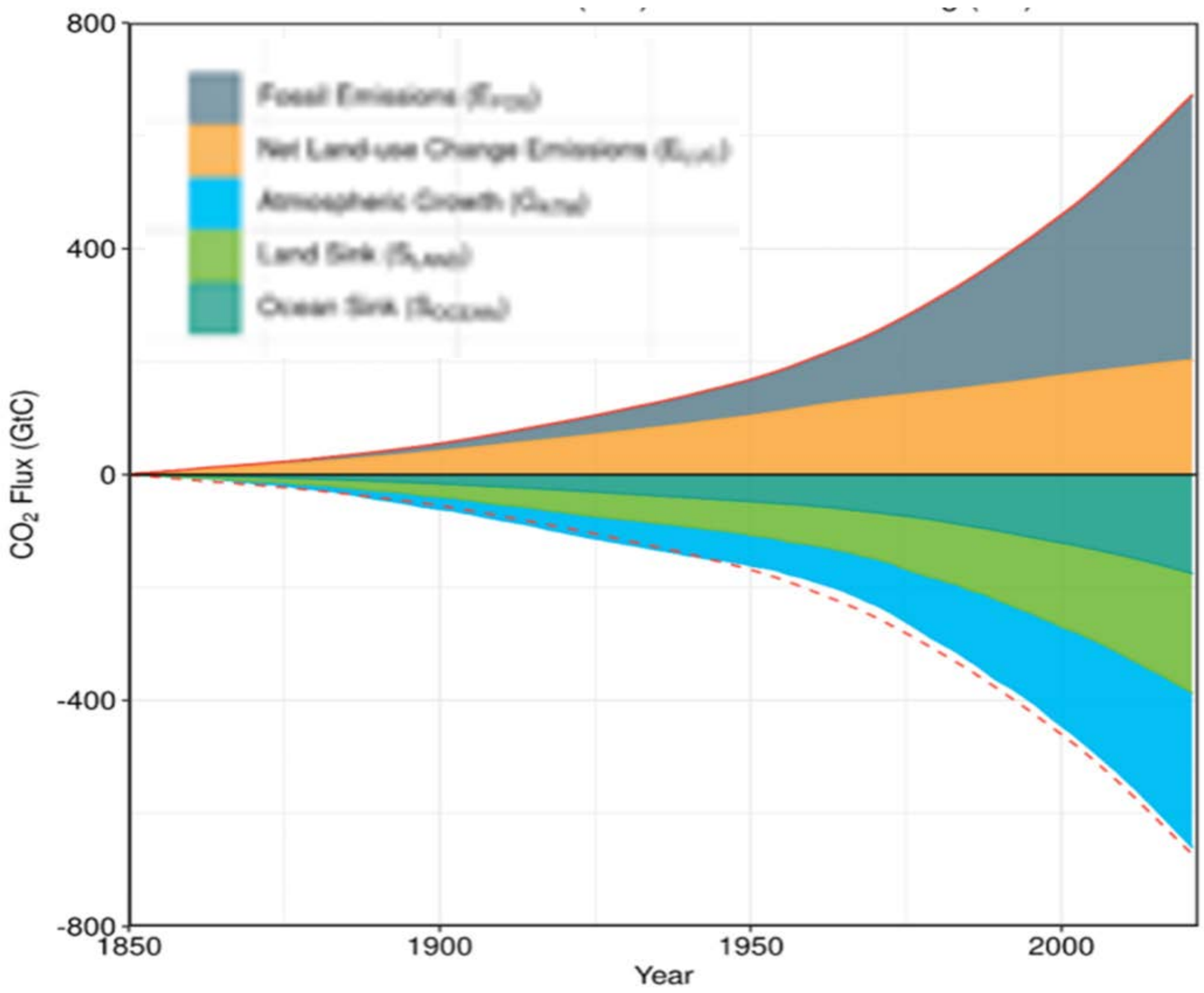
# Challenges in simulating the historical trajectory of carbon stocks on land

David Lawrence, Charlie Koven, Abby Swann, Daniel Kennedy, Forrest Hoffman, Gordon Bonan, and many others

NSF | NCAR

Image: Joel Vodell

# Cumulative historical carbon emissions and sinks



# Historical land carbon trajectories in CMIP6

Cumulative land carbon fluxes

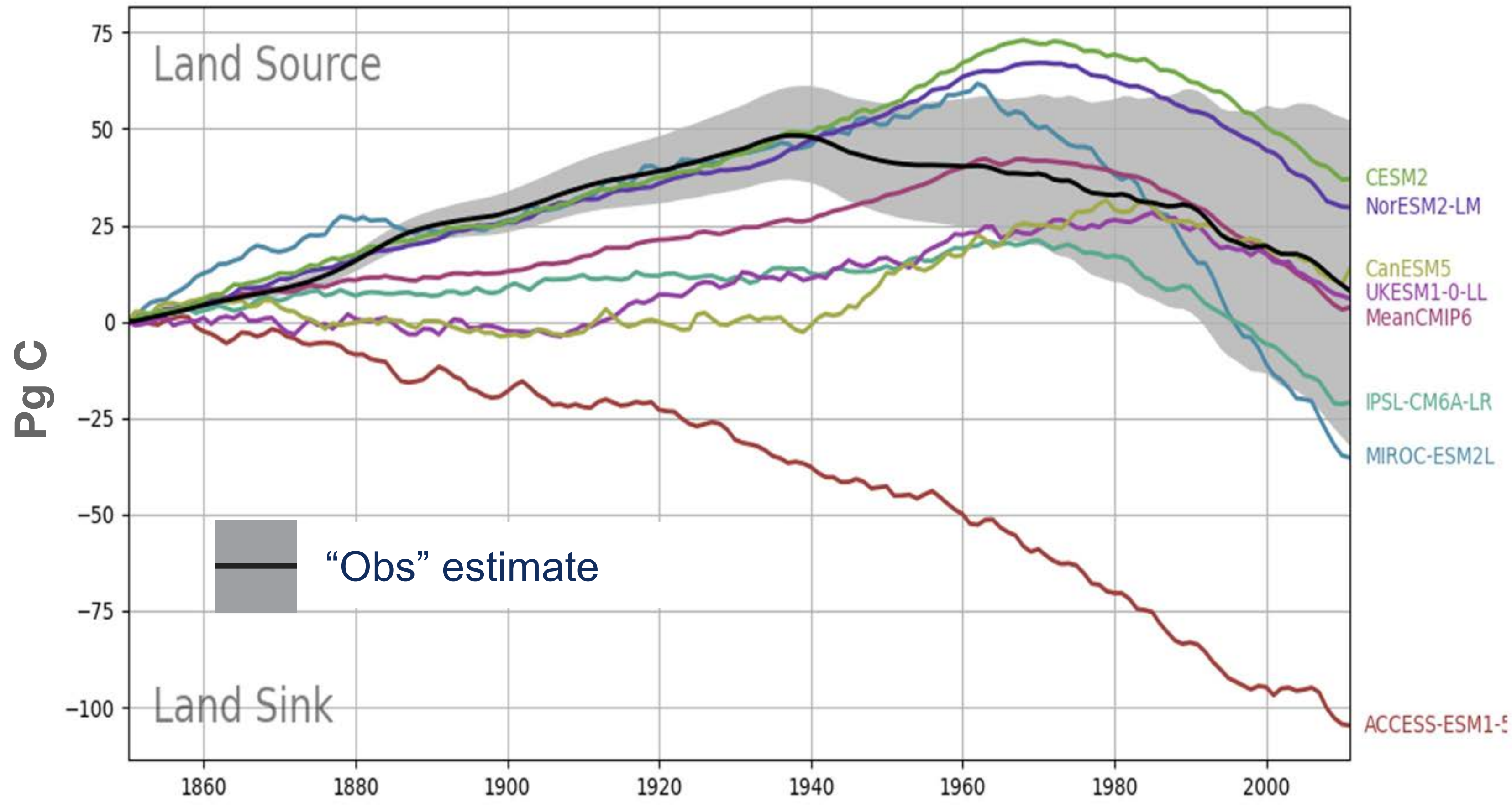
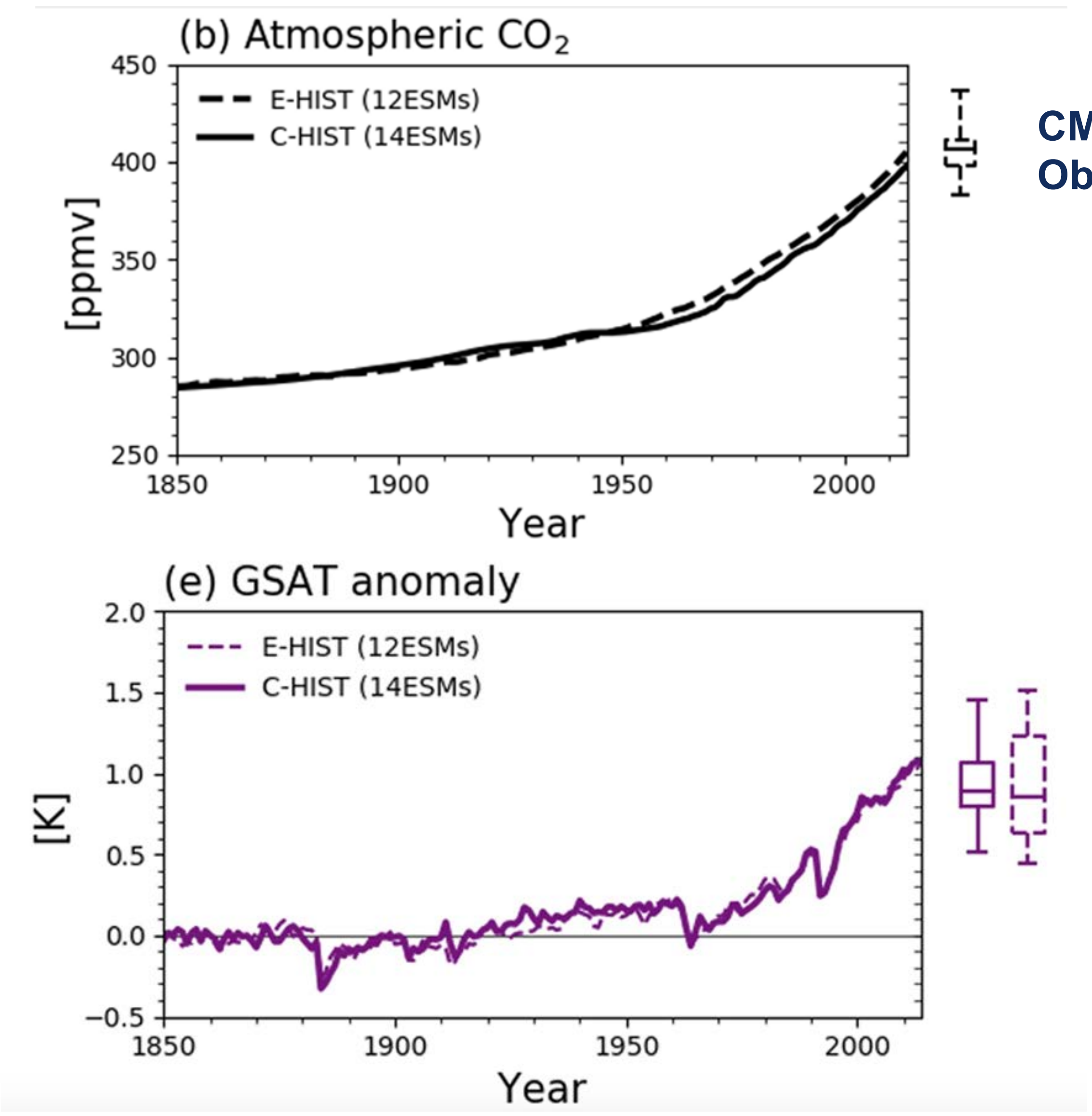


Figure from International Land Model Benchmarking (ILAMB) package (Collier et al., 2018)

$\Delta C_{land}$ “Obs” (Hoffman et al. 2014) is actually a residual of other terms in global carbon budget

$$\Delta C_{land} = FF_{emis} - \Delta C_{atm} - \Delta C_{ocn}$$

# Impact in emissions-driven simulations

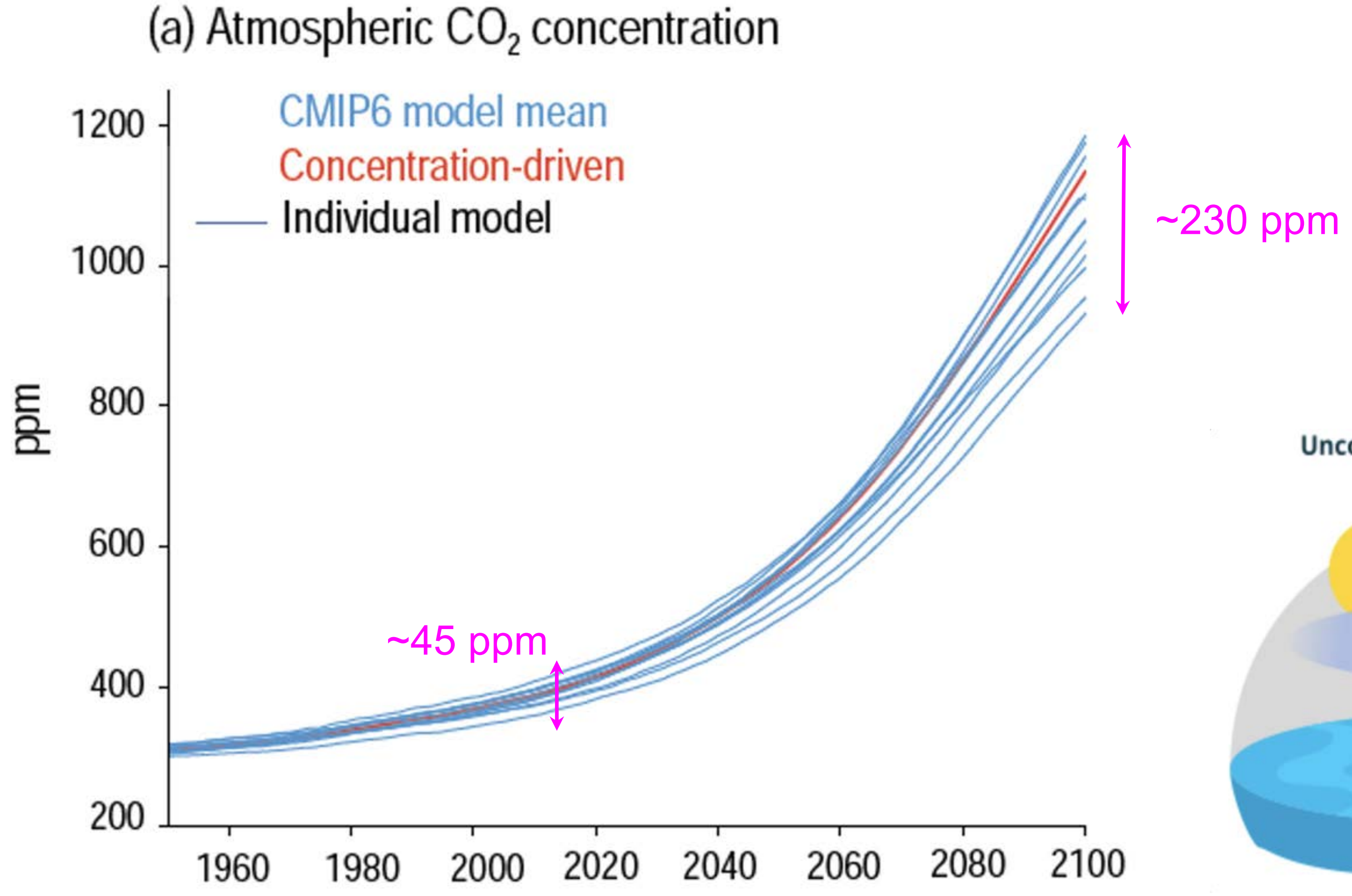


**CMIP6 Models:** 405 ±15 ppm
**Obs:** 398 ppm

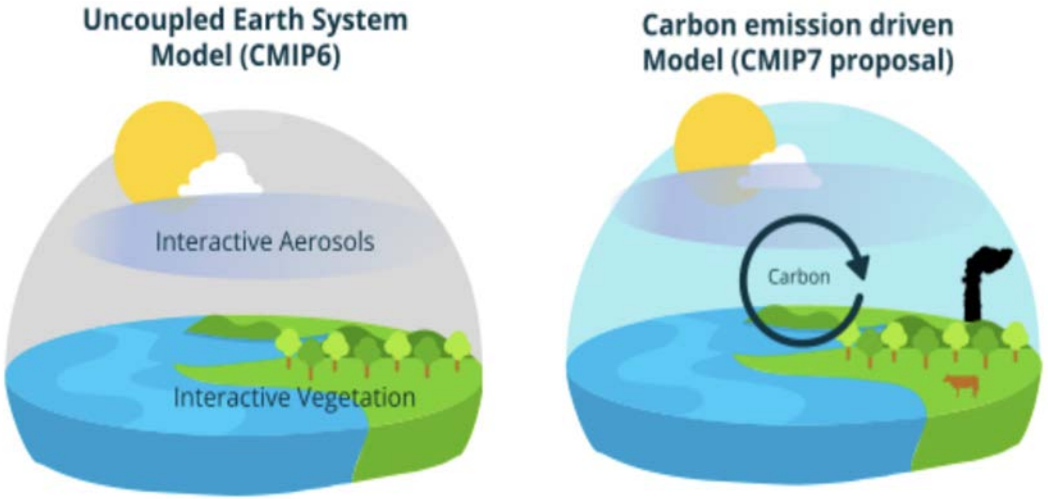
**C-Driven:** +0.97 ± 0.28$^{o}$C
**E-Driven:** +0.95 ± 0.37$^{o}$C

Hajjima et al., 2024

# Emissions-driven $CO_2$ projection simulations


(a) Atmospheric $CO_2$ concentration

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

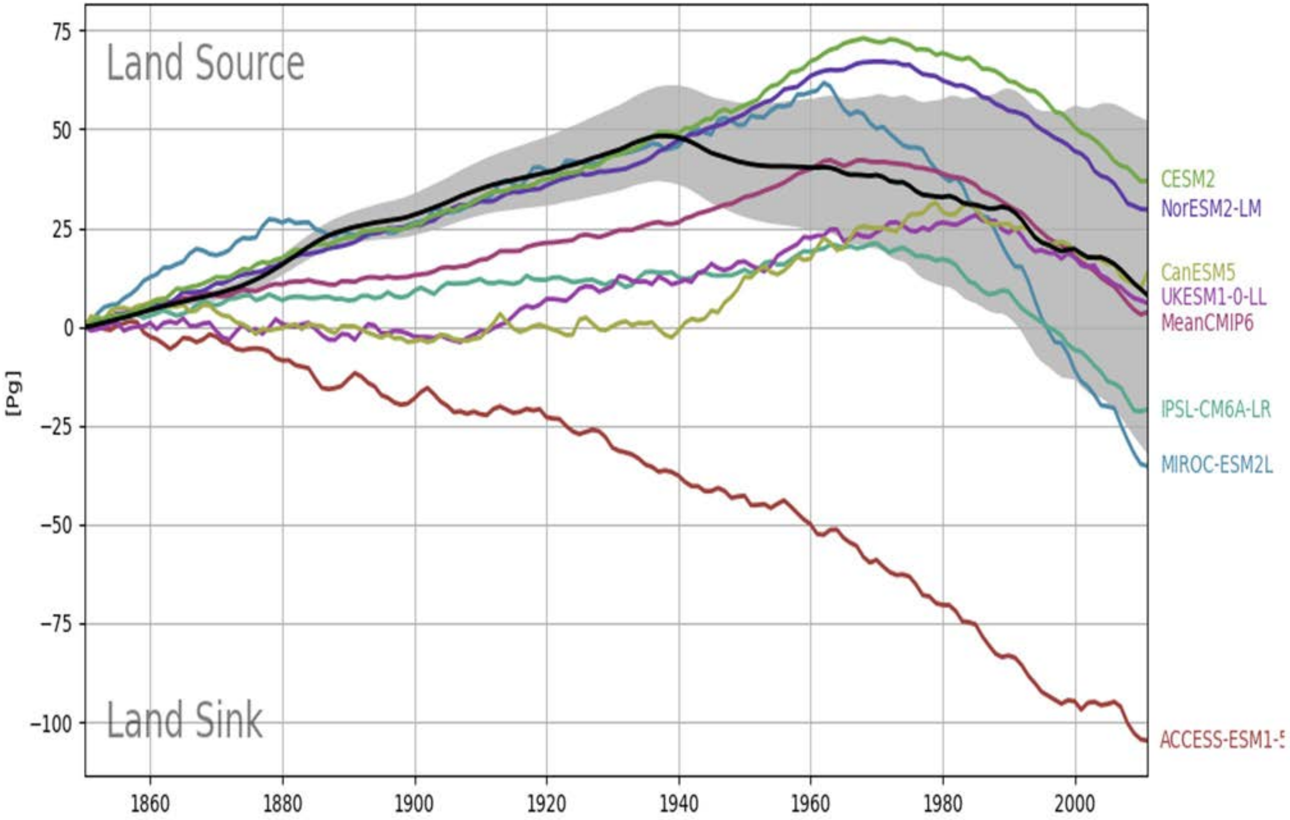


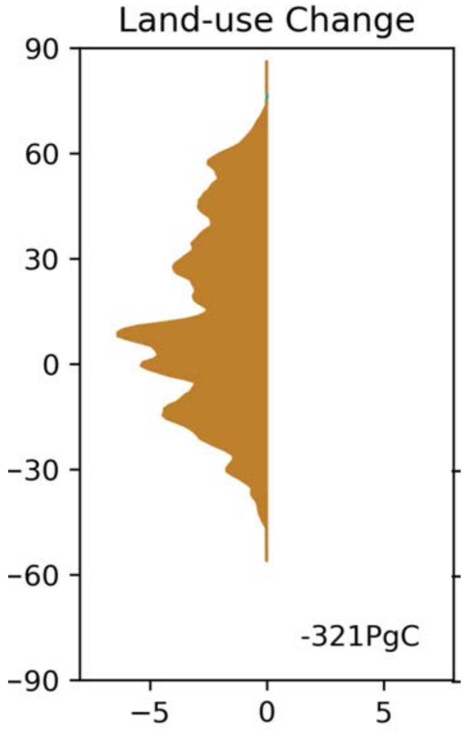
IPCC AR6 WGI, Fig. 4.3

# Where are we going to put the carbon (and will it stay there)?

- Land-based mitigation strategies (e.g., reforestation, BECCS) are likely required to achieve 1.5$^{o}$ C or 2$^{o}$ 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)

# What drives the land carbon stock trajectory?





1700-2020 zonal mean carbon flux (PgC

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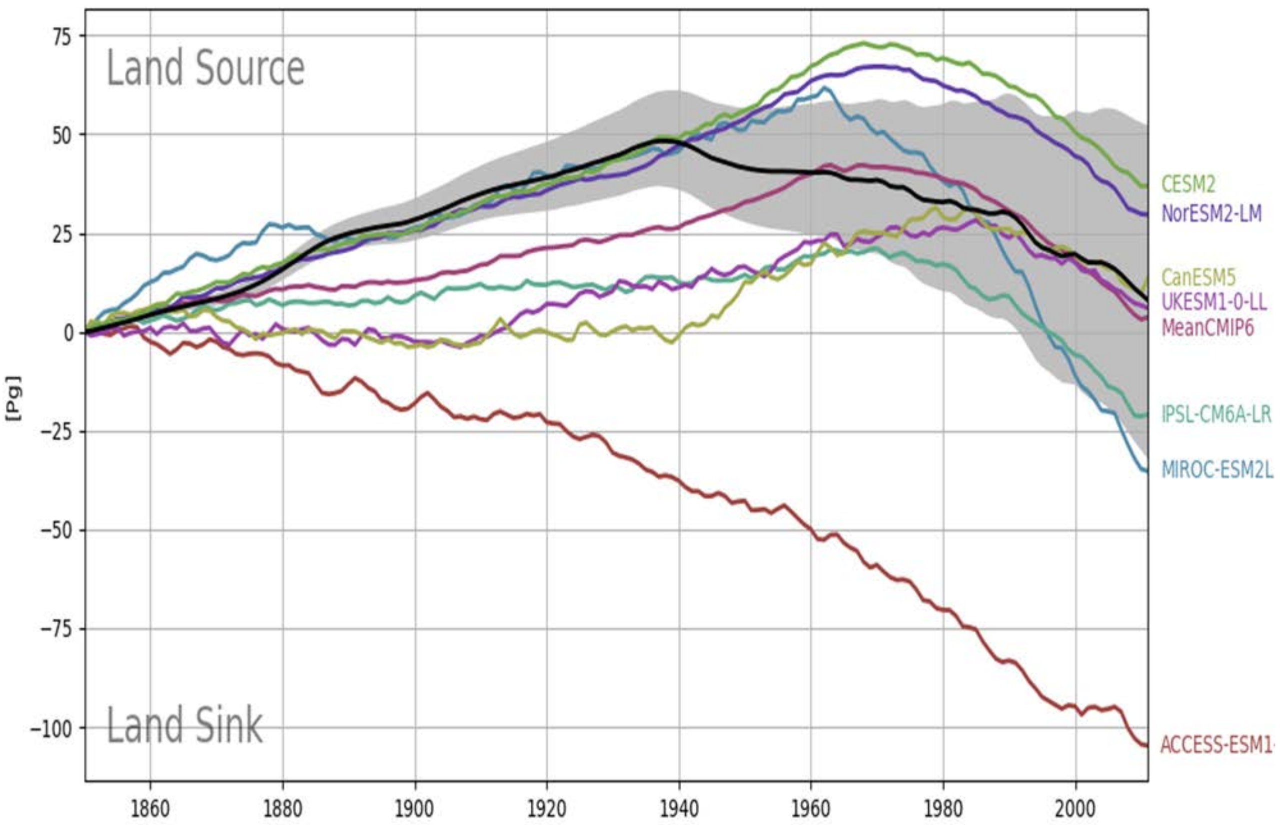

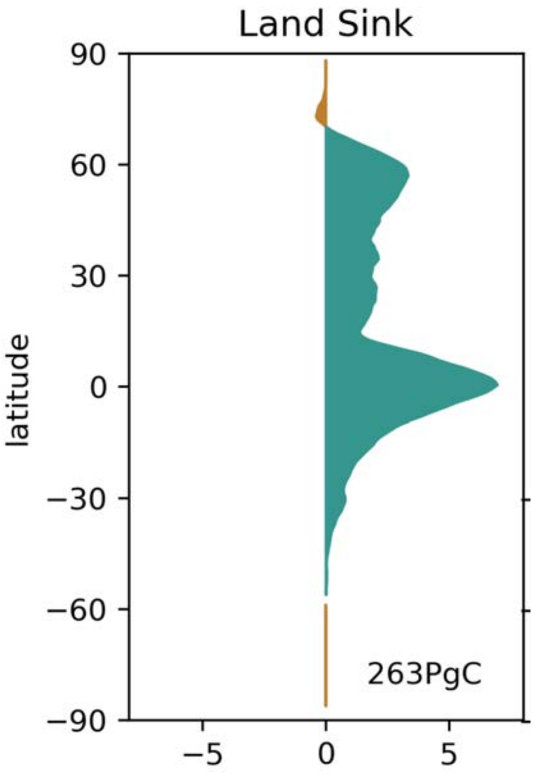

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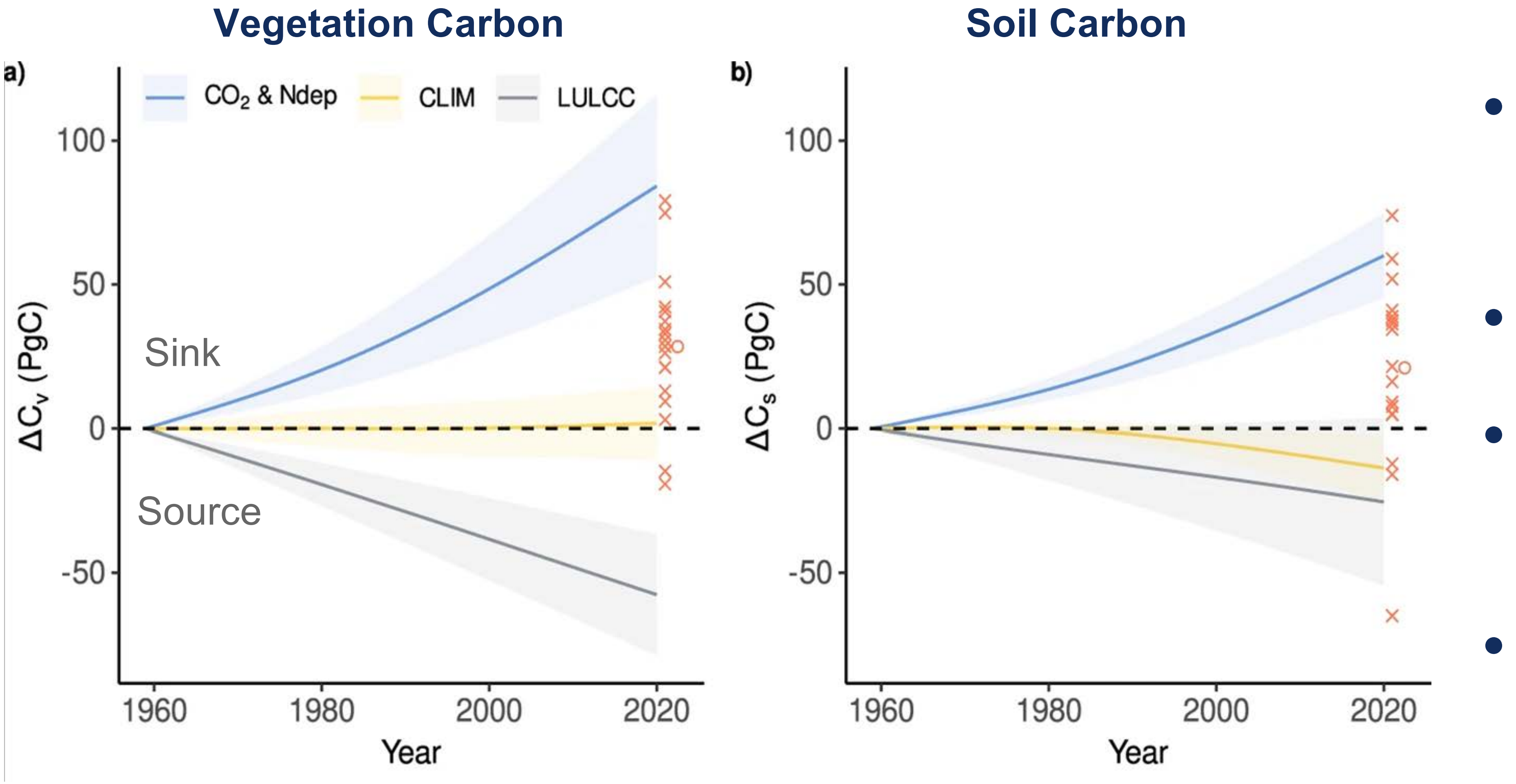


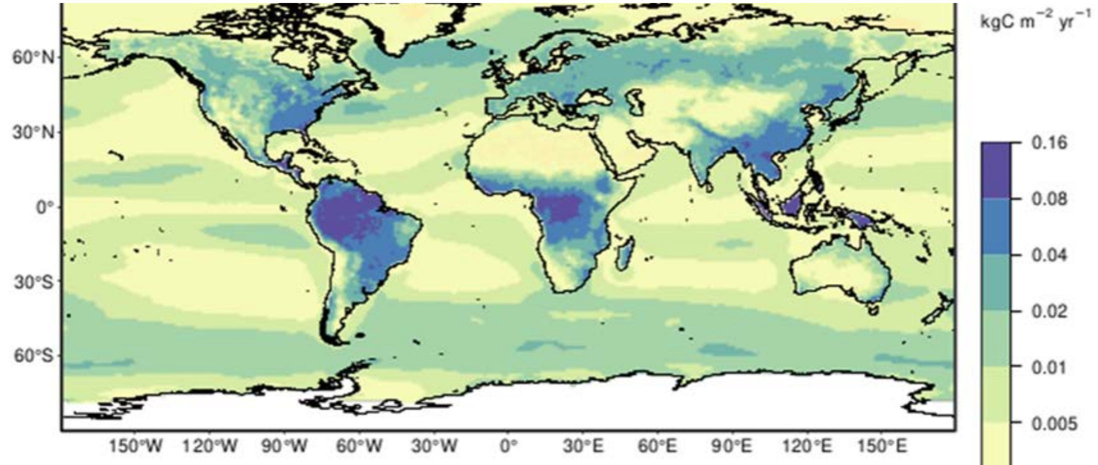
- Land-use and land-cover change (LULCC) (e.g., deforestation, agriculture, wood harvest)
- Fertilization of plants from $CO_2$ and N
- Vegetation and soil carbon response to climate change and variability
- Residence time of carbon in different carbon pools (soil, vegetation, litter)

x individual land-only models cumulative total flux

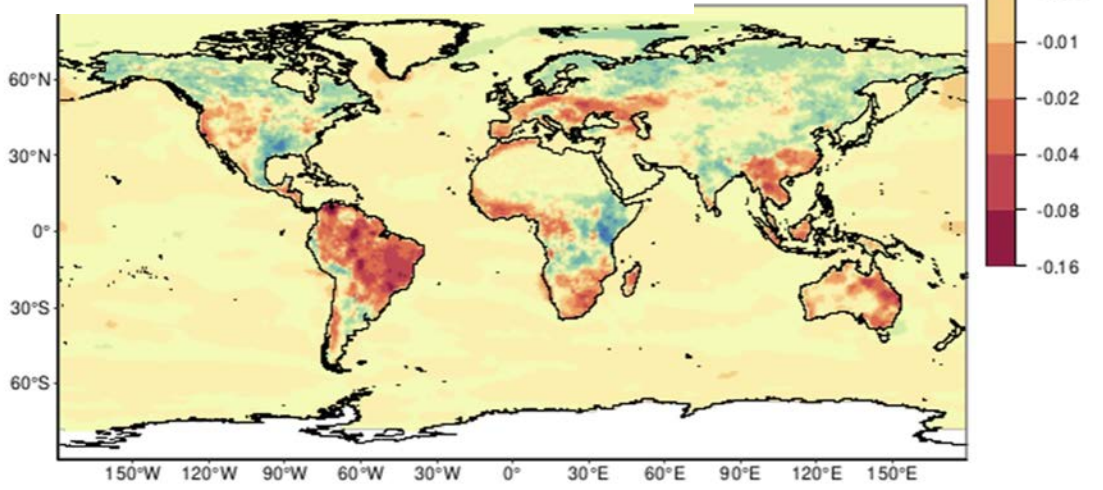
Sullivan et al. (2022)

# What drives the land carbon stock trajectory?

CO2 effect



Climate effect



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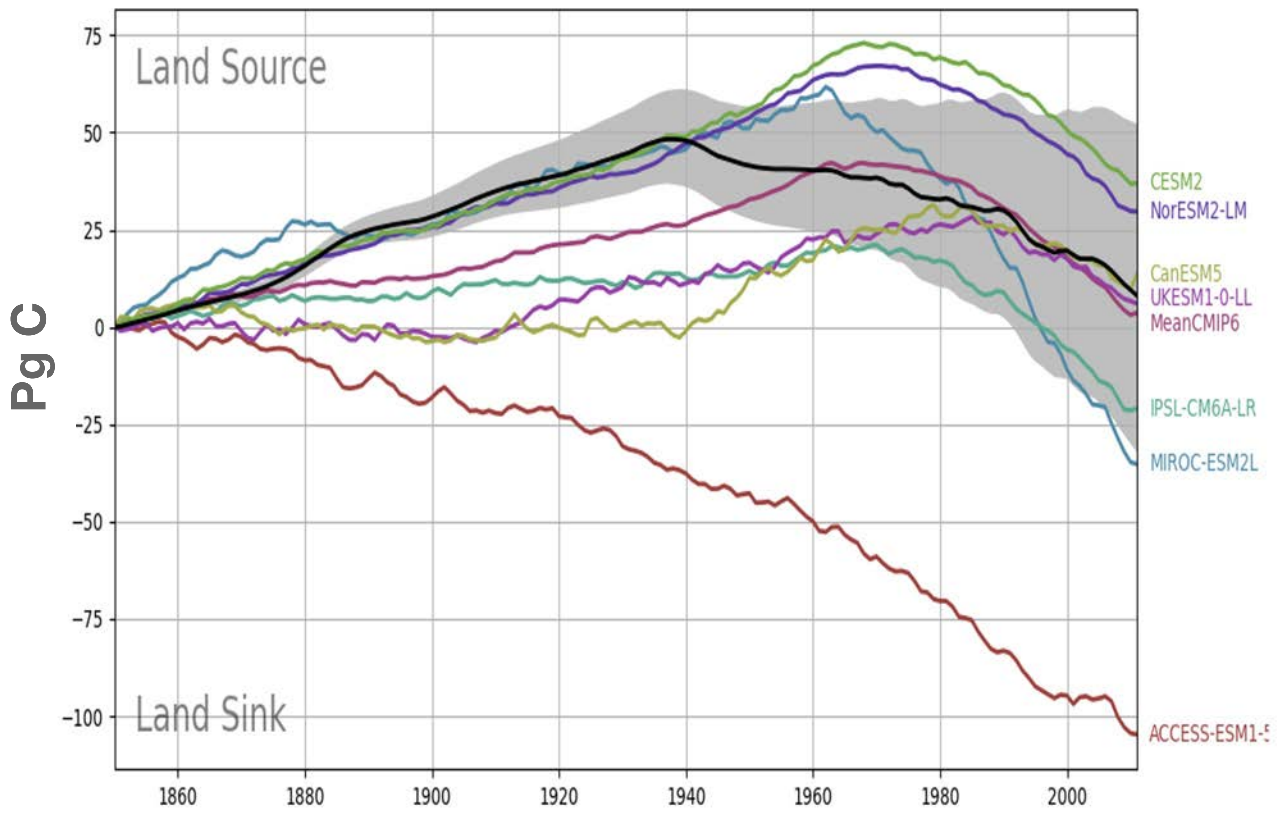
Friedlingstein et al. (2022)

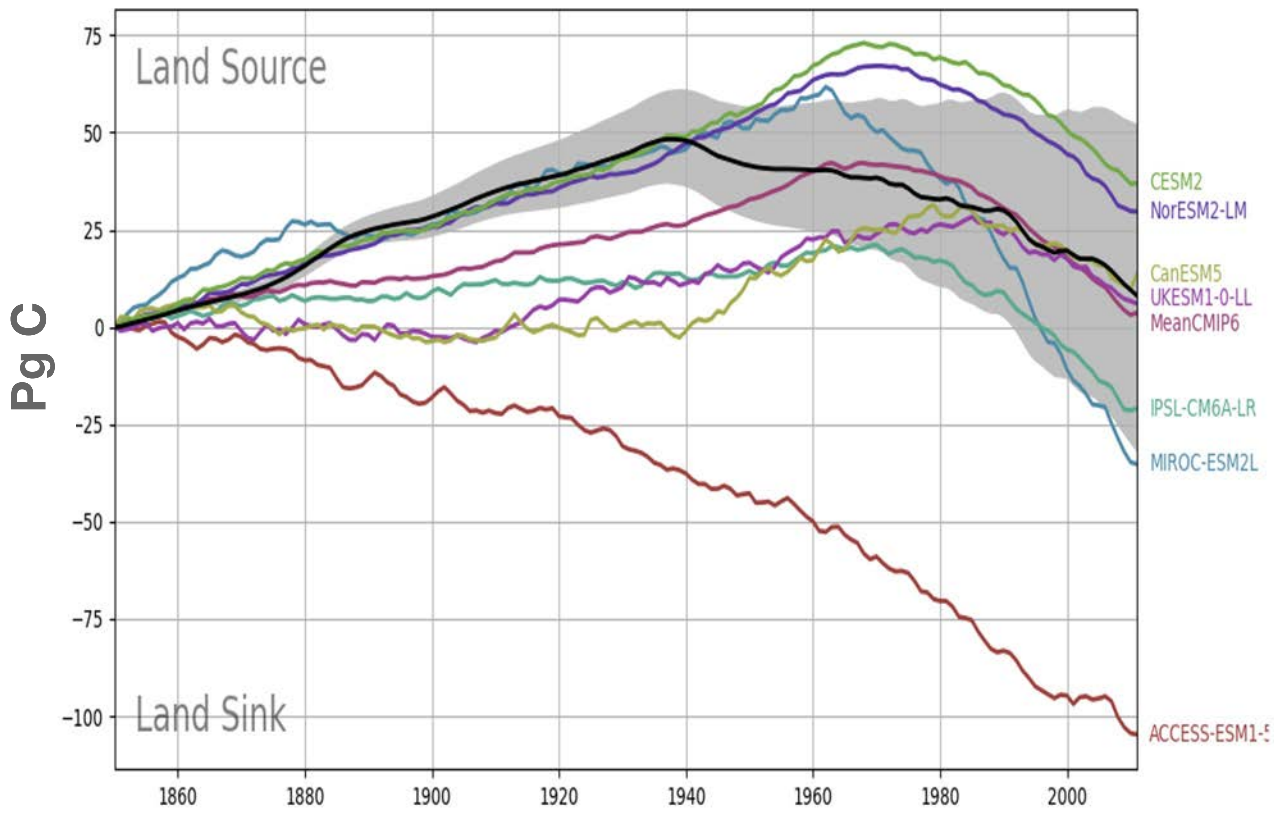
## Cumulative land carbon fluxes



## Two significant challenges:

1. All models are missing some relevant processes, examples include:
    - Land use change processes
        - Wood harvest
        - Shifting cultivation
        - Agricultural management (e.g., soil tilling)
        - …
    - Nutrients
    - Permafrost carbon processes
    - Fire
    - Lateral carbon flows in rivers
    - …
2. “Observed” land carbon stock trend is not an observation
    - Other observed trends we can use?

## Cumulative land carbon fluxes



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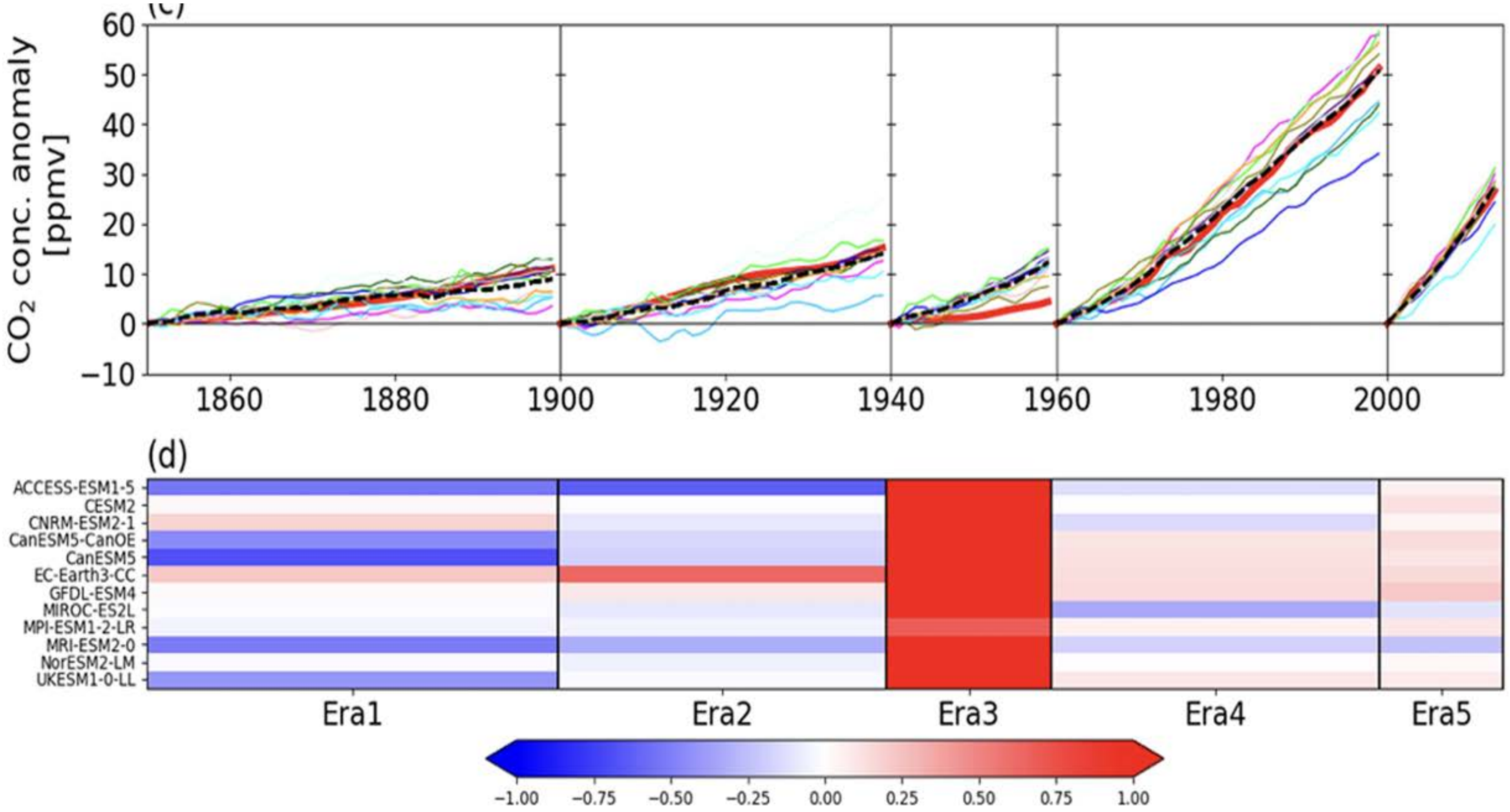
# Atmospheric $CO_2$ record provides clues



All models overestimate the $CO_2$ trend by ~5 ppmv in 1940 to 1960.

(1) **$CO_2$ emissions incorrect?** The Law Dome CO2 ice core record shows almost no increase during 1940s, which is inconsistent with 14 PgC emissions during this decade

(2) **Internal variability?** Ocean and/or land sink stronger than simulated due to decadal climate variations

(3) Land use change emissions could be too large because of unrepresented **land abandonment during World War II** (Bastos et al., 2016)

Hajjima et al., 2024

# Utilizing ecosystem manipulation experiments to assess models


**Nutrient addition experiments**

**Land-only CLM expts**

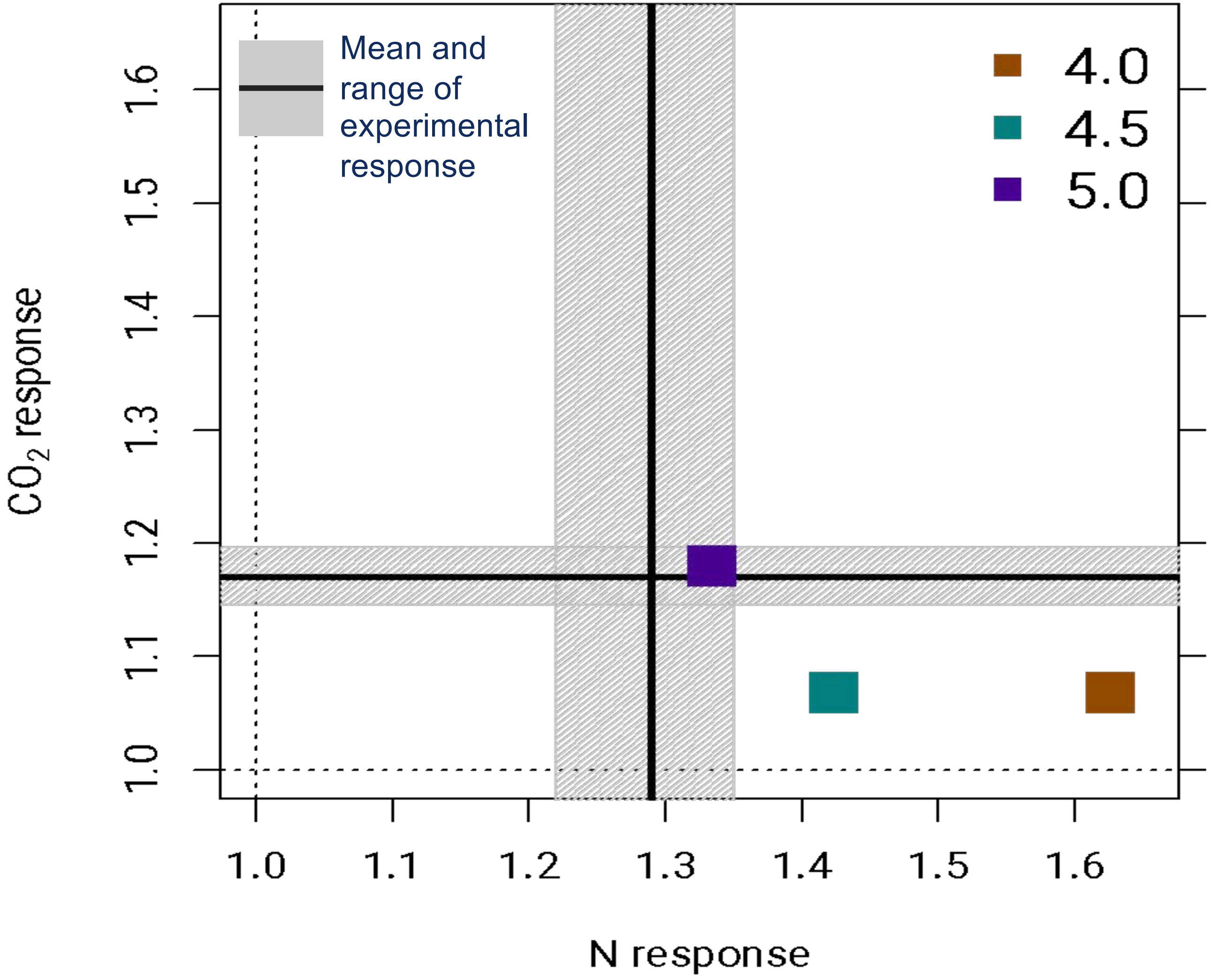
Control
+N (50 kg N $ha^{-1}$ $y^{-1}$)
+$CO_2$ (200 ppm)

Evaluate **Treatment / Control** against synthesis of responses at different sites


**Free Air Carbon Enrichment (FACE) experiments**

Medlyn et al. 2015 *Nature Clim. Change*
Wieder et al. 2019

# Net primary productivity response to fertilization



Improved agreement with manipulation expts across generations of the CESM Community Land Model

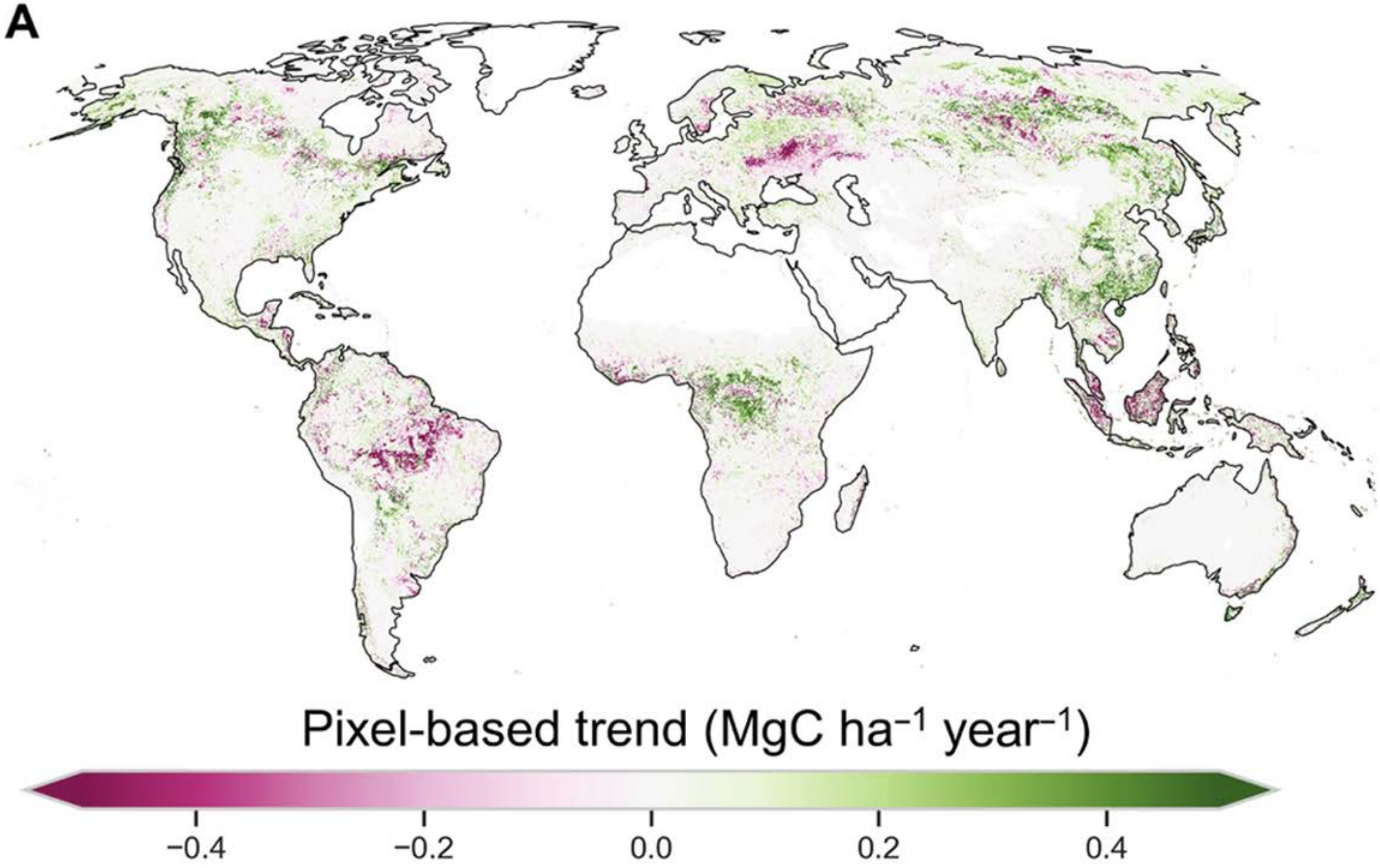
Caveats seen in manipulation expts

- Old growth forests show muted response compared to younger forests
- Response saturates after X years for some experiments
- Nutrient effects
- Incomplete coverage of plant types

Wieder et al. 2019

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

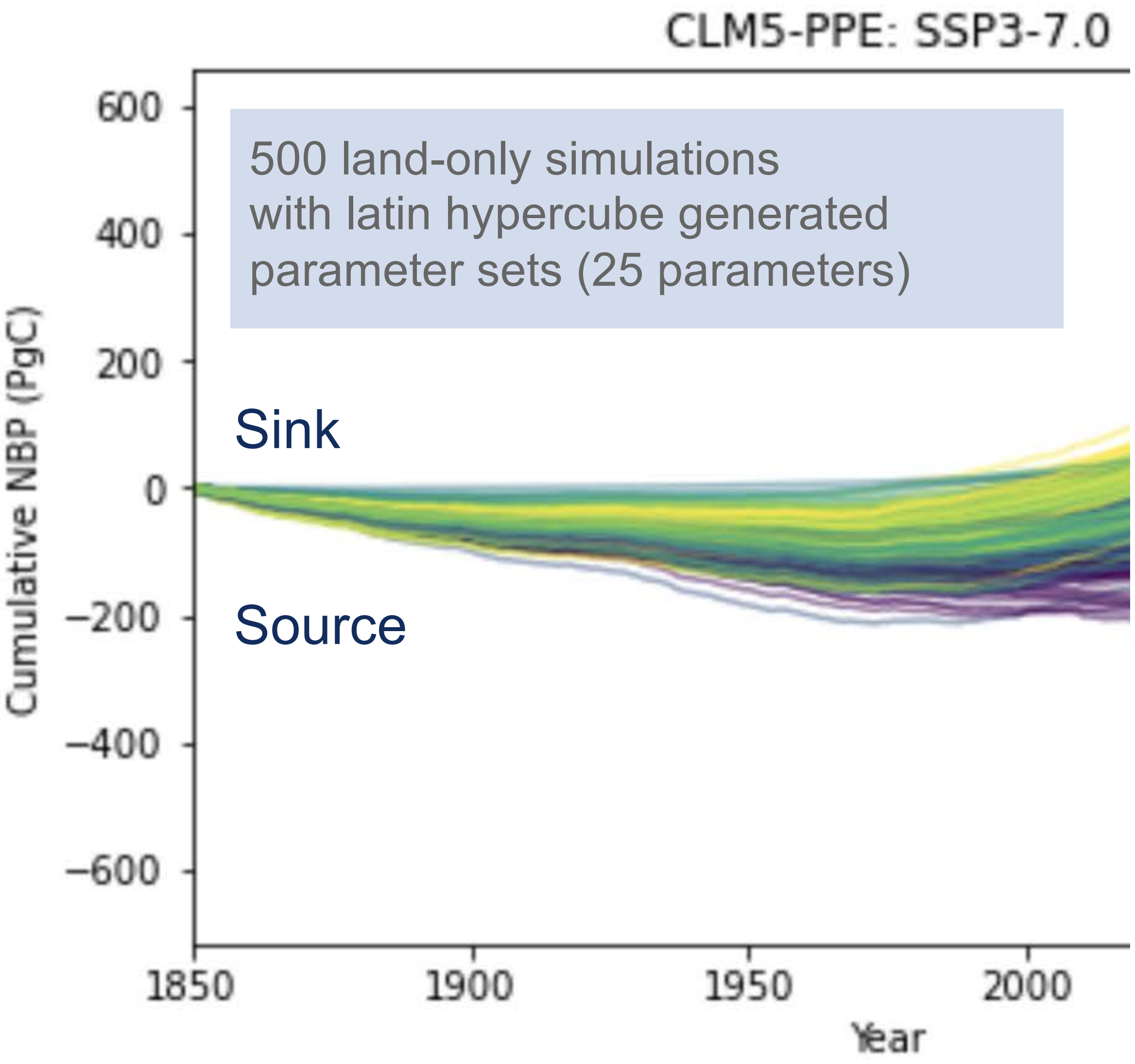
## Live woody biomass trend estimates from forest inventory and satellites



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

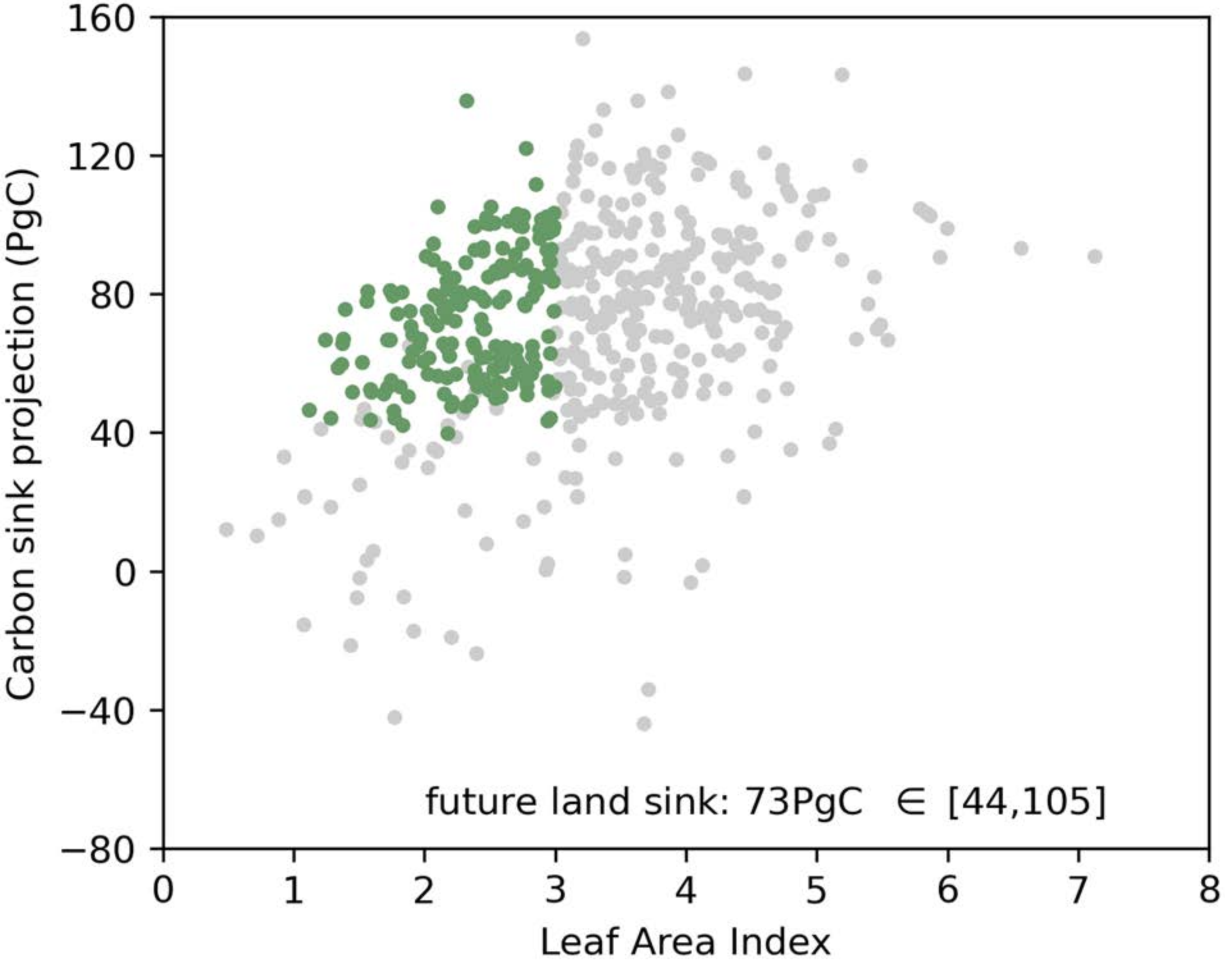
Xu et al. 2021, Science Advances

# Learning from parameter perturbation experiments



500 land-only simulations with latin hypercube generated parameter sets (25 parameters)

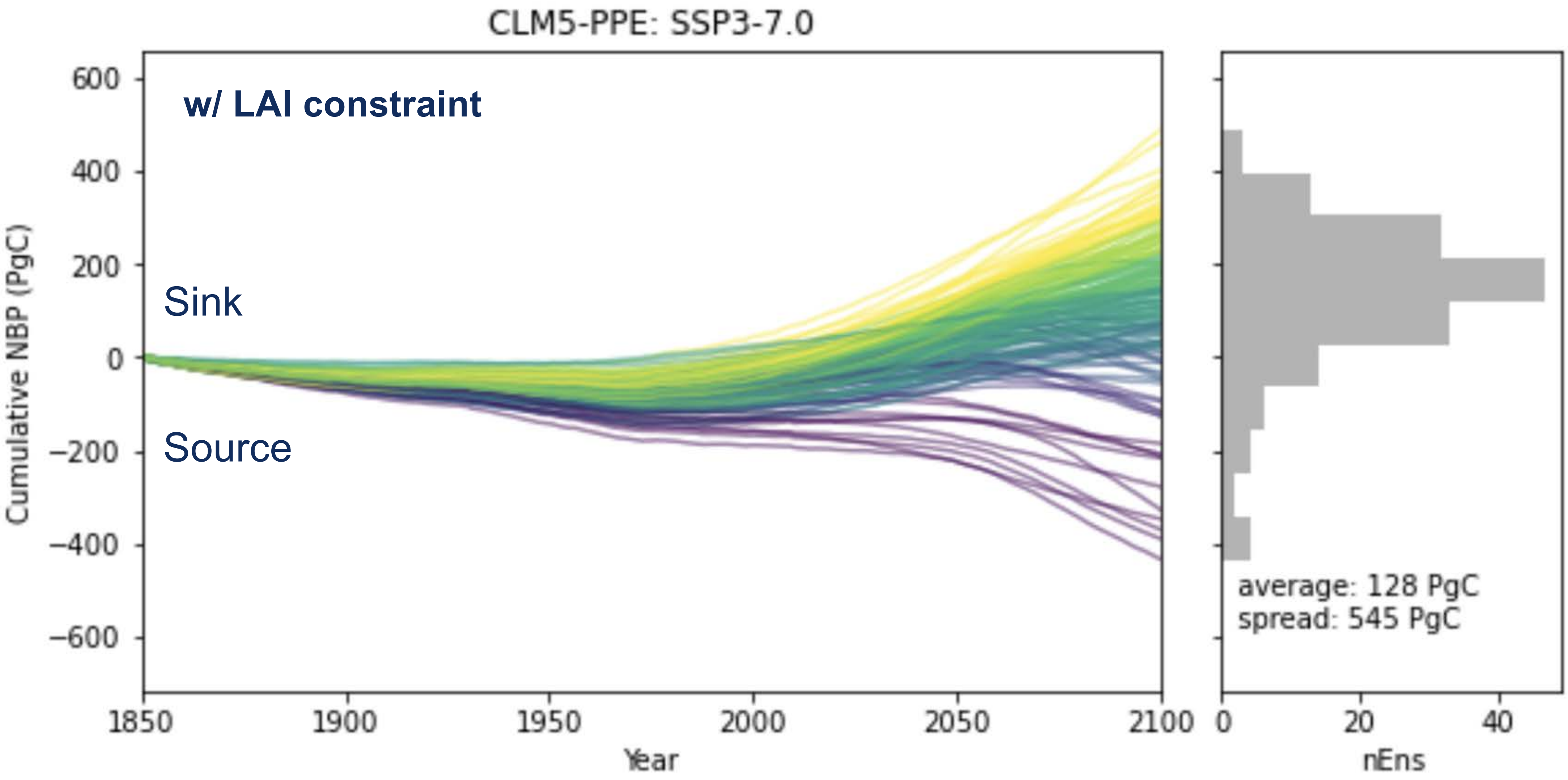
# Constraining Land Carbon Cycle Projections



Retain only parameter sets with reasonable

- leaf area index mean / trend
- total land use flux
- recent historical C sink trend

# Learning from parameter perturbation experiments



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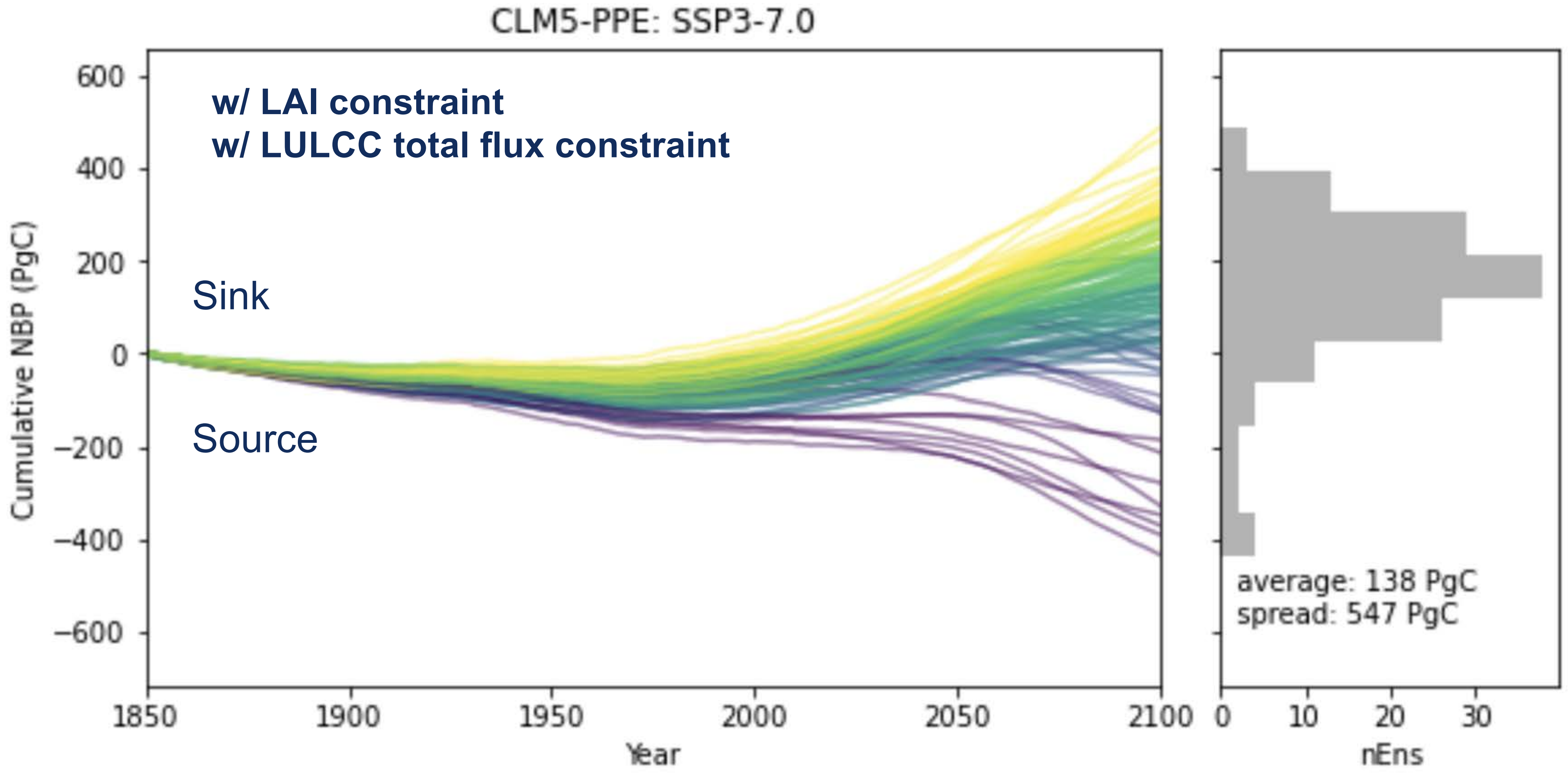

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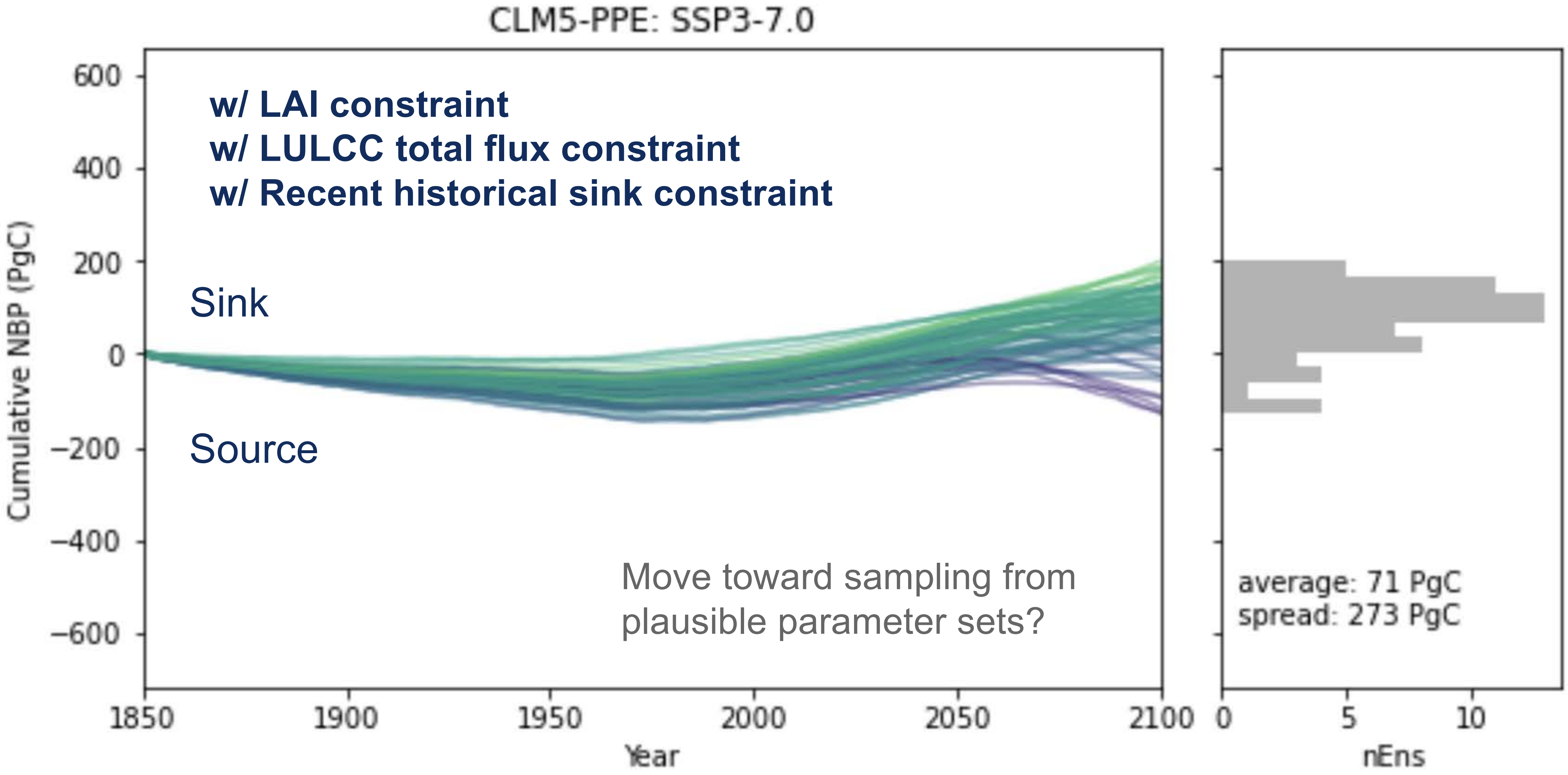


**w/ LAI constraint**
**w/ LULCC total flux constraint**
**w/ Recent historical sink constraint**

Sink

Source

Move toward sampling from plausible parameter sets?

# Summary

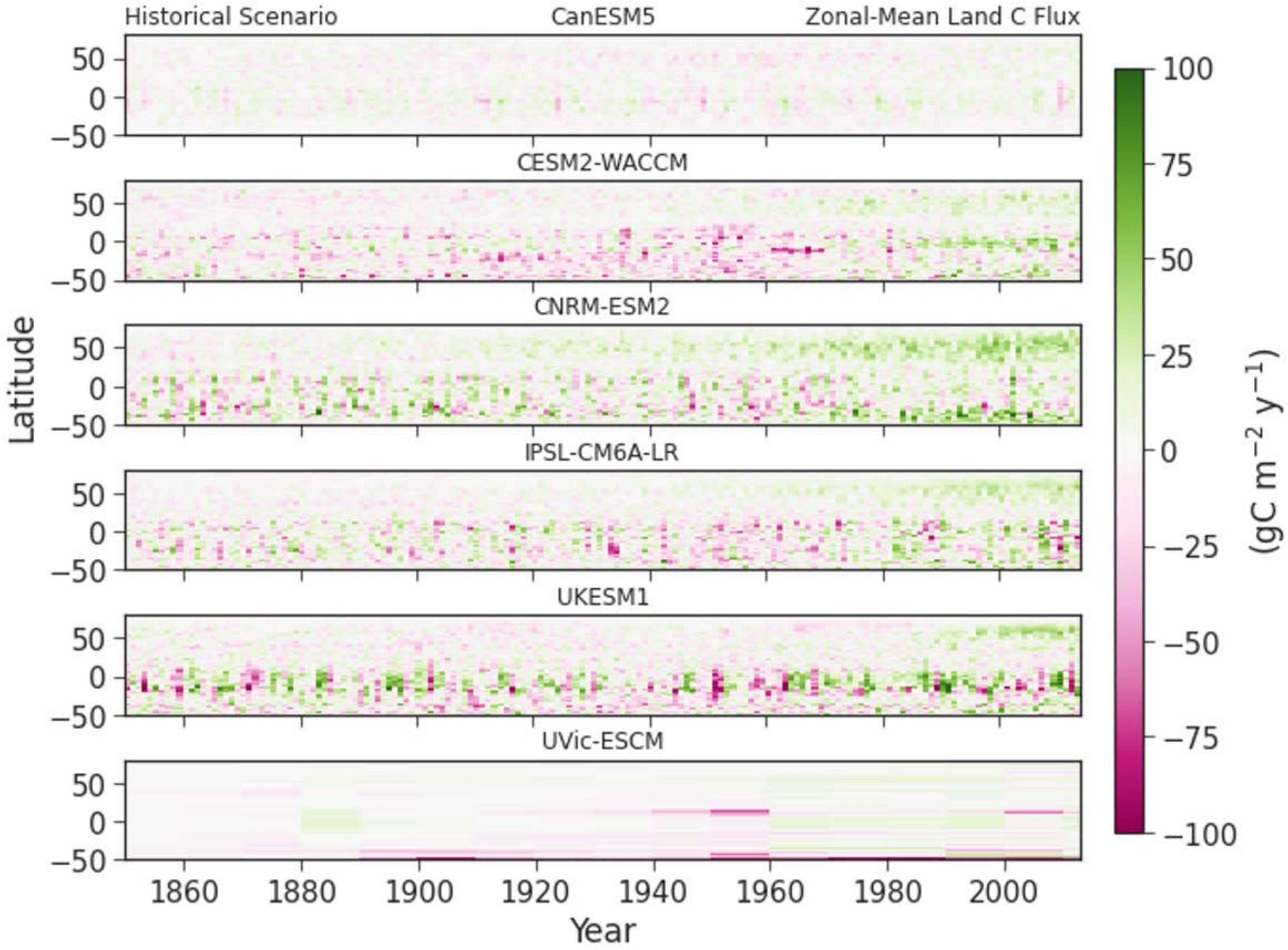
- Models do not agree on historical or projected land carbon sink, which drives considerable climate change uncertainty
- The strength of the sink is driven by complex set of factors (incl. land use change, fertilization, and climate change)
- Historical sink is not observed, but some observational records from satellite, Flux Tower Sites, forest inventories, and the $CO_2$ record are now long enough that they may be able to provide useful constraints on model trend behavior

Image: Joel Vodell

# CO2 fertilization / climate

Arora plots

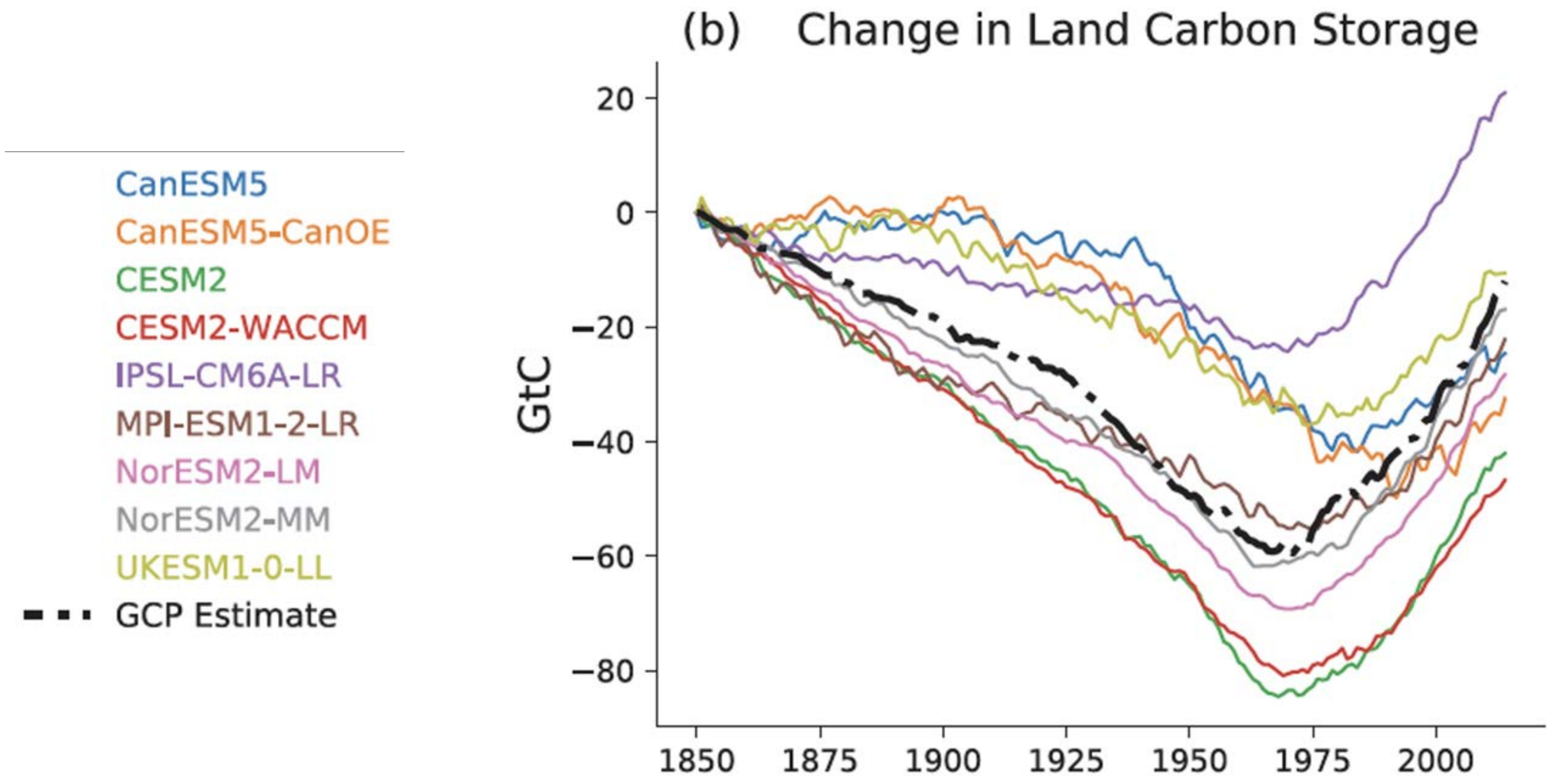
# Carbon Cycle Uncertainty in Land Model Projections

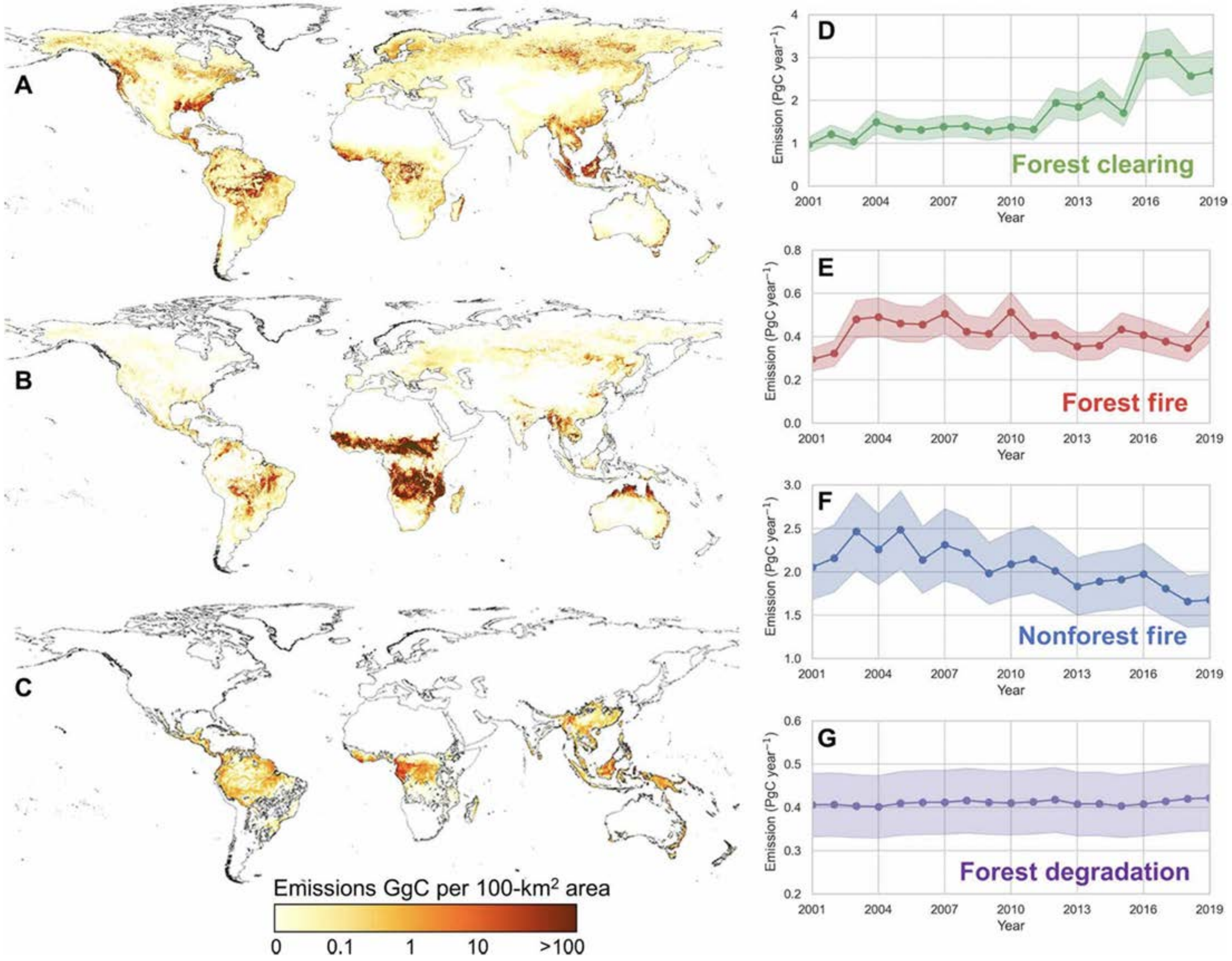


The response of the terrestrial biosphere to increasing atmospheric CO 2 concentration is incompletely understood, leading to major uncertainty in model predictions of carbon dynamics and future scenarios of climate change (Arora et al. 2013). Moreover, despite evidence that the CO 2 fertilisation of 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).

Wu et al. 2021, Science Advances

# ILAMB results





Wu et al. 2021, Science Advances

# Thank you!

Time for questions, comments and discussion

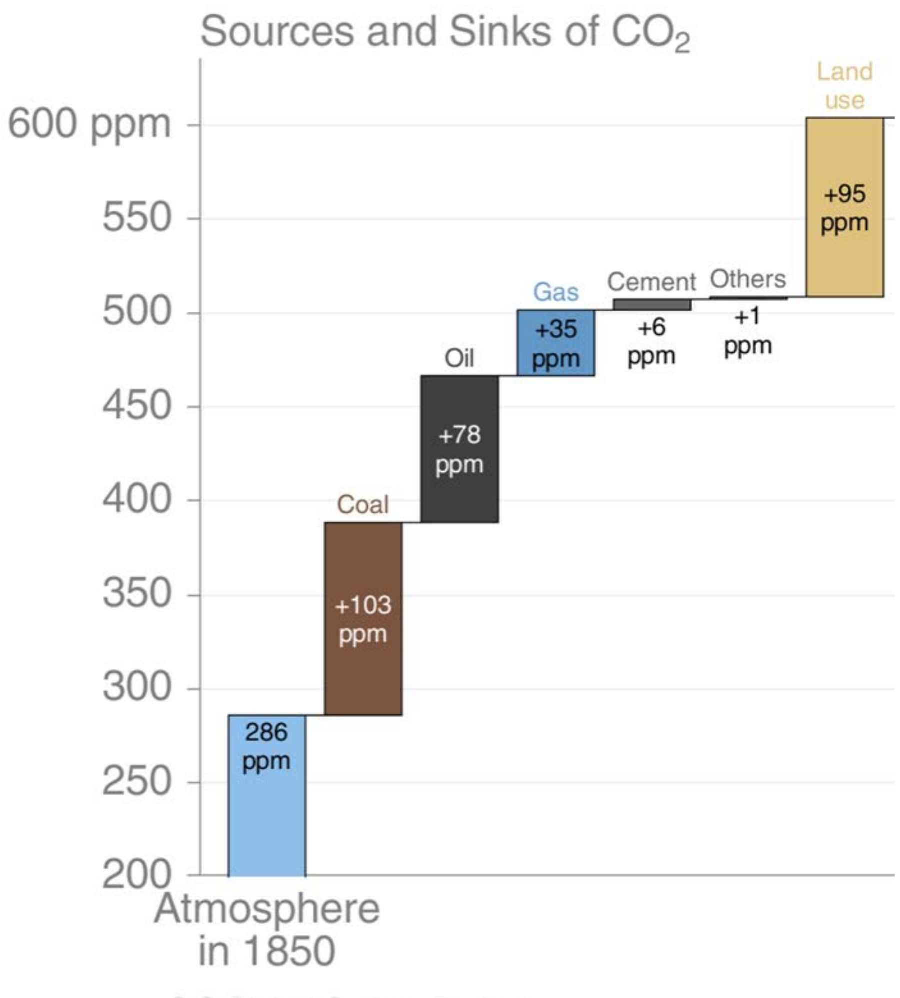
# Papers

Hoffman et al., 2014 https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2013JG002381

https://egusphere.copernicus.org/preprints/2024/egusphere-2024-188/egusphere-2024-188.pdf

# Global carbon budget

## The cumulative contributions to the global carbon budget from 1850



# Fate of anthropogenic $CO_2$ emissions (2012–2021)

## Sources

35.2 $GtCO_2$/yr

89%

11%

4.5 $GtCO_2$/yr

## Sinks

19.1 $GtCO_2$/yr

48%

29%

11.4 $GtCO_2$/yr

26%

10.5 $GtCO_2$/yr

Source: Friedlingstein et al 2022; Global Carbon Project 2022

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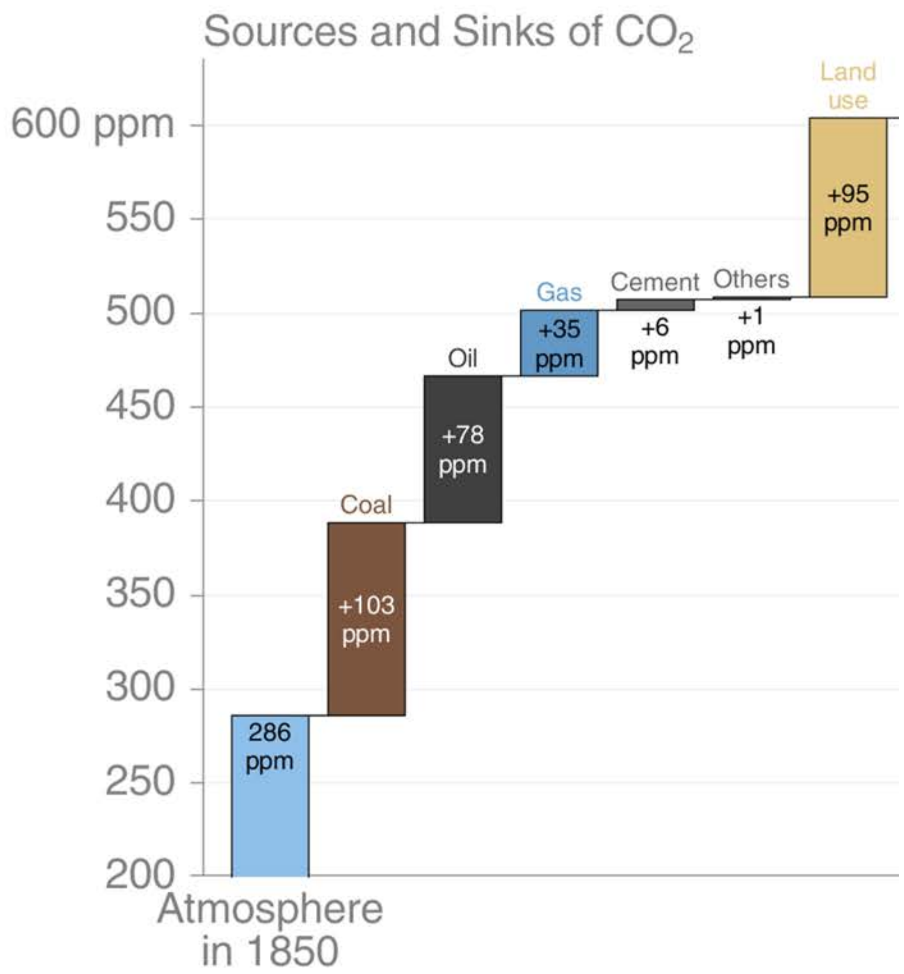

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