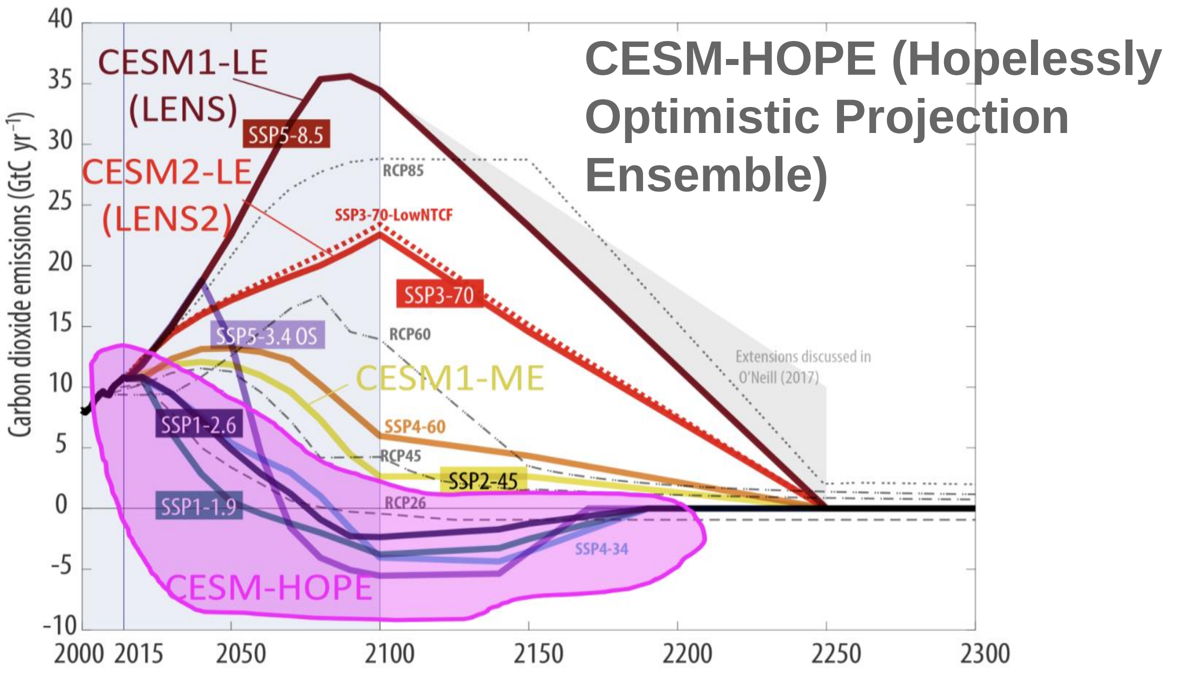


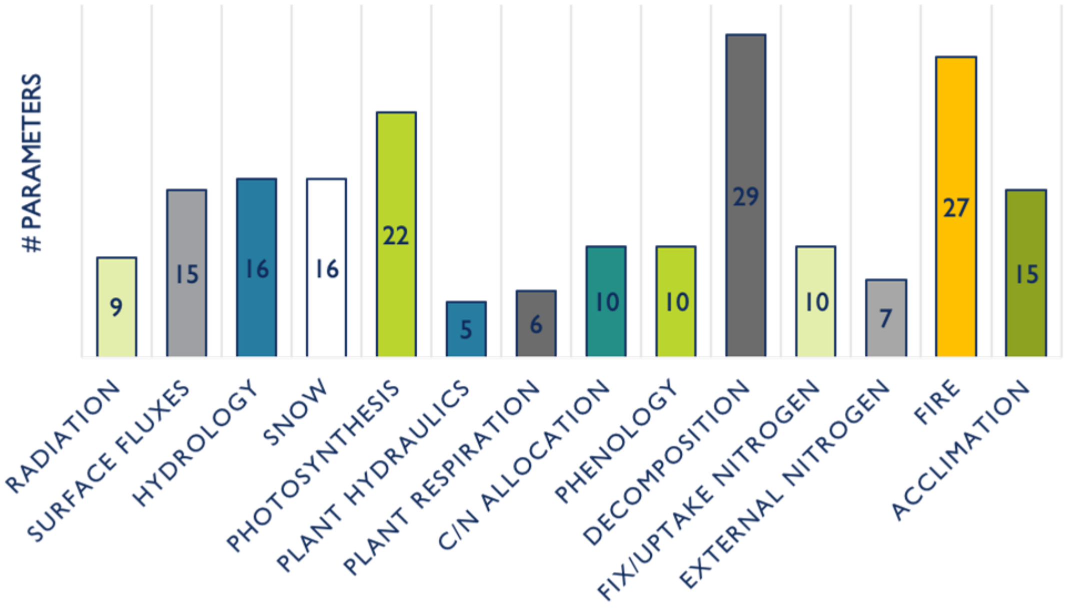
CLM5 Perturbed Parameter Ensemble Project

- **Phase 0:** Infrastructure development (fast spinup, expose parameters, identify parameter ranges, ensemble and analysis scripting)
- **Phase 1:** One-at-a-time parameter ensembles under range of environmental perturbations (low/high CO_2, PI and future climate, N-dep)

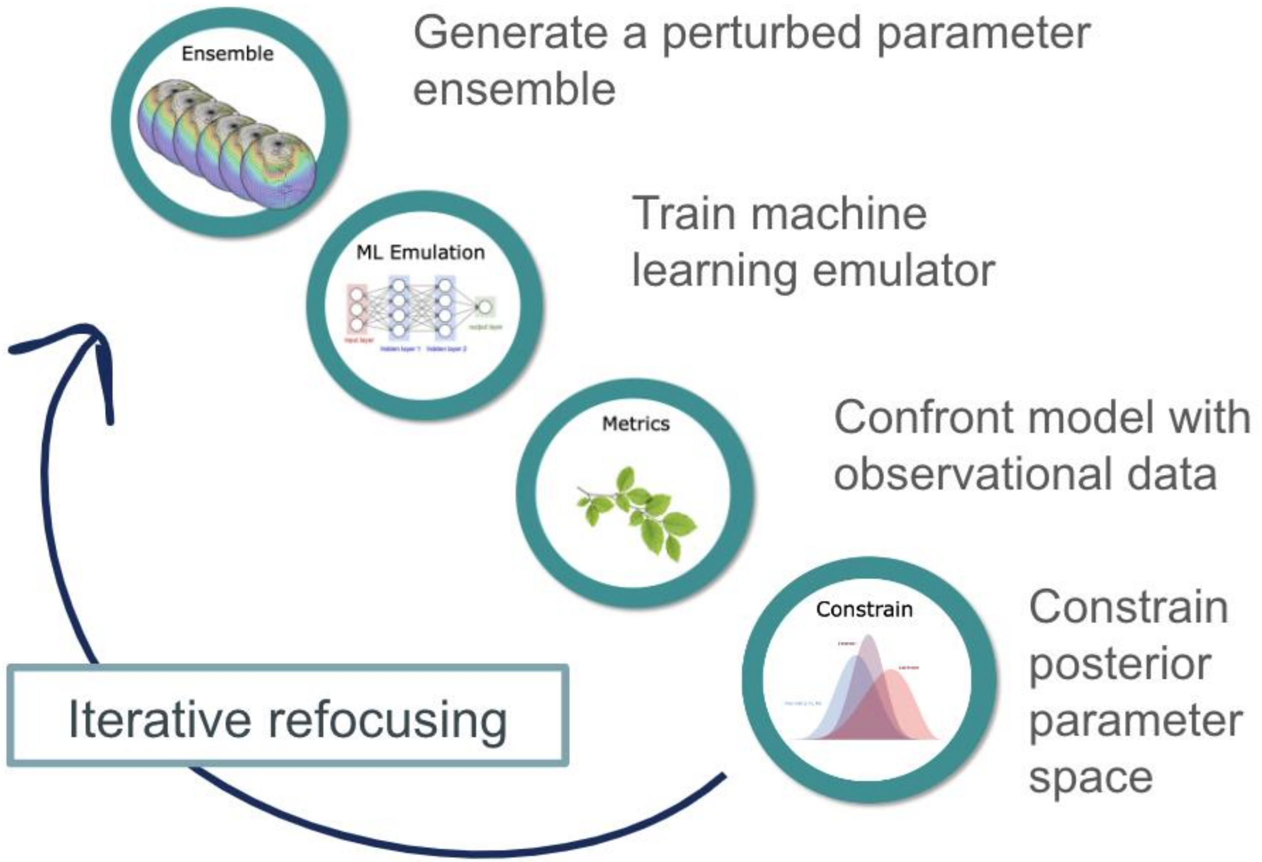
CLM PPE Spinoff Projects

- Land-atmosphere interactions (Univ Washington)
- NEON site calibration (Auburn Univ)
- ET recession timescales (Oregon State)
- Arctic river flow (RAL)
- Land influence on drought (CGD)
- Hydrologic sensitivity (Cornell Univ)
- Tropical carbon cycle interannual variability (JPL)
- GPP response to permafrost thaw (Northern Arizona U)
- …

CLM5 has over 200 parameters



Towards global parameter calibration (testing with LAI calibration)



Important params for Leaf Area Index

Parameter	Param type
jmaxb0	Photosynthesis
jmaxb1	
wc2wjb0	
theta_cj	
leafcn (PFT)	
jmaxha	
tpu25ratio	
hksat_sf	Soil hydrology
fff	
sucsat_sf	
d_max	
kmax (PFT)	Plant water use
medlynslope (PFT)	
medlynintercept (PFT)	
crit_dayl	Phenology
soilpsi_off	
leaf_long (PFT)	Leaf physiology
slatop (PFT)	
lmr_intercept_atkin	Respiration
lmrha	
froot_leaf (PFT)	Allocation
FUN_fracfixers (PFT)	Nitrogen uptake
pc	Snow

LEAP

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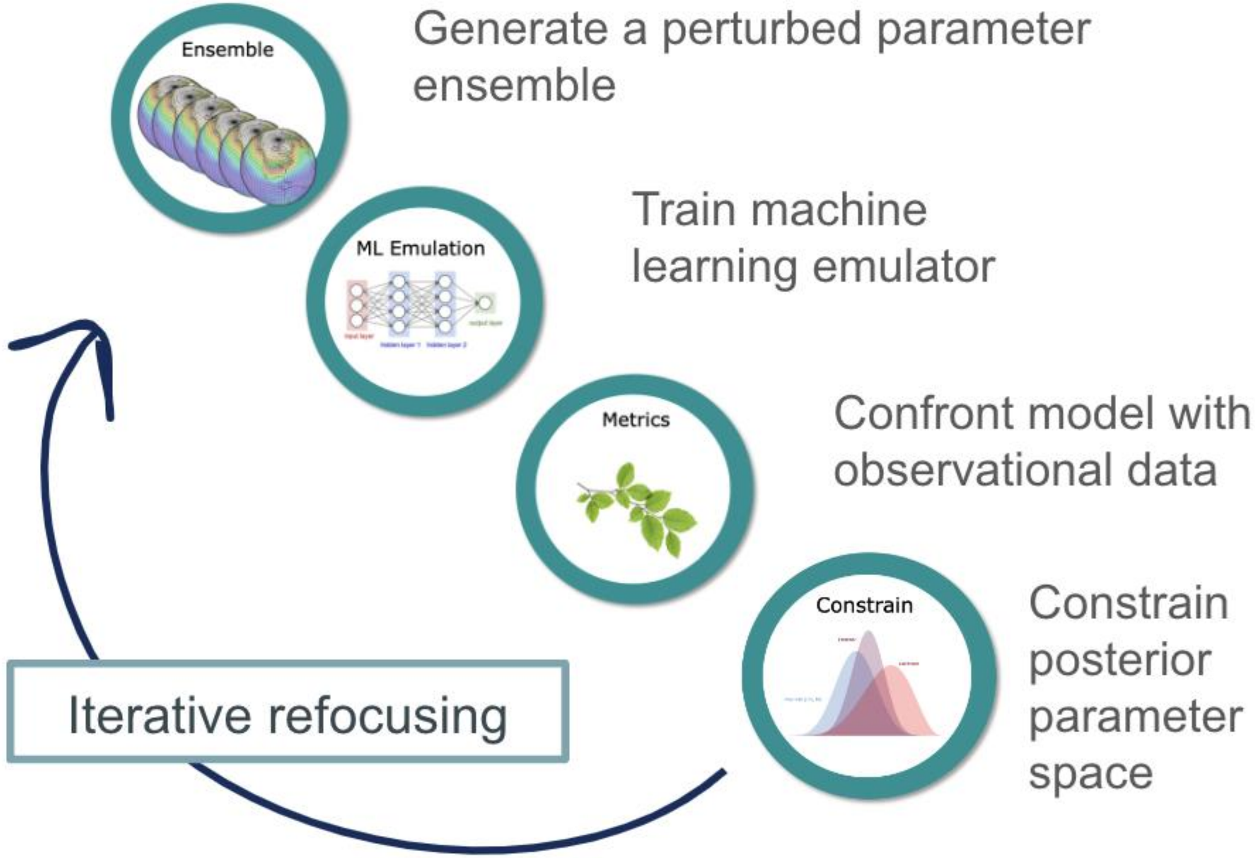
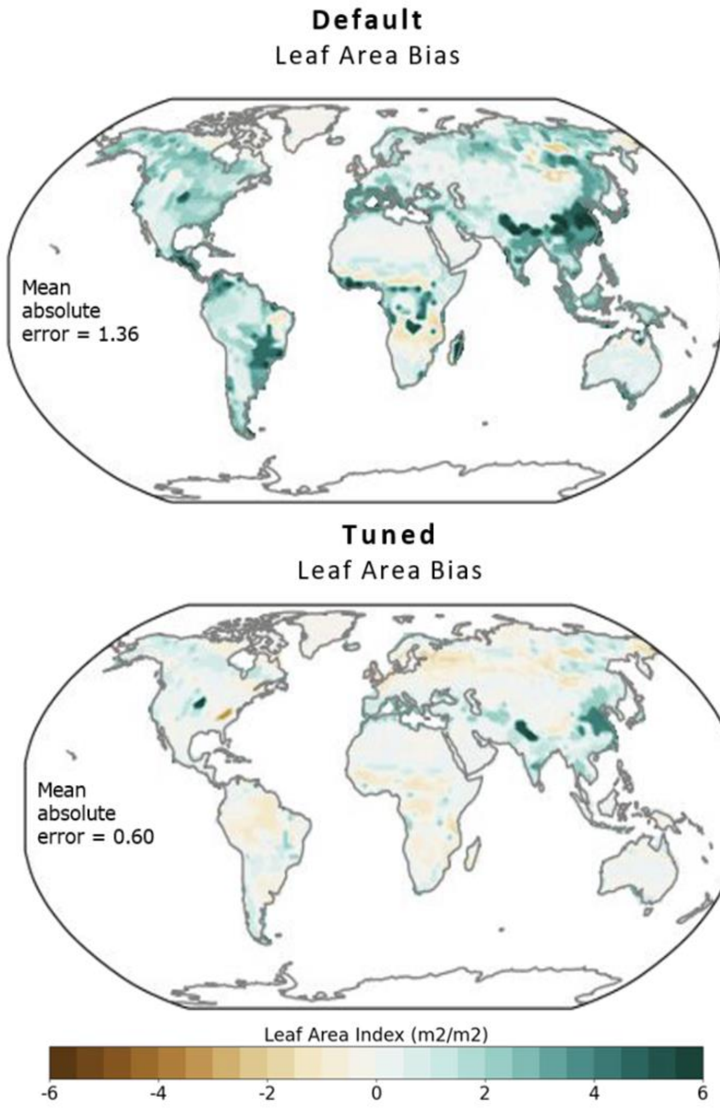
Towards global parameter calibration (testing with LAI calibration)

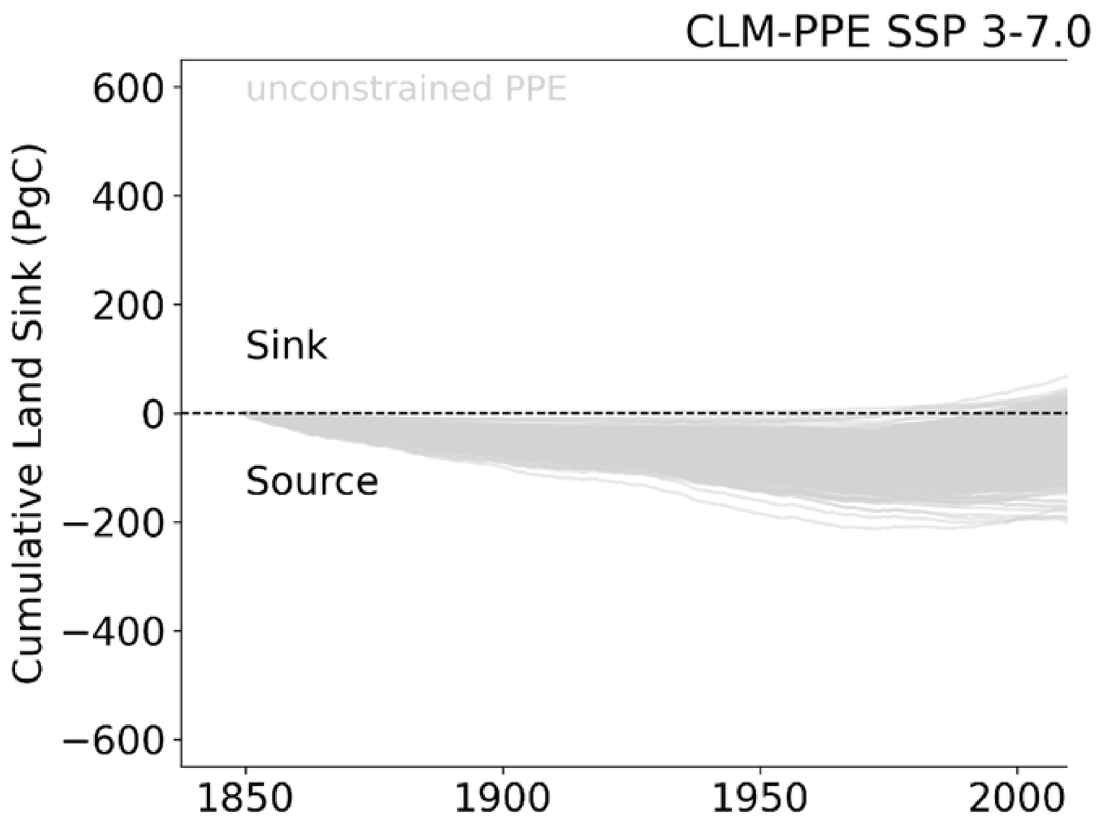




LEAP

Constraining land carbon cycle projections

500 land-only simulations with Latin Hypercube generated parameter sets (25 parameters)



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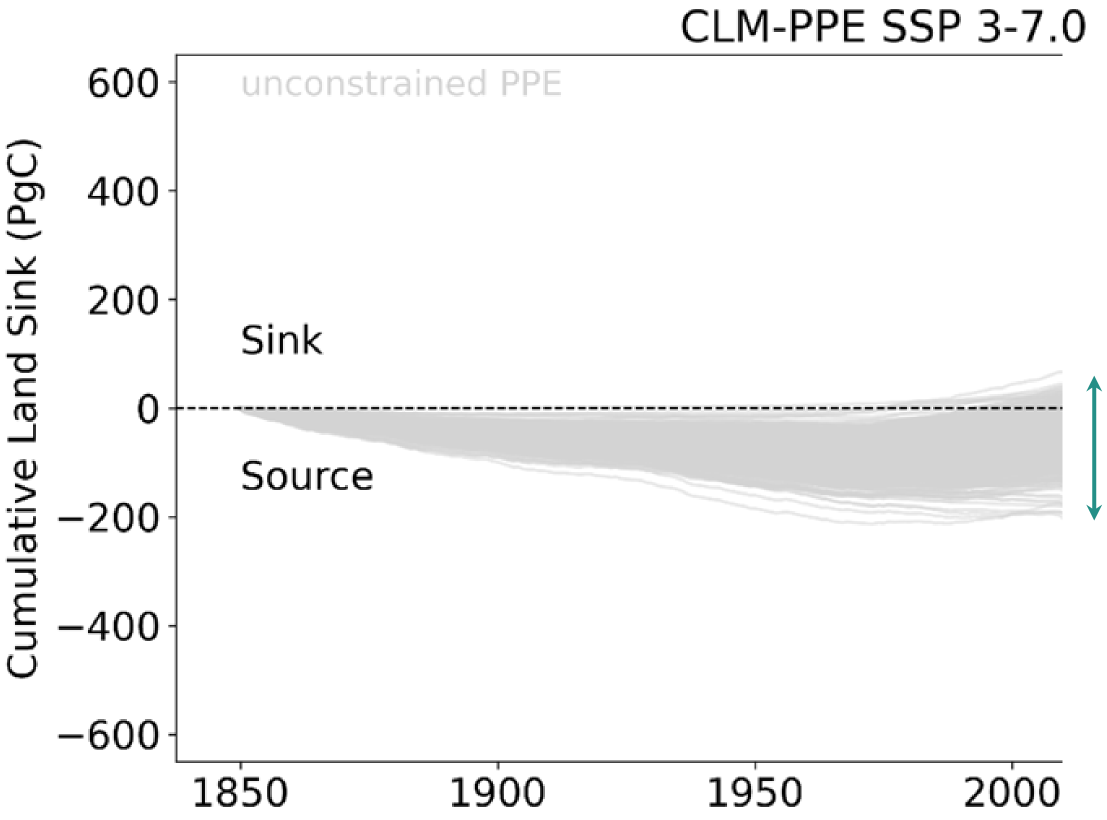
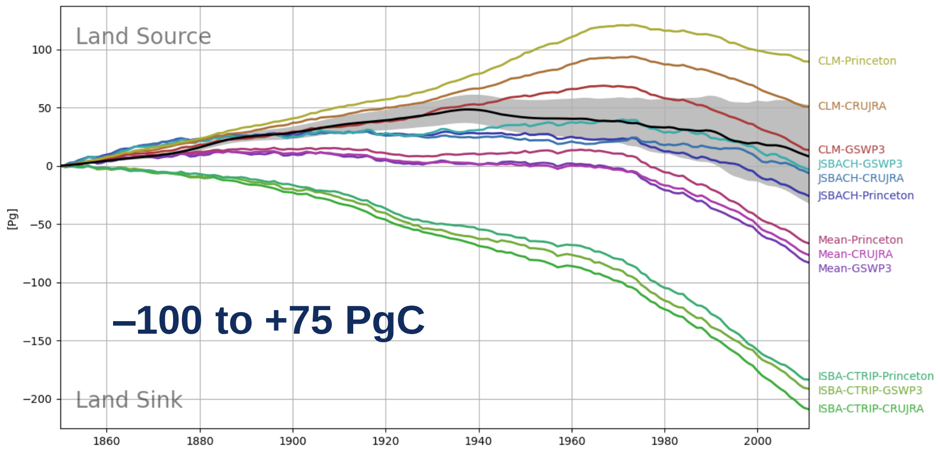


–200 to +50 PgC

Land-only CMIP6 (ILAMB)



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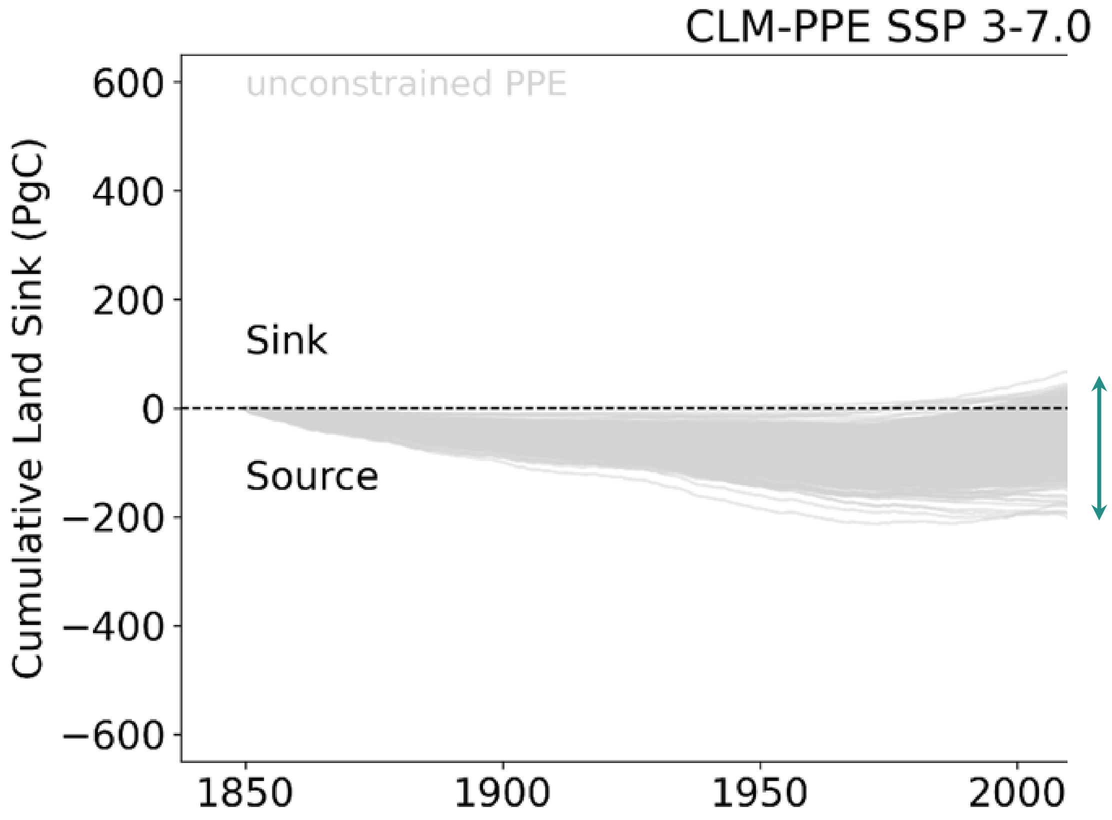

–200 to +50 PgC

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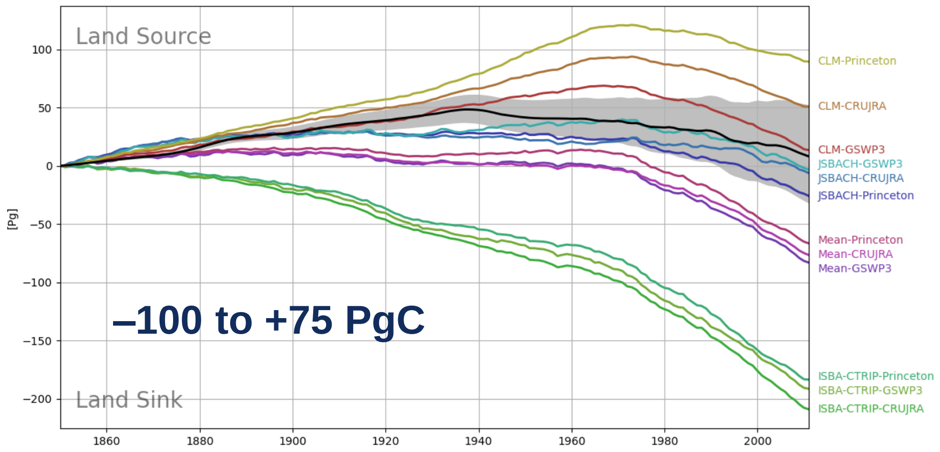

–100 to +75 PgC

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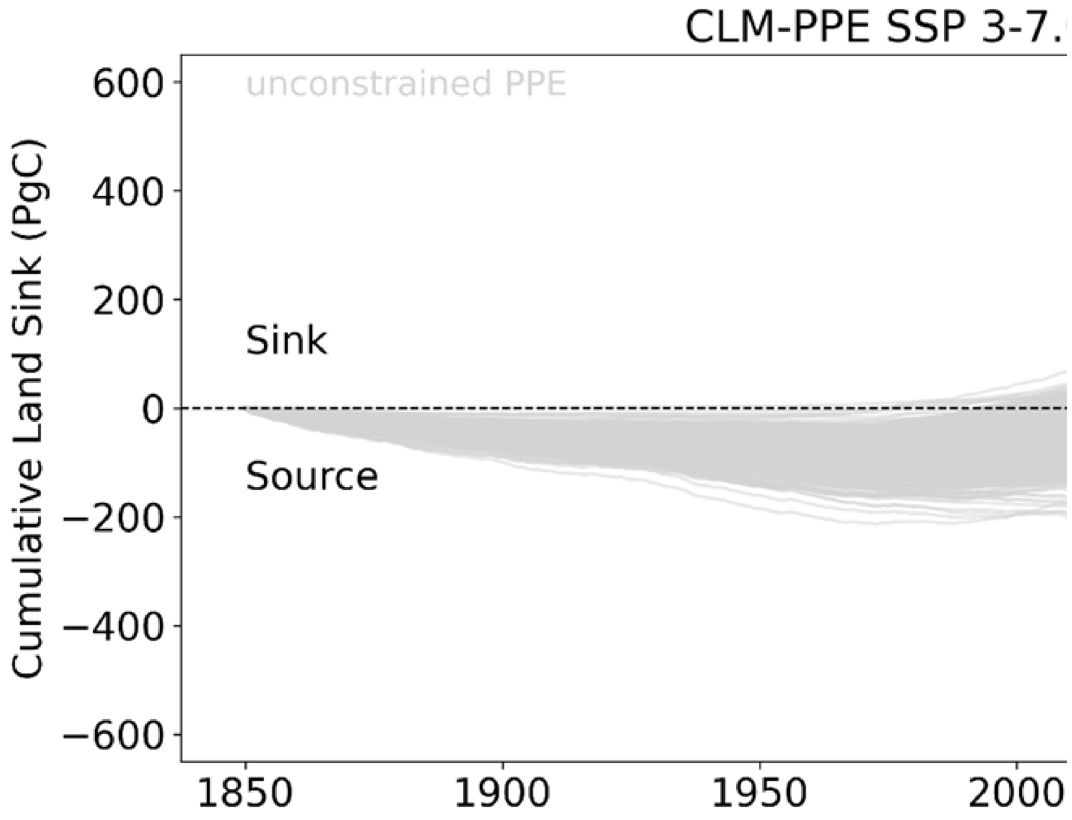

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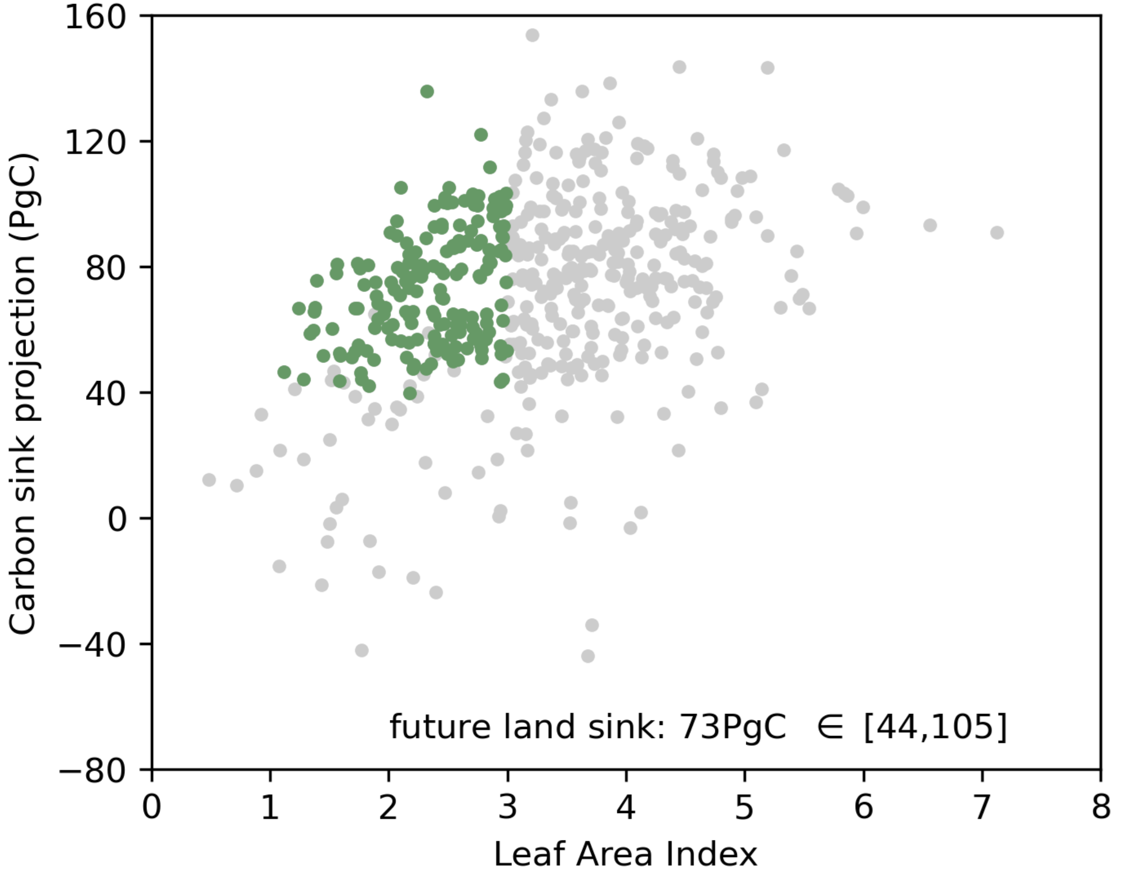
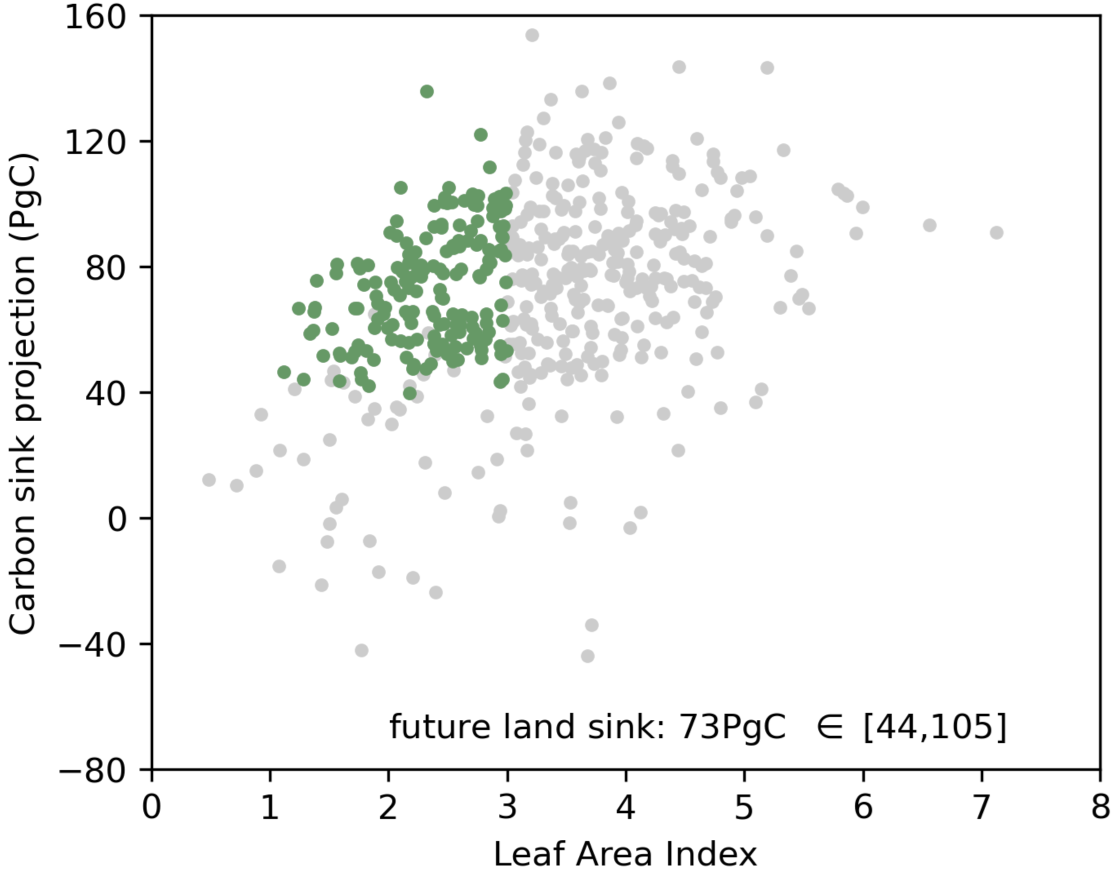


Can we constrain by retaining only parameter sets with reasonable values for 'observed' quantities?

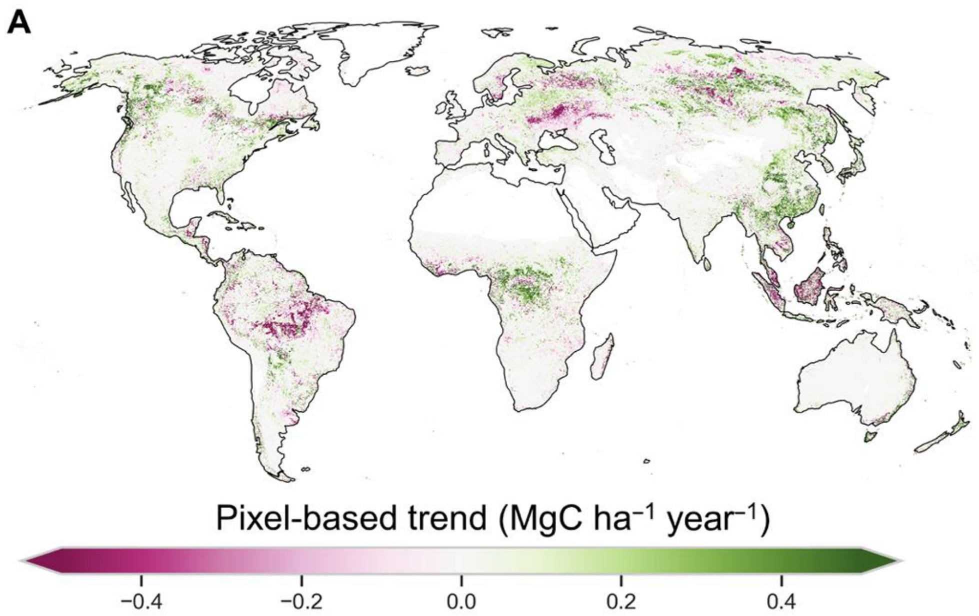
- leaf area index mean / trend

Constraining land carbon cycle projections



Can we constrain by retaining only parameter sets with reasonable values for ‘observed’ quantities?

- leaf area index mean / trend
- total land use flux (e.g., from bookkeeping models)
- radiocarbon NPP constraint (Graven et al., 2024)
- recent changes in live woody biomass from inventories/satellite (Xu et al, 2021)



Constraining land carbon cycle projections

500 land-only simulations
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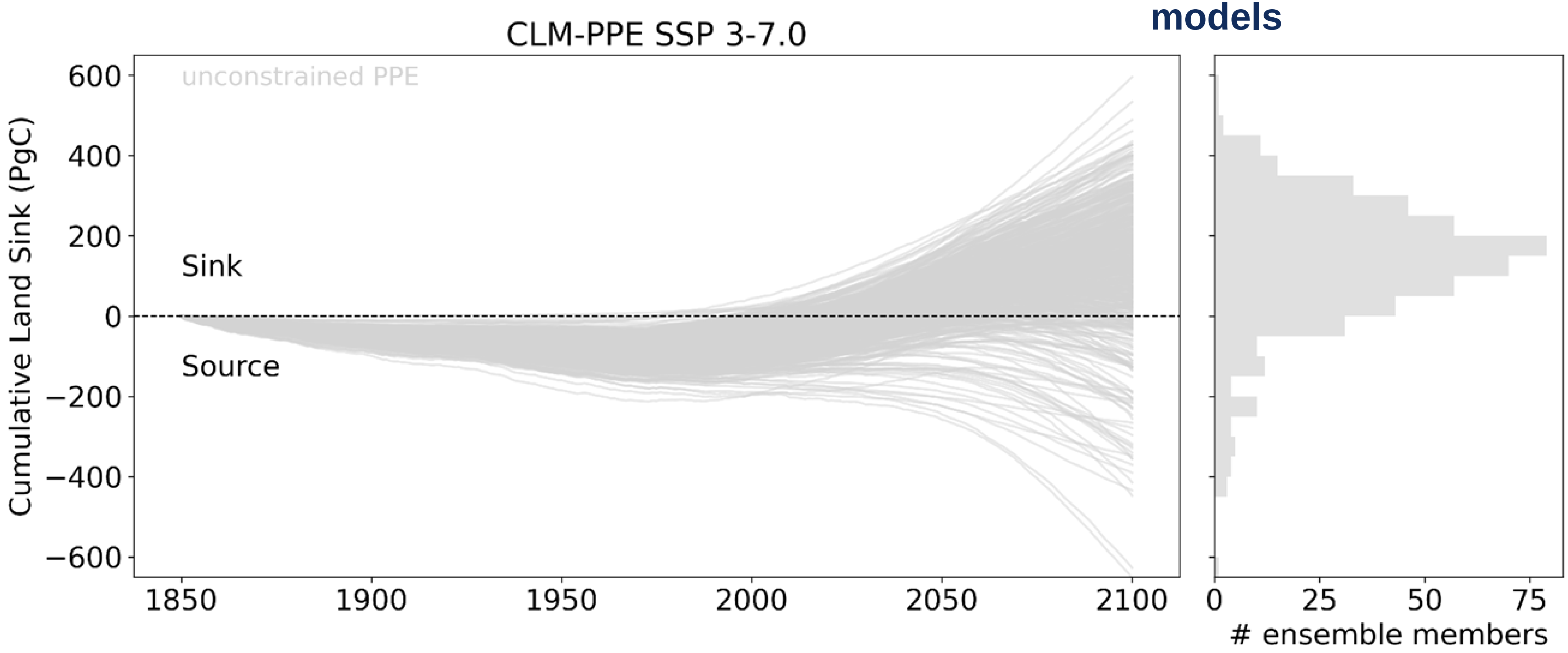
Range ±600PgC is as large as across CMIP6 models



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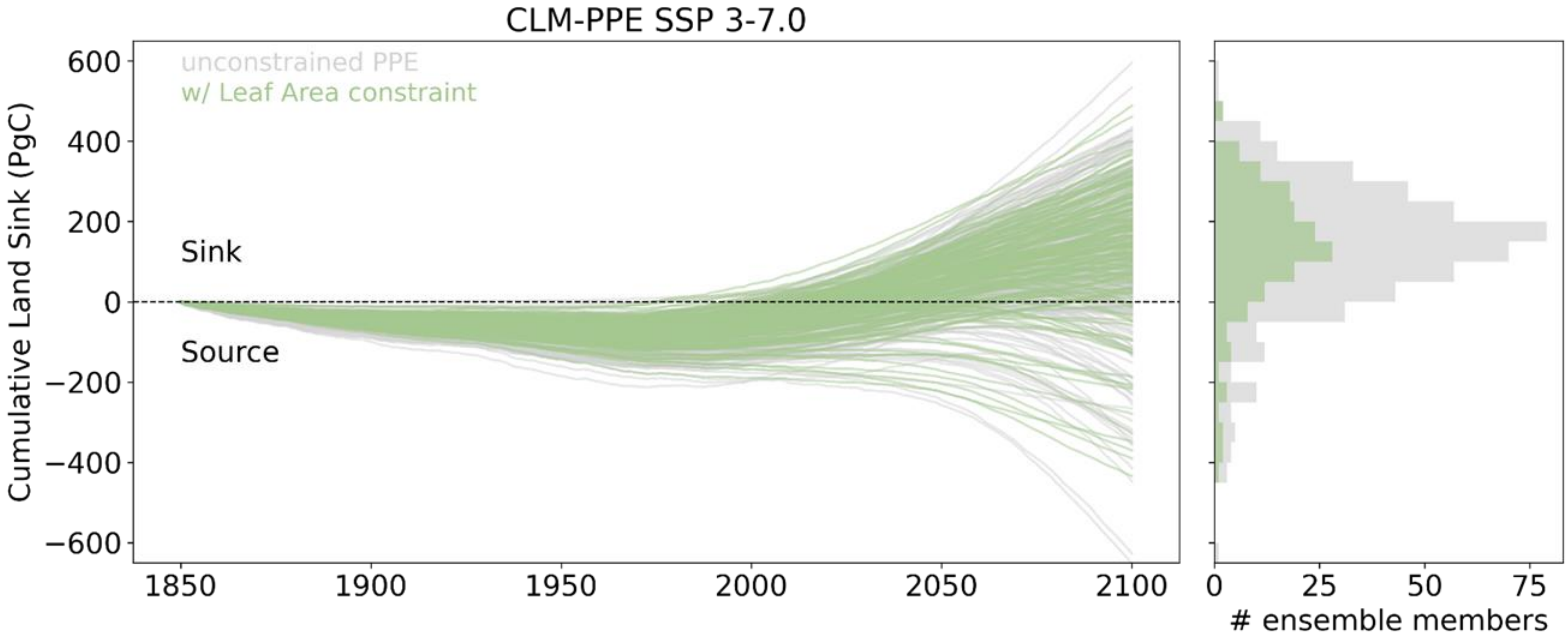

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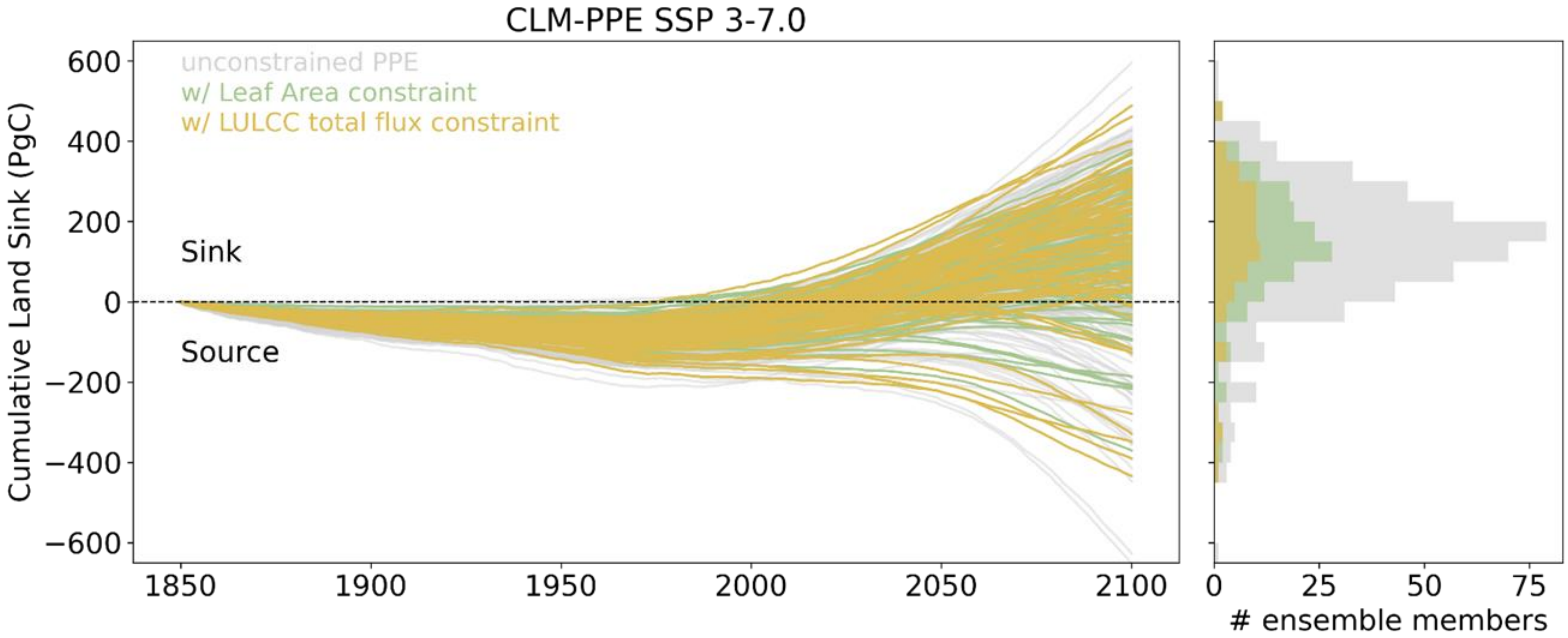

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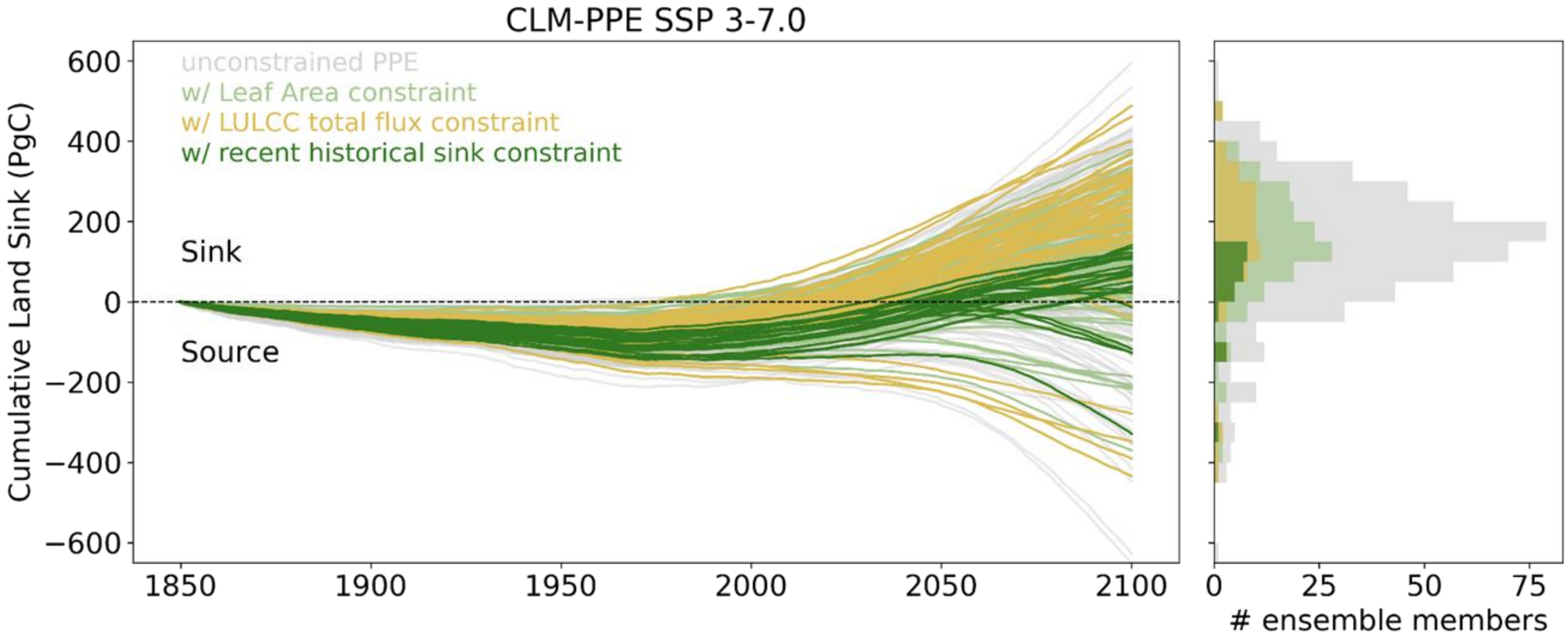

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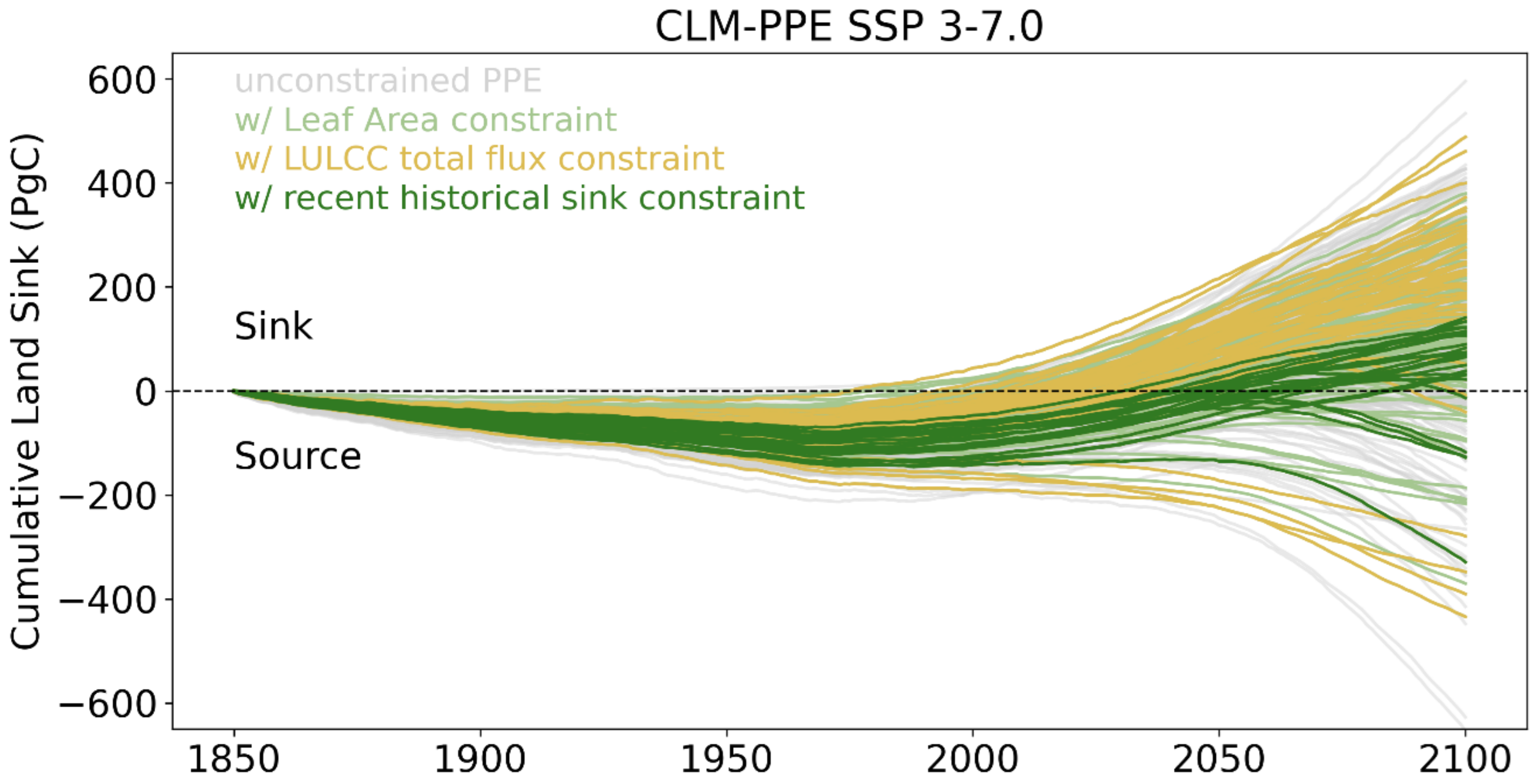


Still a diversity of carbon trend responses, even in constrained sets

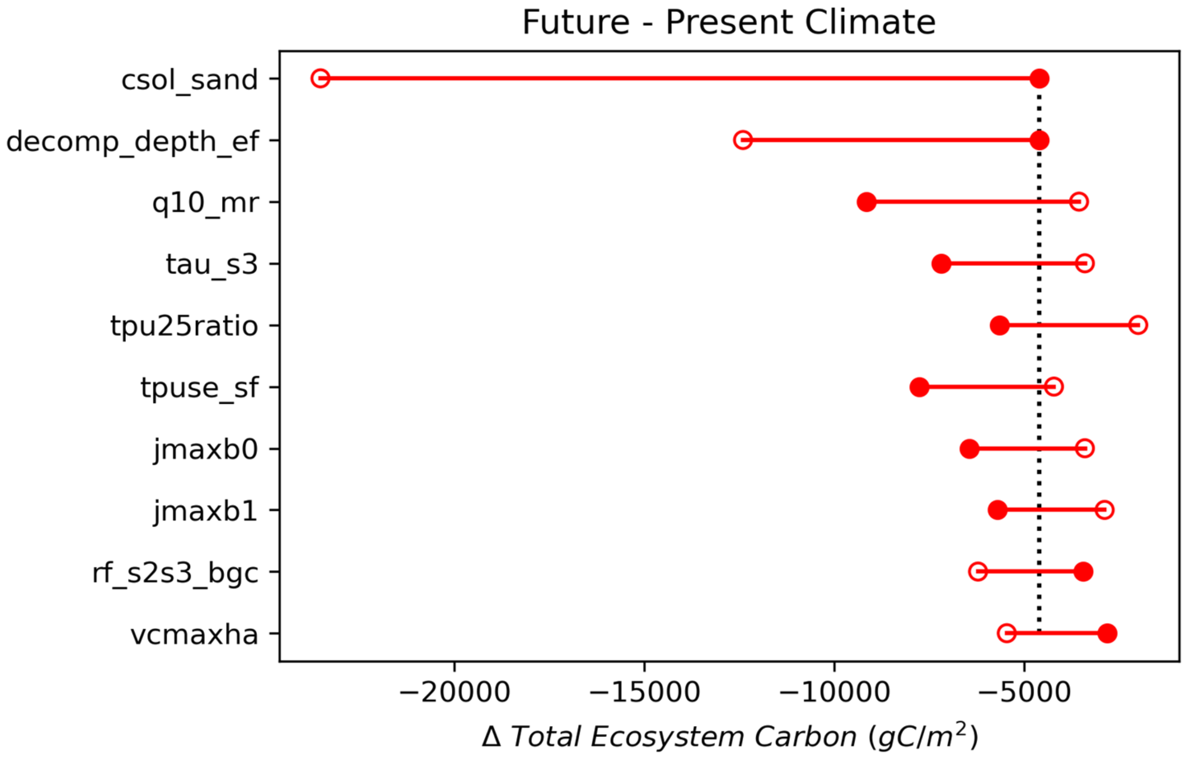
Can we build a future emissions-driven CESM3 Large Ensemble by including multiple land carbon parameter sets to span this uncertainty as another dimension (in addition to Initial conditions)?

Towards an emissions-driven, constrained land C parametric uncertainty, CESM3 Large Ensemble

Note: No soil carbon parameters!

From one-at-a-time ensemble

Δ Total Ecosystem Carbon



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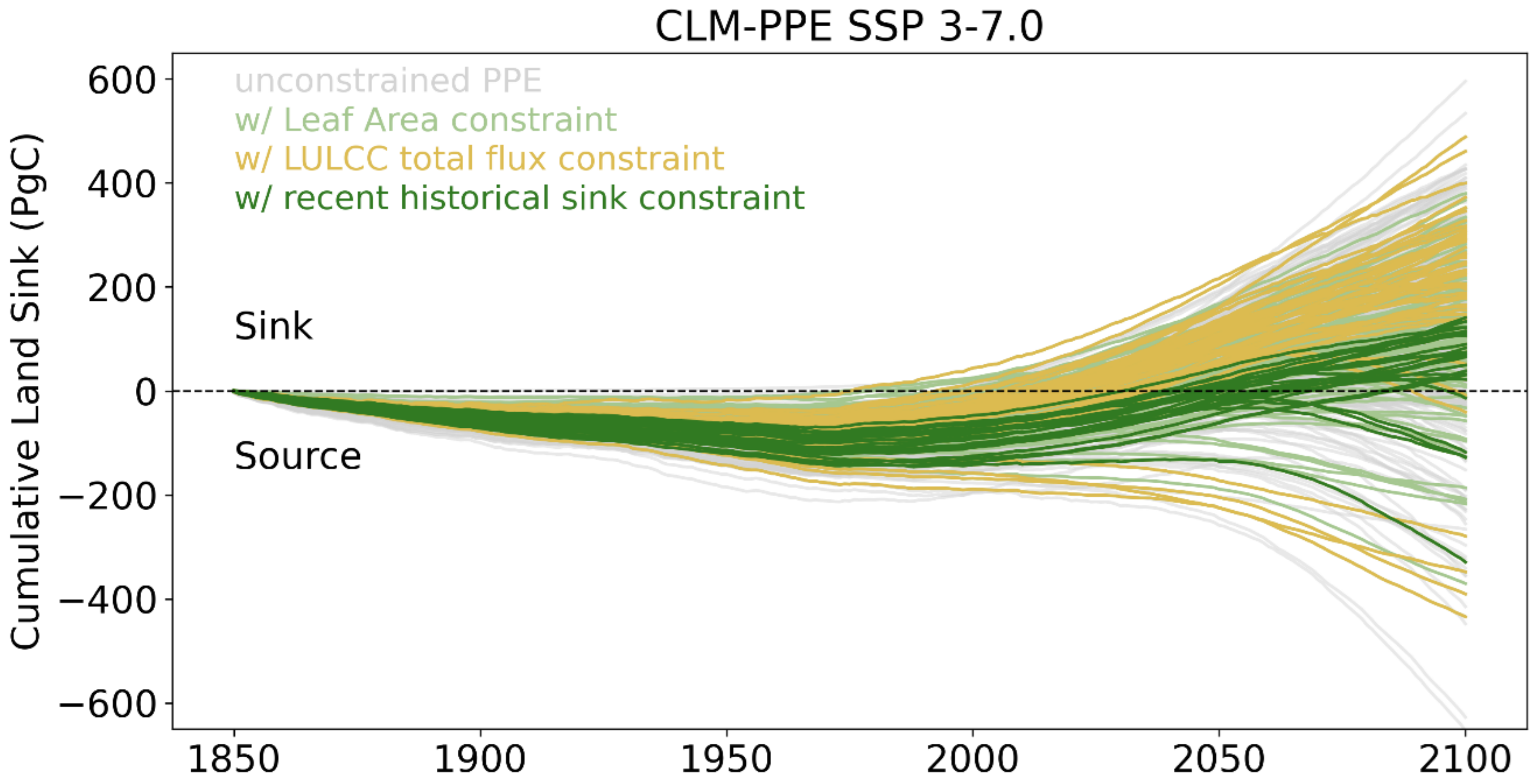
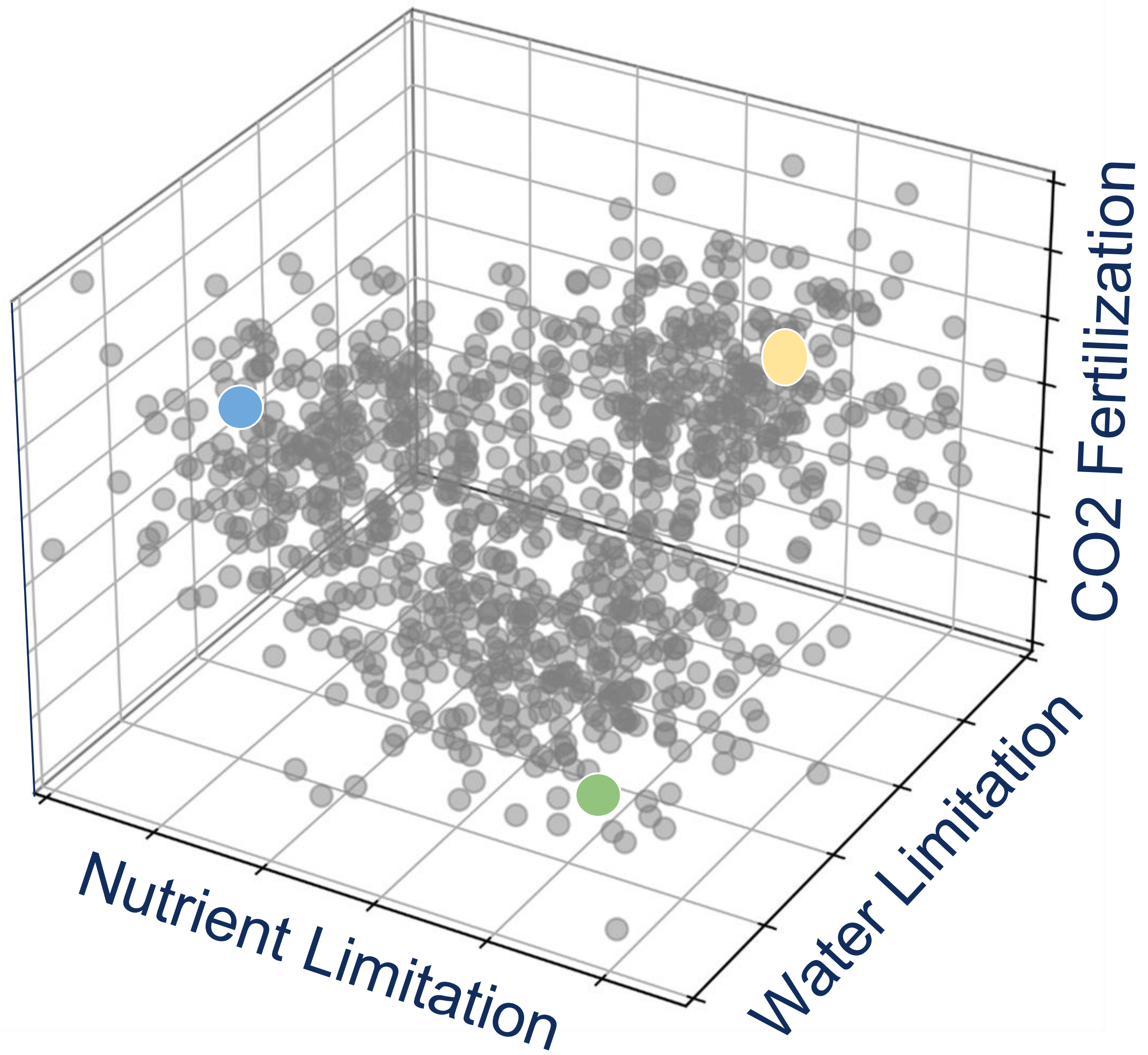


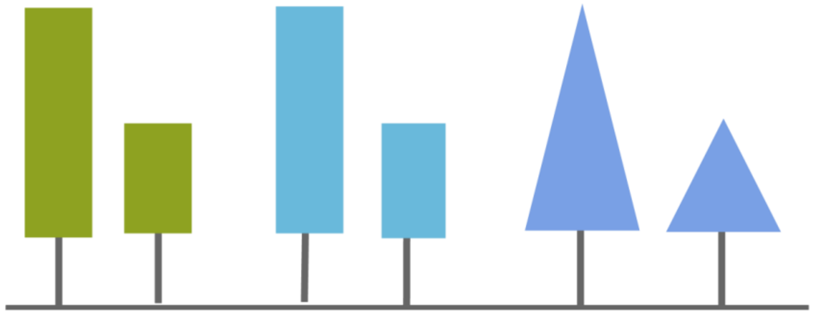


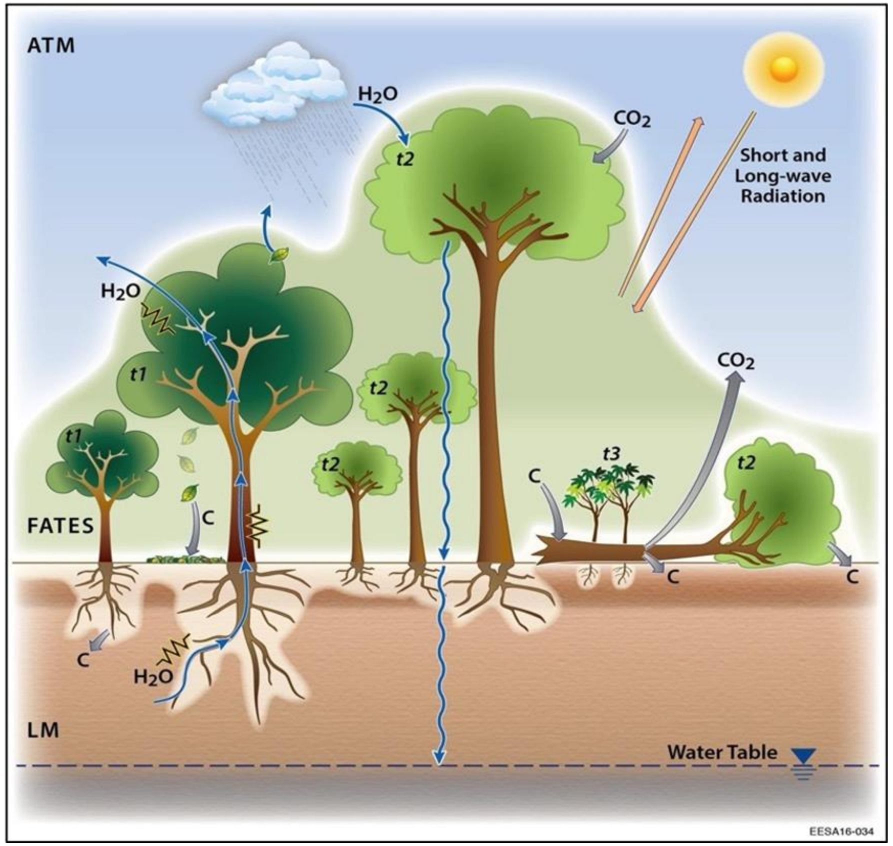
Presuming we can only run with about 5-10 parameter sets, how to choose out of the constrained sets?

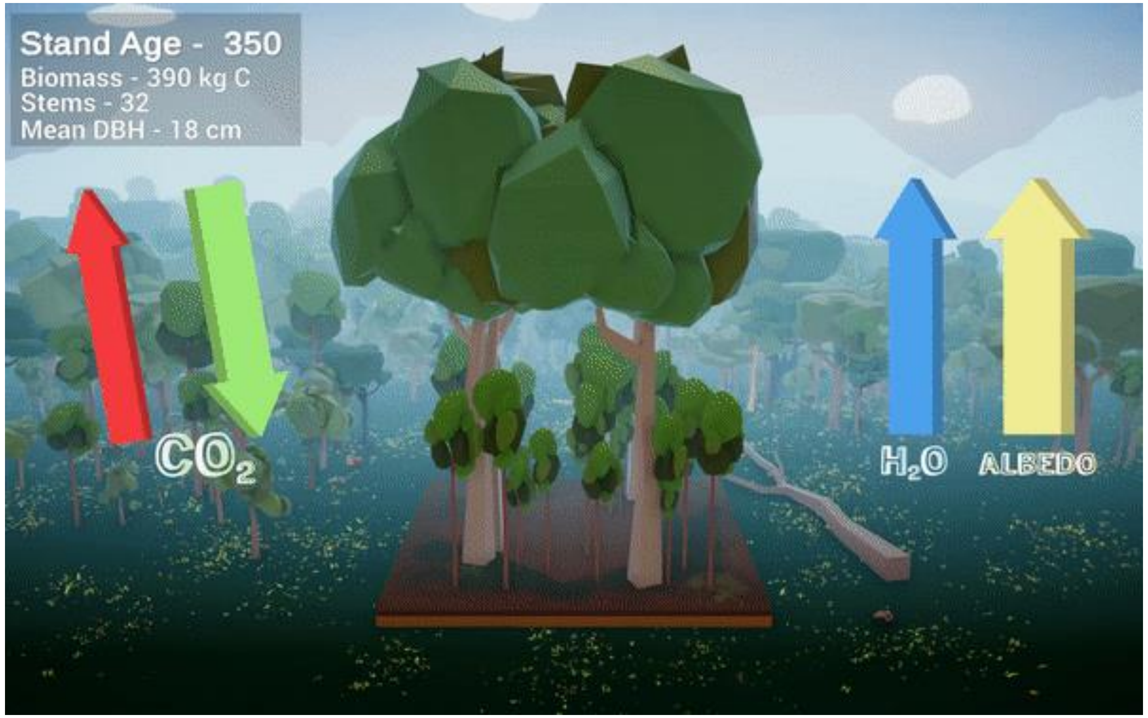
- Perhaps, select parameter sets that show distinct behavior with respect to CO_2 fertilization, nutrient limitation, water limitation
- High / low permafrost climate-carbon feedback
- High / low Amazon vulnerability to climate change
- Northern mid-lat vs tropical sink
- ???

CLM-FATES (Functionally Assembled Terrestrial Ecosystem Simulator)

FATES







vegetation cohort-specific model (stand structure)
30-minute photosynthesis and fluxes
daily growth and allocation
competition and coexistence

Summary

- Developing configurations of CESM2 and CESM3 that include more comprehensive treatment of processes that are likely important for mitigation scenarios
- Drawing on CLM PPE project, we appear to be able to identify constrained parameter sets that can reproduce features of the land carbon states and trends
- By carefully choosing sets of parameters from those that pass the constraints, we can form the basis for an emissions-driven parameter mini-ensemble to better characterize uncertainty in land carbon sink and associated climate feedbacks

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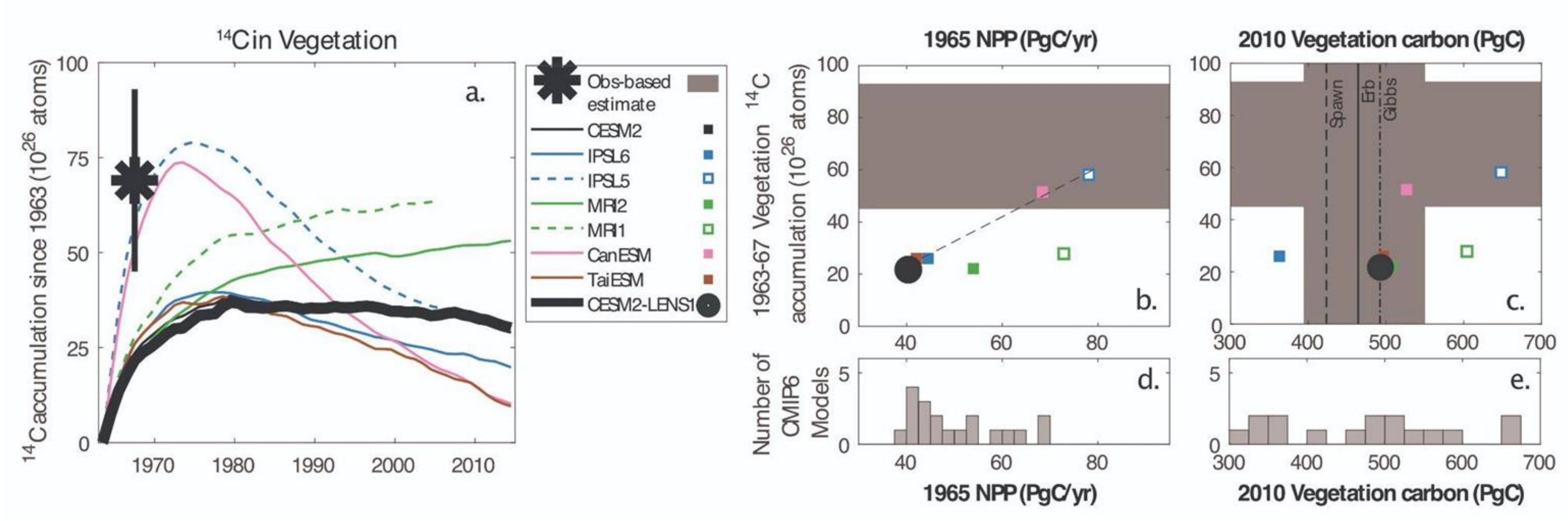
Image: Joel Vodell

Radiocarbon constraints on the land carbon cycle



CESM2: Published C isotope data in CMIP6

Underestimates ^{14}C accumulation &

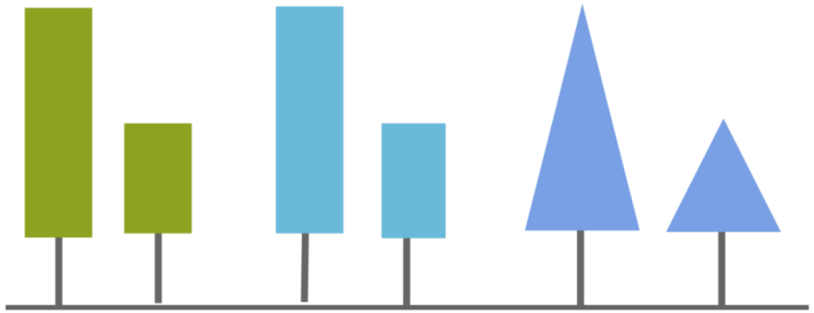
Misallocates C to pools with fast turnover times

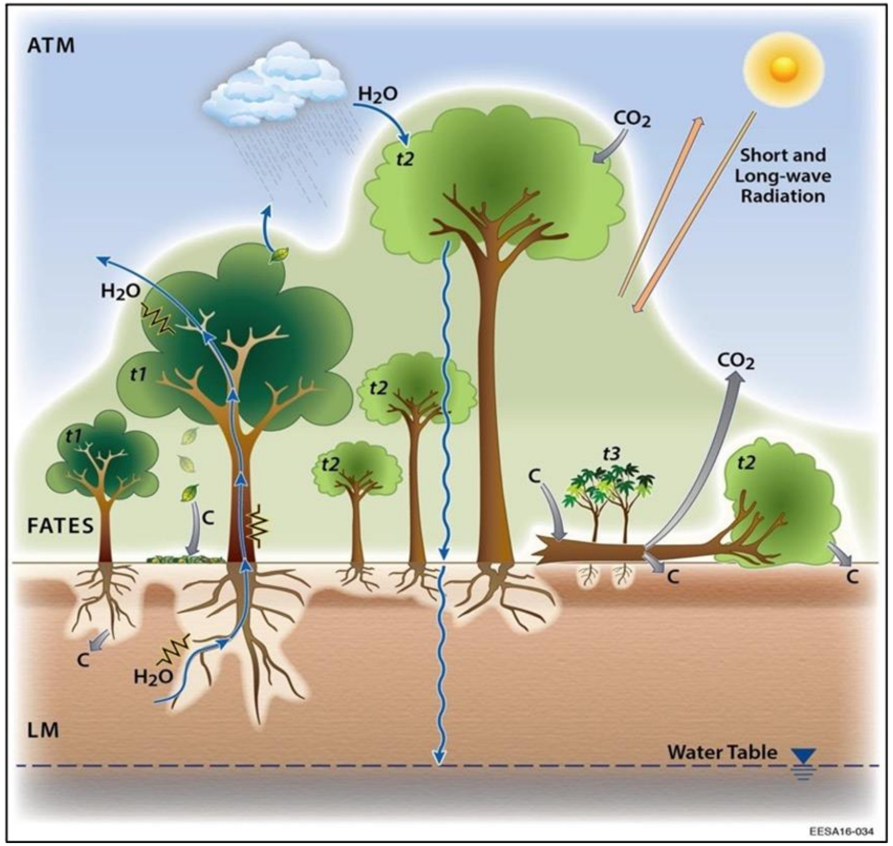
Anderson Spinup

Samar Khatiwala. “Efficient spin-up of Earth System Models using sequence acceleration.” In: Science Advances 10.18 (2024). • Samar Khatiwala. “Fast Spin-Up of Geochemical Tracers in Ocean Circulation and Climate Models.” In: Journal of Advances in Modeling Earth Systems 15.2 (2023).

CLM-FATES (Functionally Assembled Terrestrial Ecosystem Simulator)

FATES





Progress
- Parts of the model are now calibrated
- Land use change (nearly) incorporated

Plans
- Full calibration at NEON sites
- Historical land-only simulations for 2024 Global Carbon Project

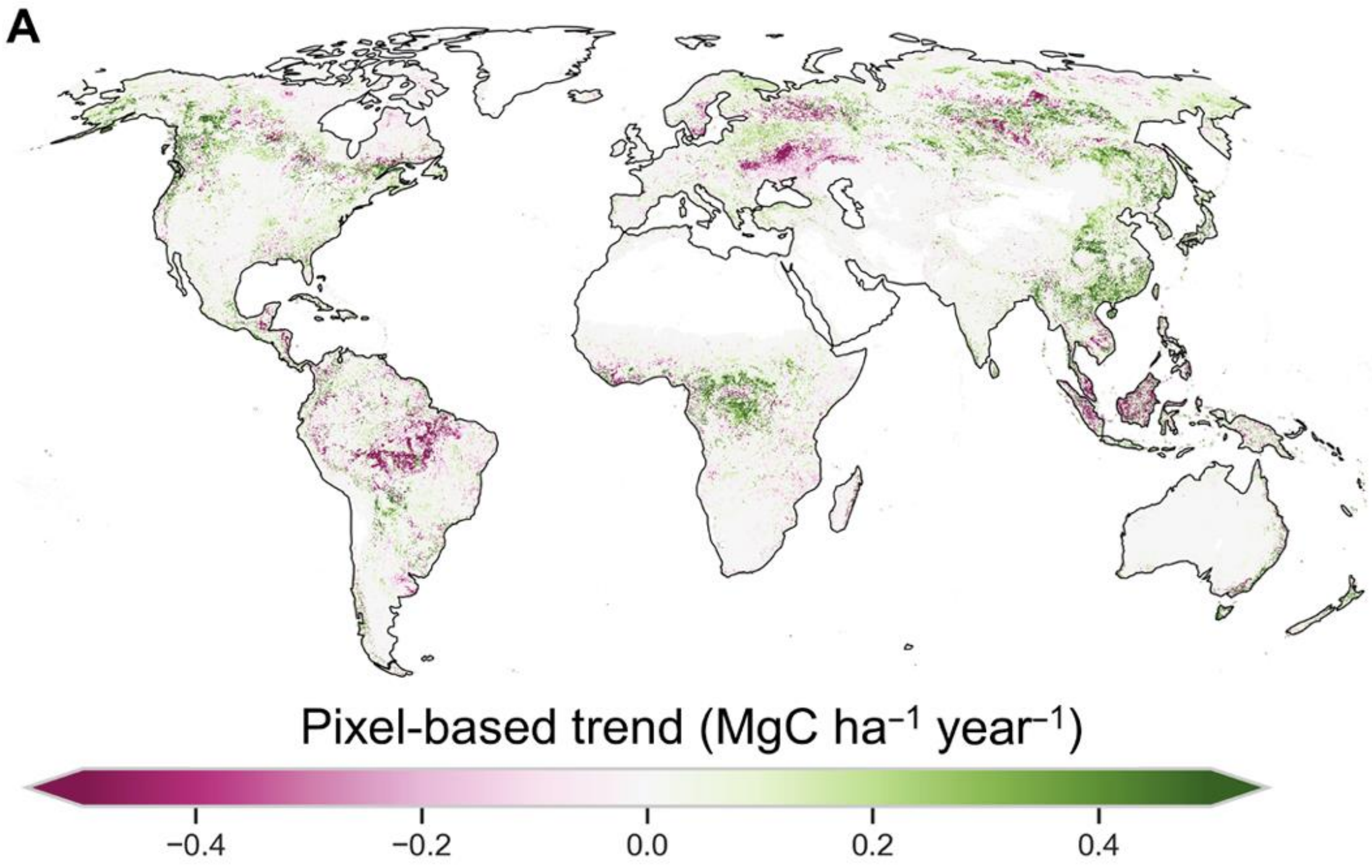
Challenges
- Constraining the powerful, but complex, full competition model configuration
- Defining governance: Shared development by DOE, NCAR, Norway

vegetation cohort-specific model (stand structure)
30-minute photosynthesis and fluxes
daily growth and allocation
competition and coexistence

Jointly developed by DOE, Norway, NCAR and others

Increasing availability of long term (20-25 years) carbon stock and flux records

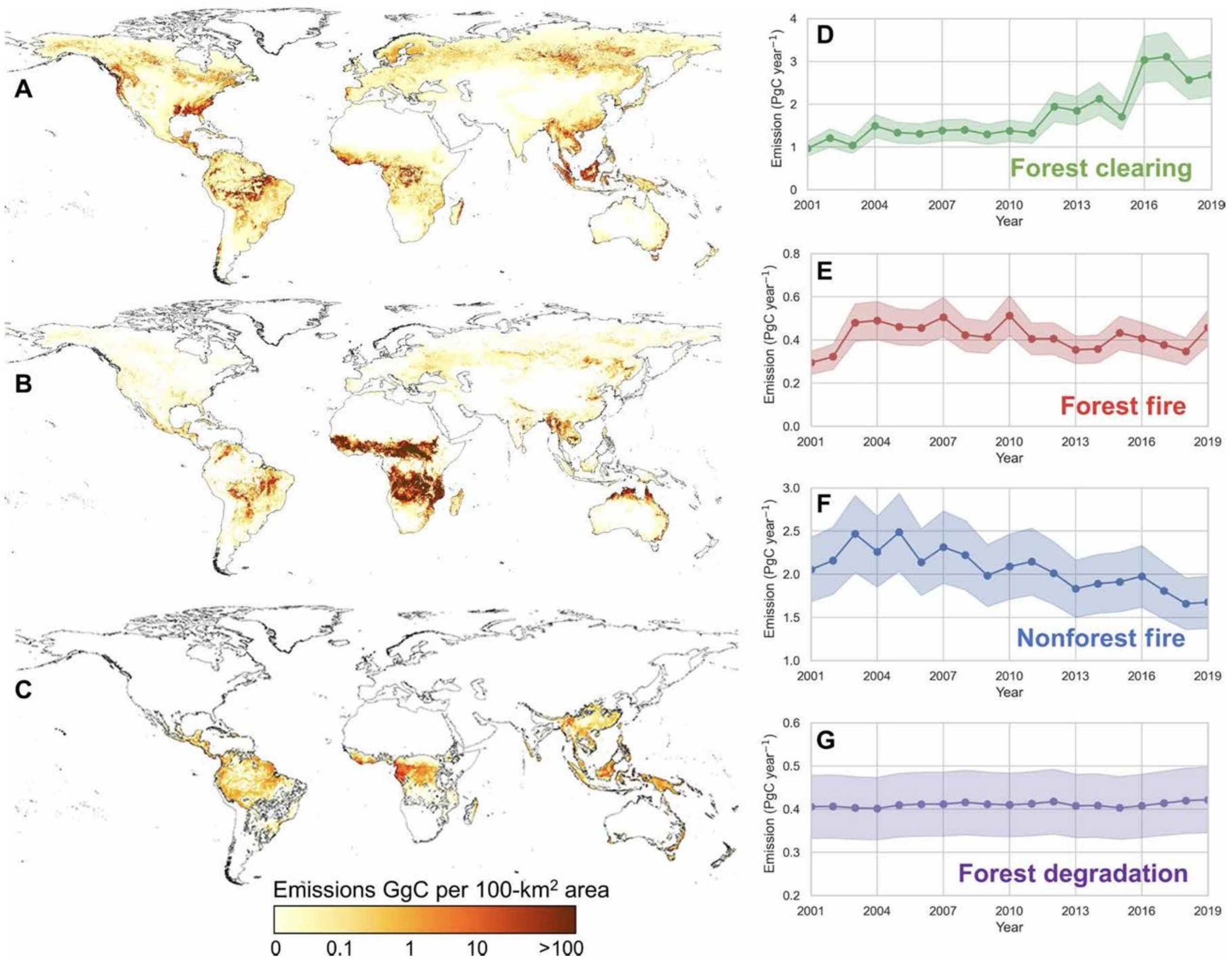
Live woody biomass trend estimates from forest inventory and satellites



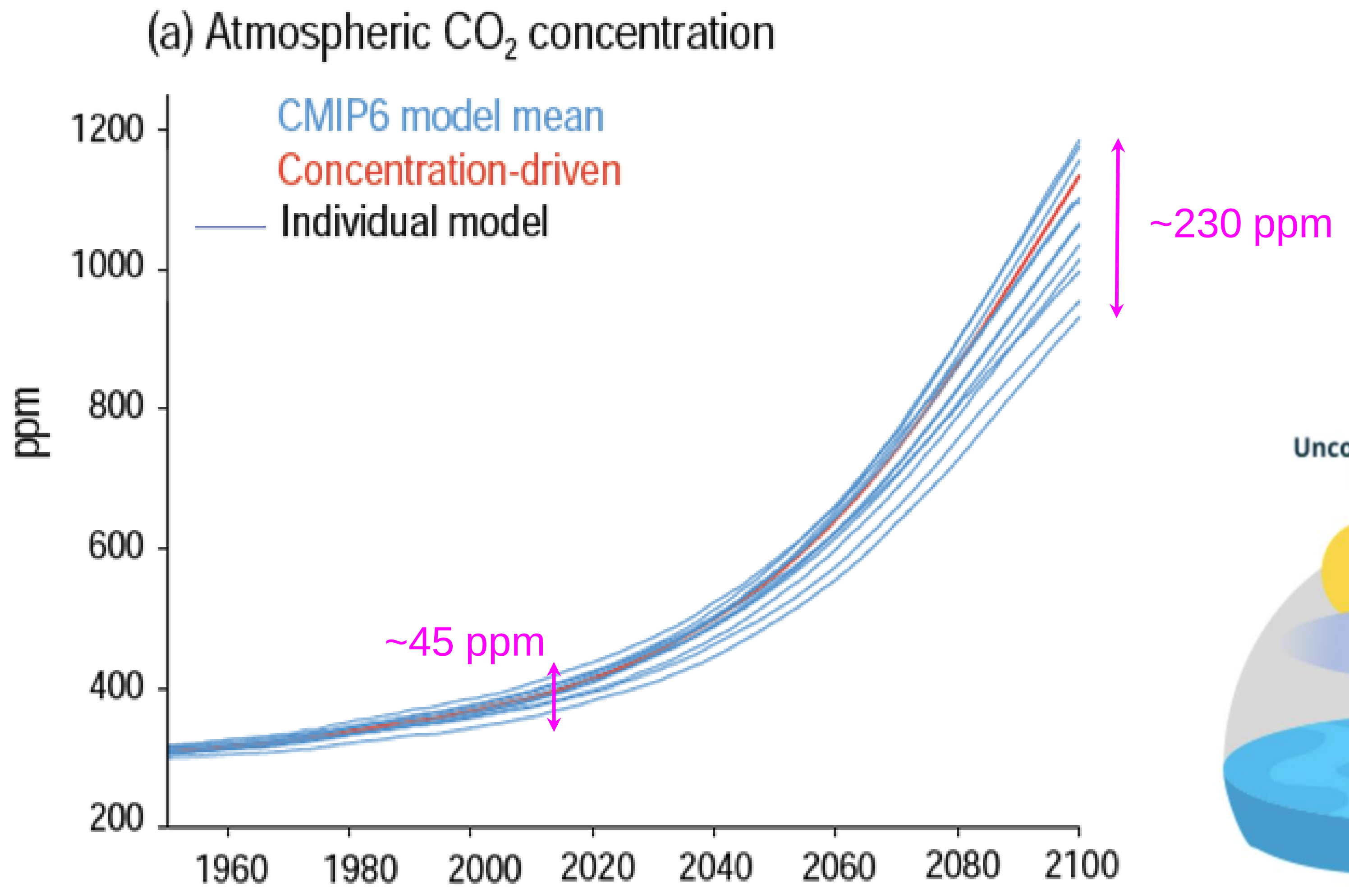
- Leaf Area Index greening and browning trends from remote sensing
- Local and upscaled estimates of carbon flux trends from long-term Flux Tower sites

Xu et al. 2021, Science Advances

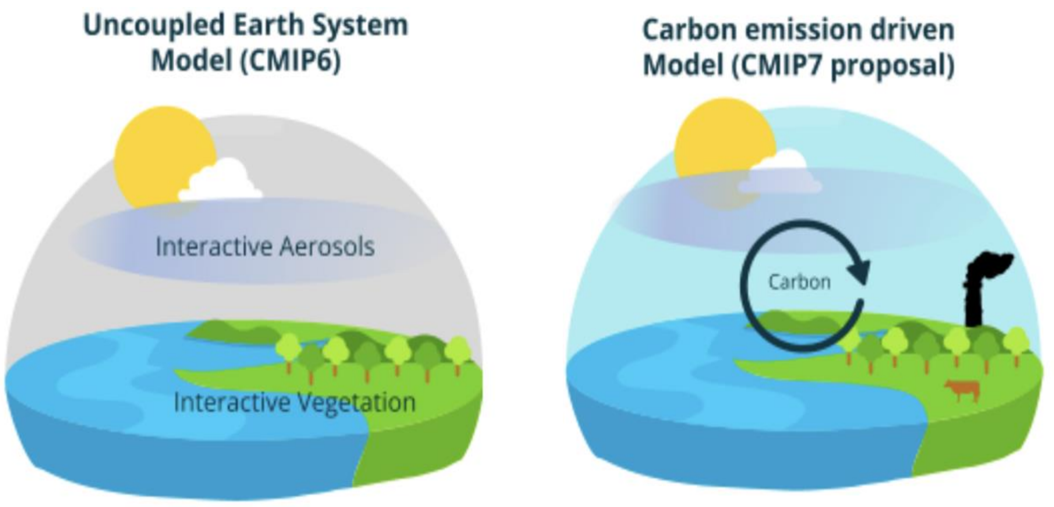
The response of the terrestrial biosphere to increasing atmospheric CO_2 concentration is incompletely understood, leading to major uncertainty in model predictions of carbon dynamics and future scenarios of climate change (Arora et al. 2013). Moreover, despite evidence that the CO_2 fertilisation of vegetation production may be limited by nutrient availability (Norby et al. 2010), nutrient feedbacks are not represented in all models and differ in mechanistic detail, often not supported by observations (Zaehle et al. 2014). Equally pressing are widespread reports that global trends in tree growth (van der Sleen et al. 2014) are not consistent with growth estimates simulated by state-of-the-art models of the CO_2 fertilisation effect. Consistent with this observational trend is data from a CO_2 manipulation experiment on 100-year-old trees in Australia: six years of CO_2 enrichment have stimulated photosynthesis, but not led to an increase in tree growth (Ellsworth et al. 2017).


A
B
C
Emissions GgC per 100-km² area
0
0.1
1
10
>100
D
Emission (PgC year⁻¹)
Year
Forest clearing
E
Forest fire
F
Nonforest fire
G
Forest degradation

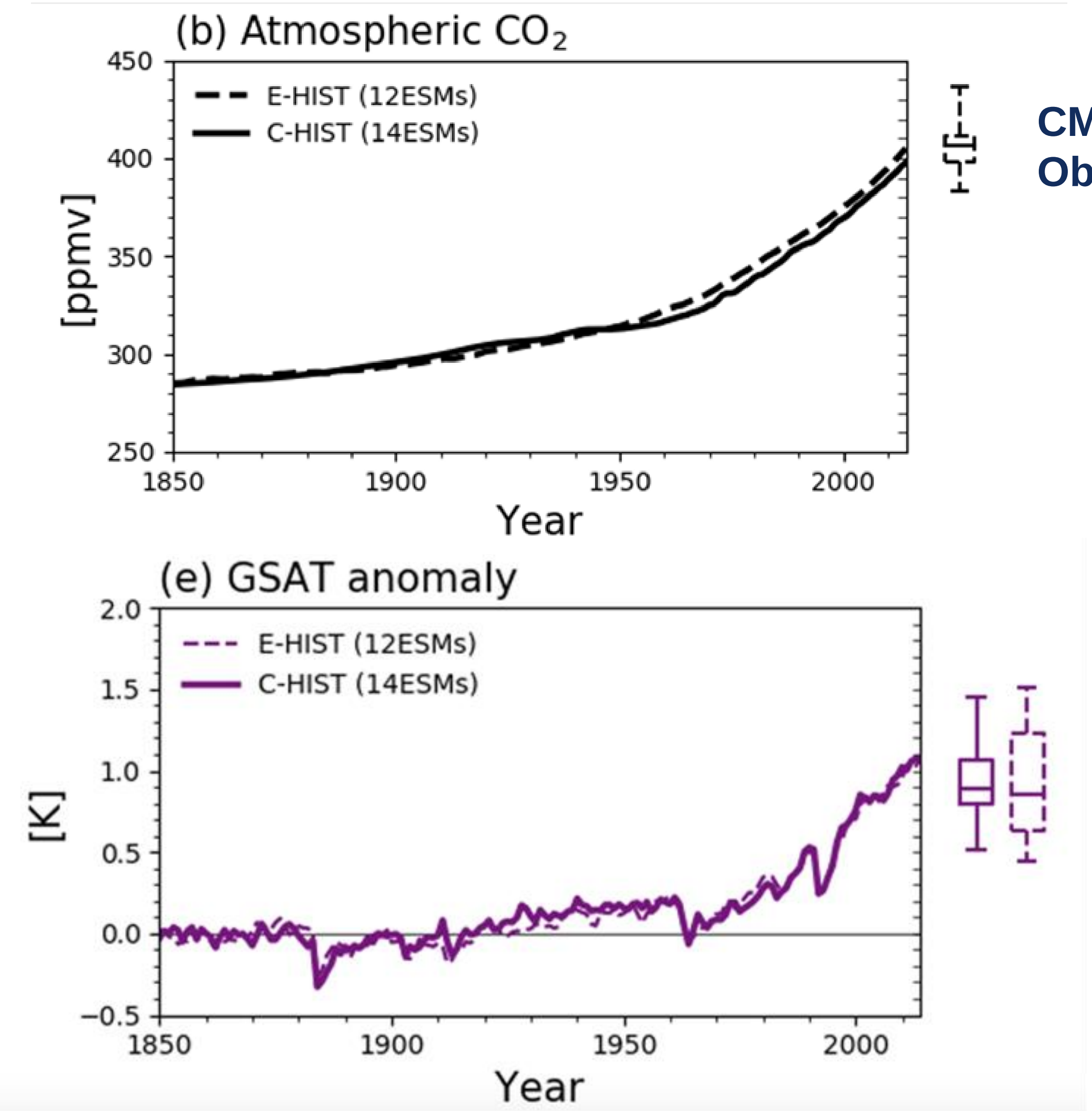
Emissions-driven CO_2 projection simulations



Uncertainty in land sink is source of about 1.2°C uncertainty for +3.7°C multi-model mean change (SSP5-8.5)



Impact in emissions-driven simulations



CMIP6 Models: 405 ±15 ppm
Obs: 398 ppm

C-Driven: +0.97 ± 0.28^{o}C
E-Driven: +0.95 ± 0.37^{o}C

Hajjima et al., 2024