Ecological and Economic Underpinnings of the Weak Terrestrial Carbon Sink Hypothesis

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Francois Primeau, Jinhyuk Kim, Sassan Saatchi, and Mike Goulden

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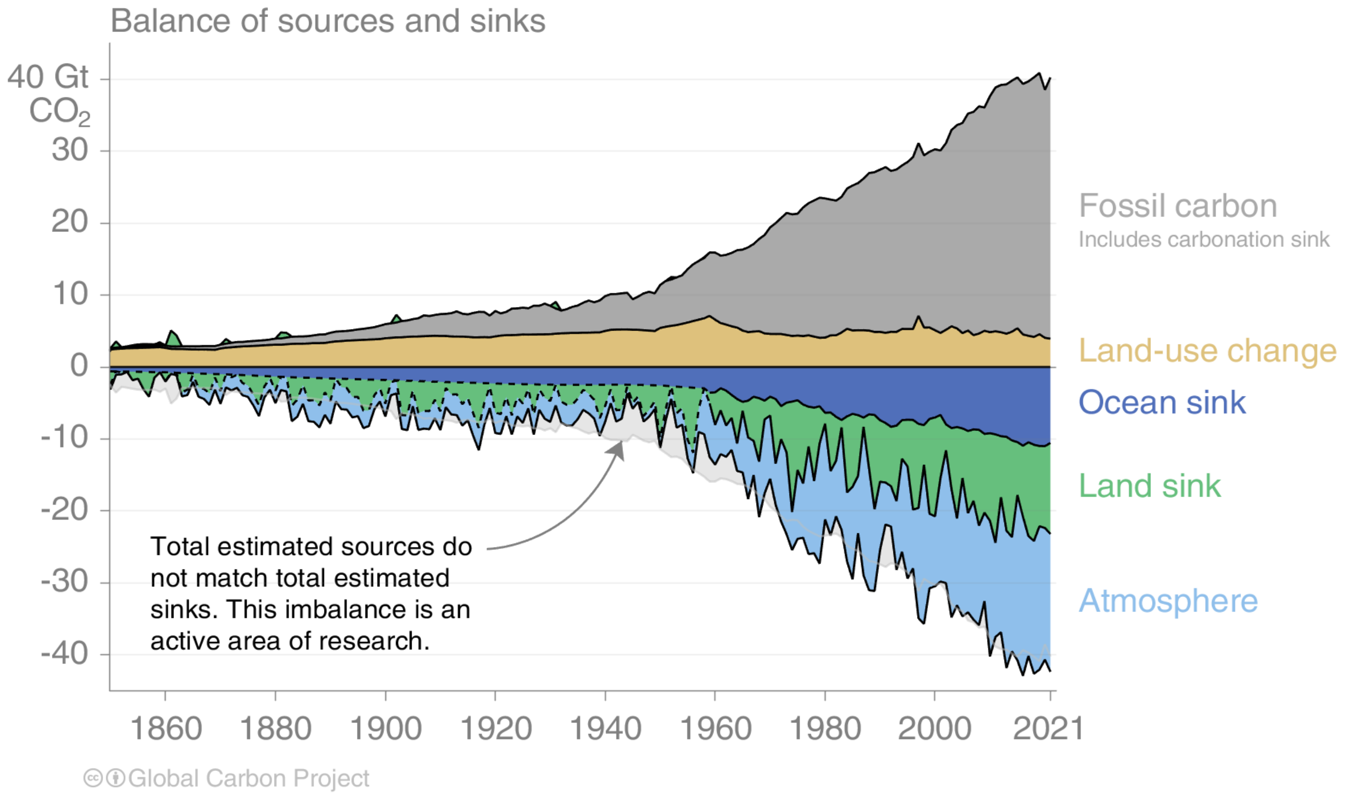
Are observed changes in land carbon stocks consistent with land carbon flux inversions?

$$\int_{t=1958}^{t=2023} F_{land}(t) \cdot dt = \Delta C_{land}$$

$$\Delta C_{land} = \Delta C_{veg} + \Delta C_{litter} + \Delta C_{soil}$$

Integrals of global and NH terrestrial sinks:

GCP: Global net land C sink integral from 1959-2021: 55 Pg C



Global budget: 1959-2021:

C_{veg} = 408 Pg C

ΔC_{land} = 55 Pg C

Percent change: 16%

Ciais et al. (2019): NH net land sink integral from 1959-2014: 79 Pg C

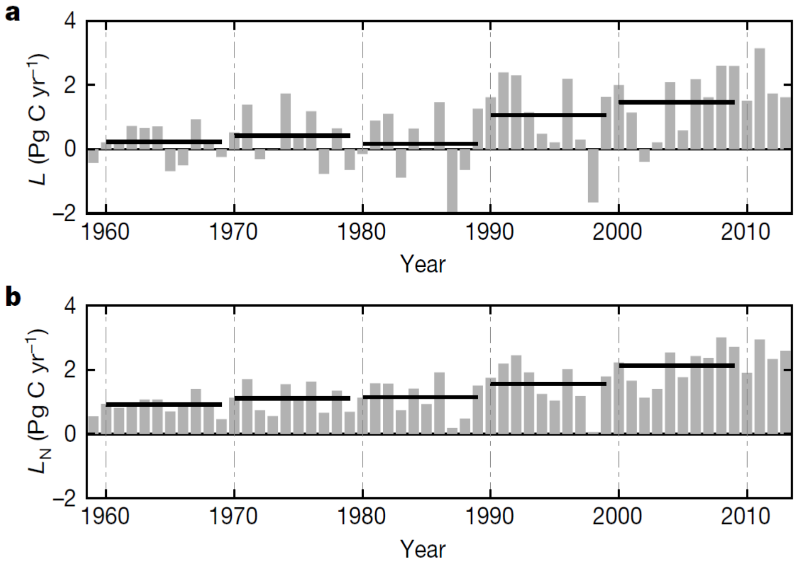


Fig. 3 | Global and Northern Hemisphere land fluxes. a, Global net land flux (L), this flux includes land-use change emissions and other processes causing land uptake. **b**, Northern land sink (L_N) inferred from the two-box inversion model constrained by measurements of the interhemispheric gradient and the ocean sink interhemispheric difference from ocean models (Methods).

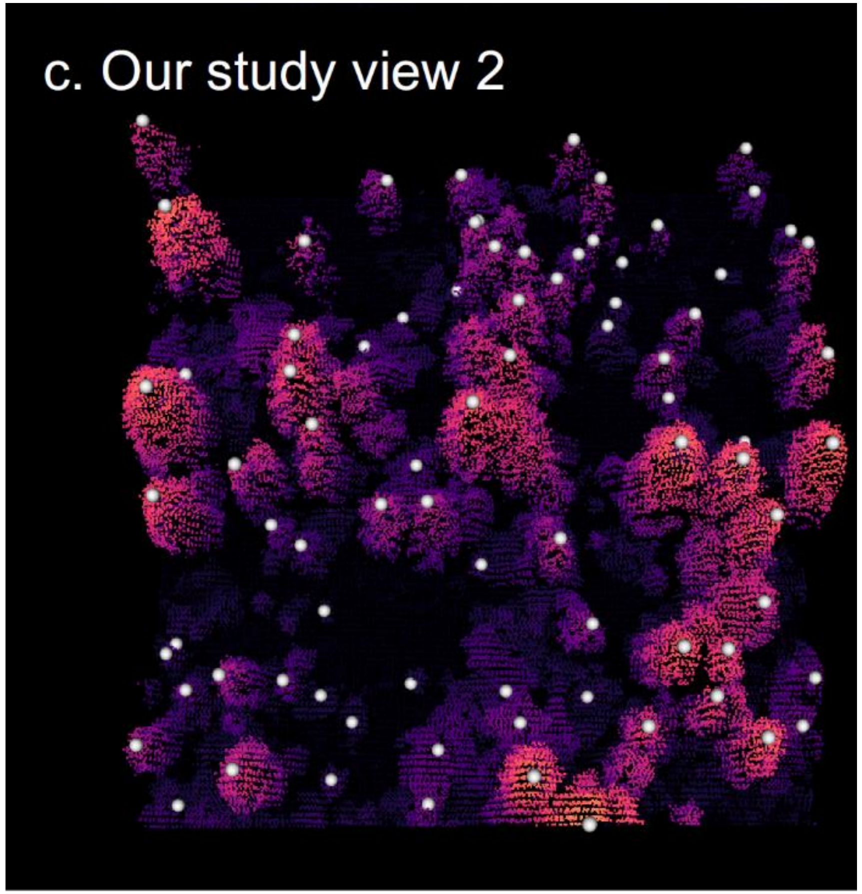
NH budget: 1959-2021:

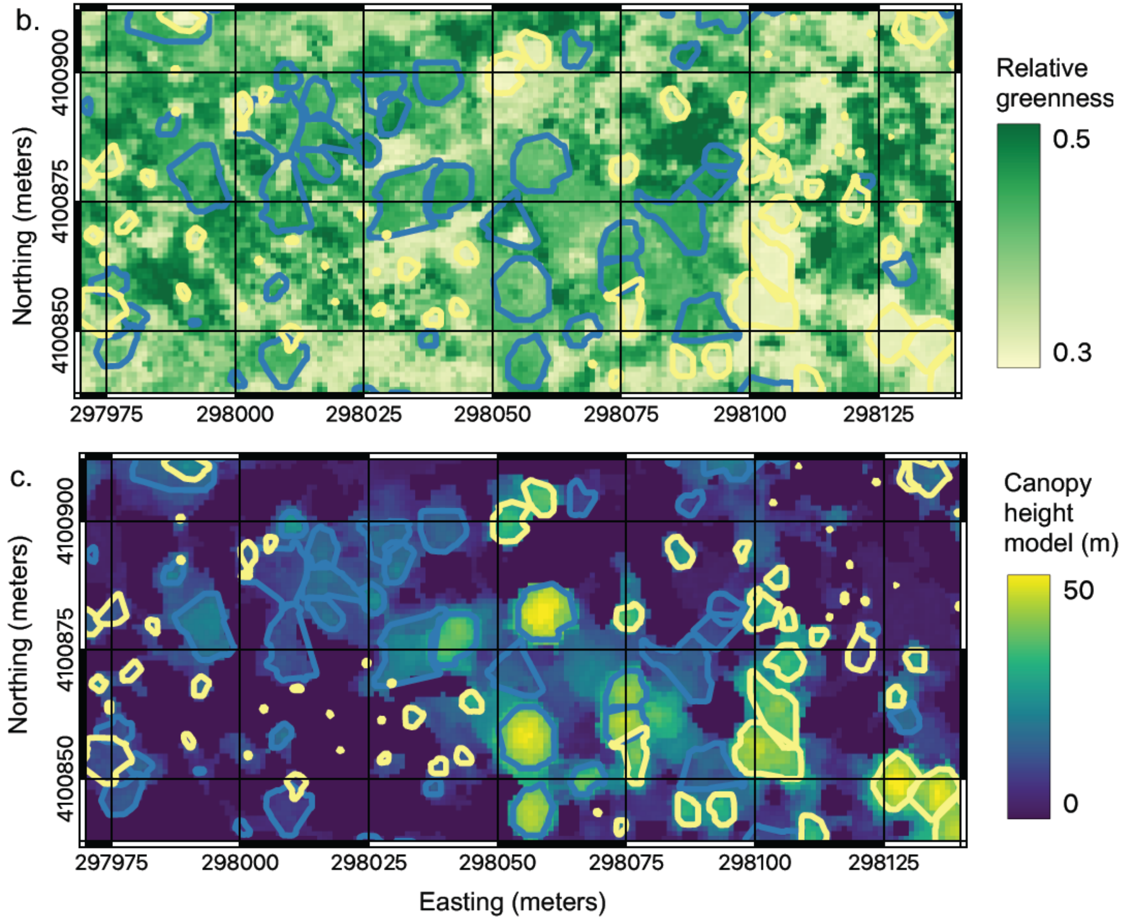
C_{veg} = 261 Pg C

ΔC_{land} = 81 Pg C

Percent change: 45%

Improvements in satellite remote sensing are narrowing uncertainties regarding the magnitude, spatial pattern, and trend of terrestrial aboveground carbon stocks





Hemming-Schroeder et al. (2023)

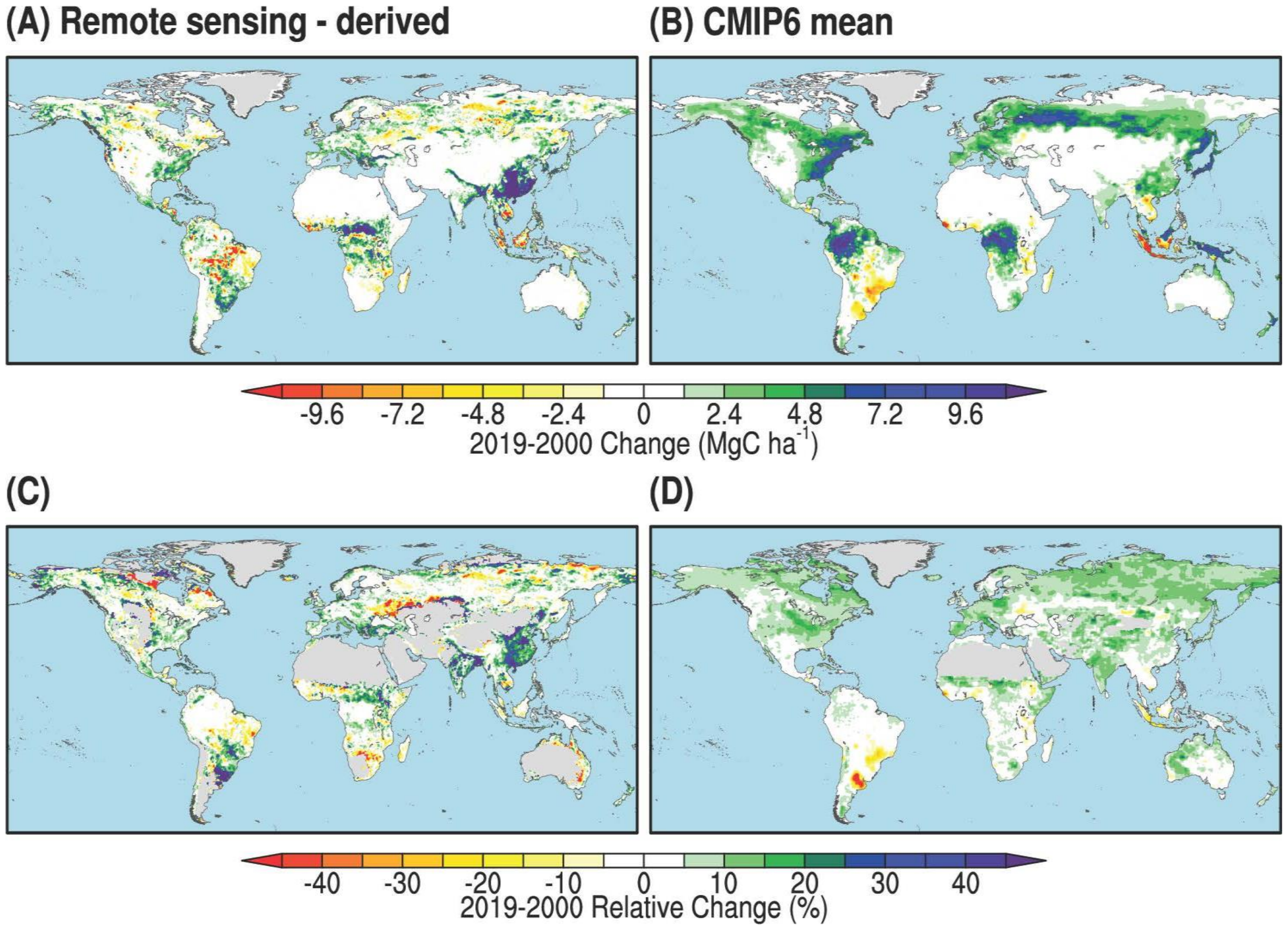
Global satellite-derived estimates of biomass carbon are considerably lower than model estimates from 2000 to 2019

Remote Sensing-derived from JPL and Chloris

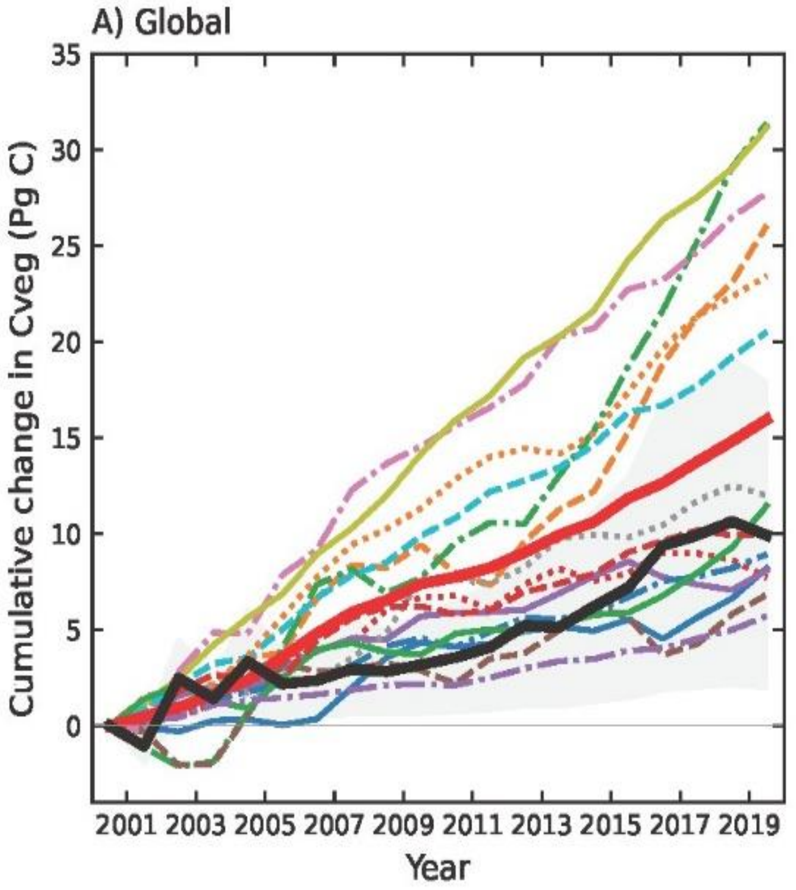
CMIP6 multi-model mean

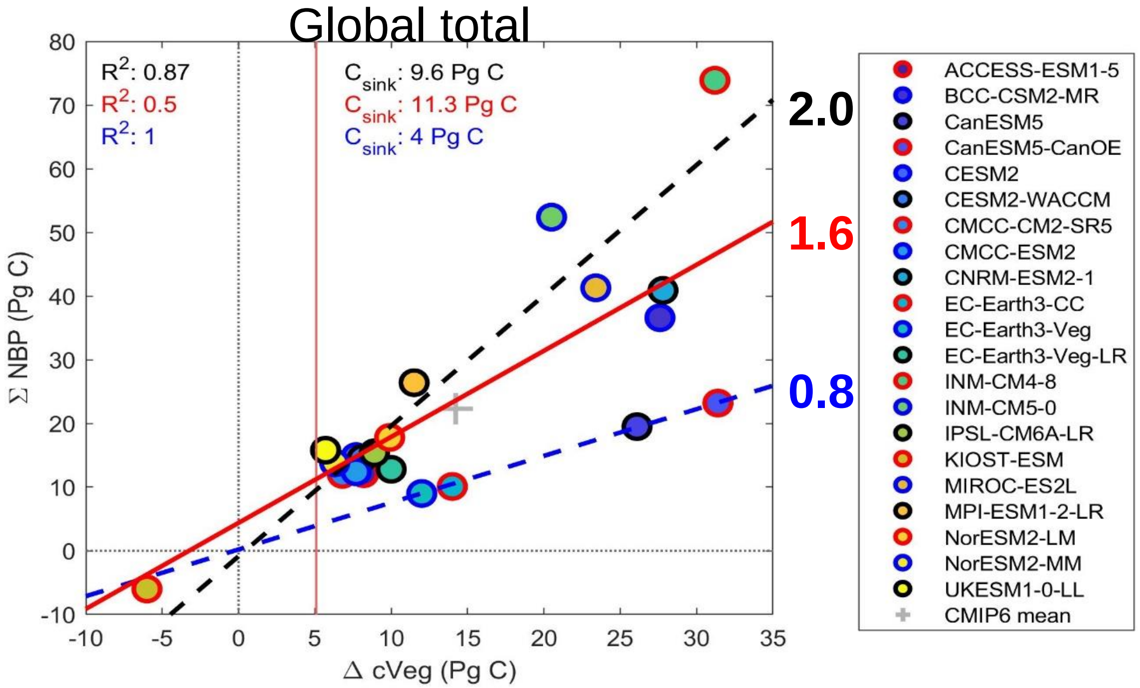
Absolute change ($Mg\ ha^{-1}$)

Relative change (% over 20 years)



Trends in modeled vegetation carbon are about 70% higher than the remote-sensing derived estimate



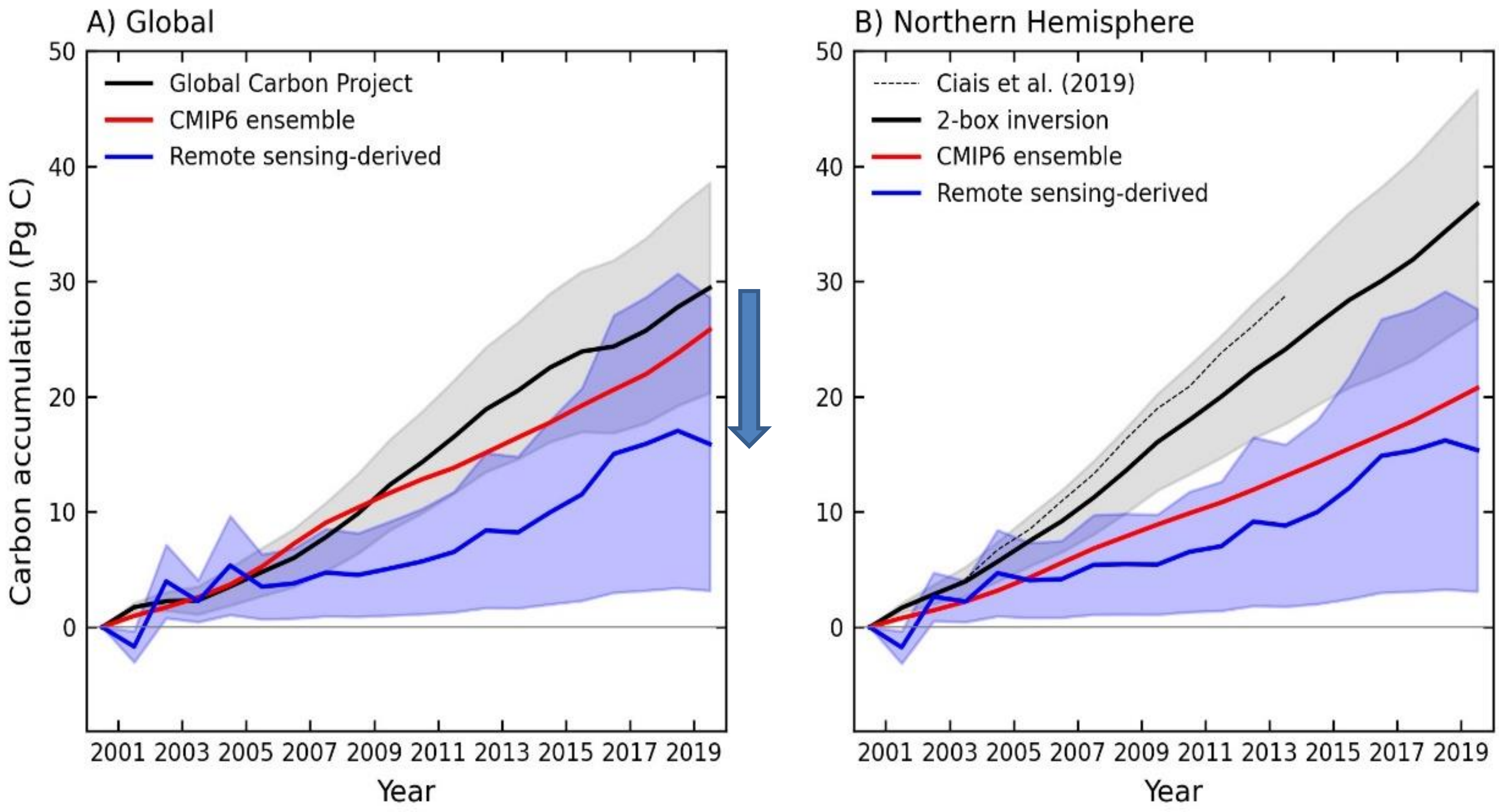


$$\frac{NBP}{\Delta C_{veg}} = \frac{\Delta C_{veg} + \Delta C_{litter} + \Delta C_{soil}}{\Delta C_{veg}}$$

Inventory measurements (Pan et al. 2024): 1.1-1.3

CMIP6 land surface models: 1.6 ± 0.5

The satellite-constrained global land carbon sink is 0.8 ± 0.7 Pg C/y for 2001-2019, about 2-fold lower than the GCP estimate of 1.6 Pg C/y

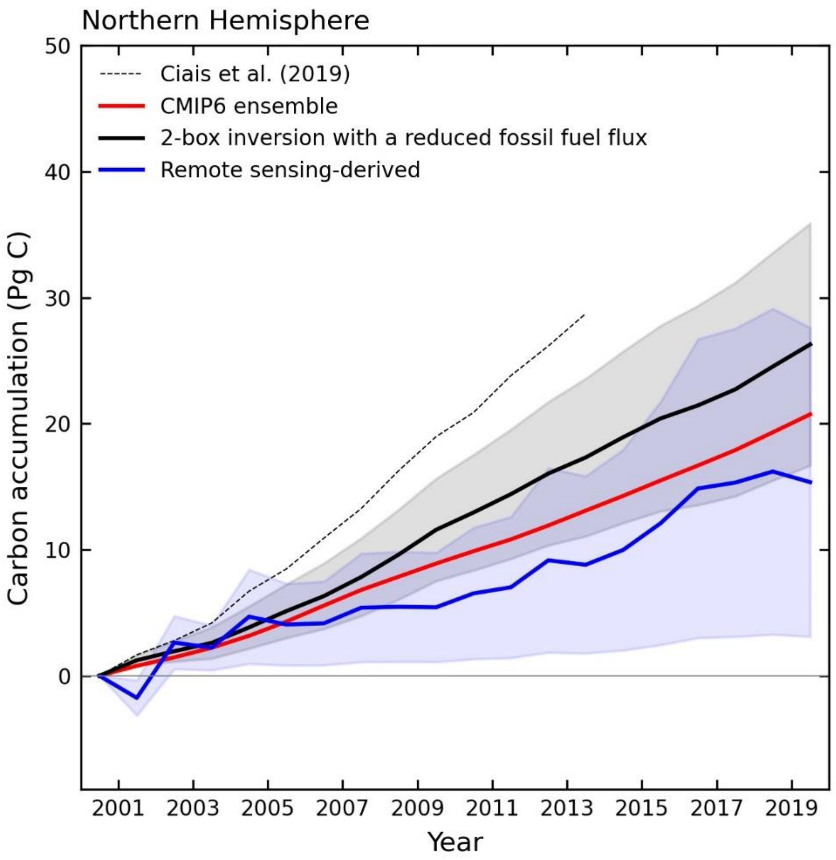


How do you then close the global carbon budget?

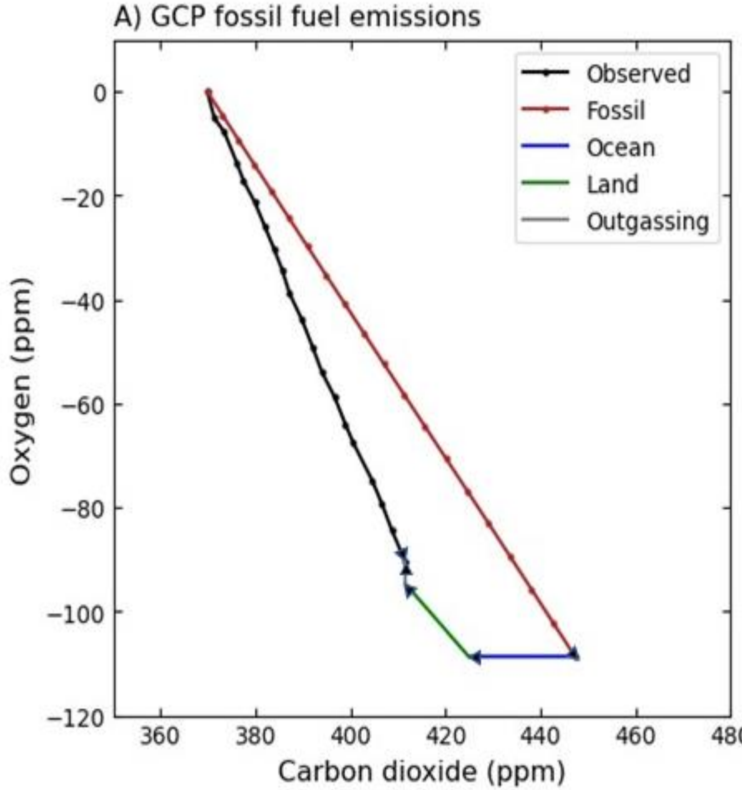
Flux component: Units: Pg C/y	Global Carbon Project:			Weak Land Sink Hypothesis:			Percent difference
	mean		1 σ	mean		1 σ	
Fossil fuel emissions	8.6	±	0.4	8.1	±	0.9	-6
Atmospheric growth rate	4.6	±	0.1	4.6	±	0.1	0
Ocean sink	2.5	±	0.4	2.7	±	0.5	8
Land sink	1.6	±	0.7	0.8	±	0.7	-47

A weaker fossil fuel flux helps to reconcile several disparate constraints:

Two-box model NH sink with 6% Reduction in FF Flux:

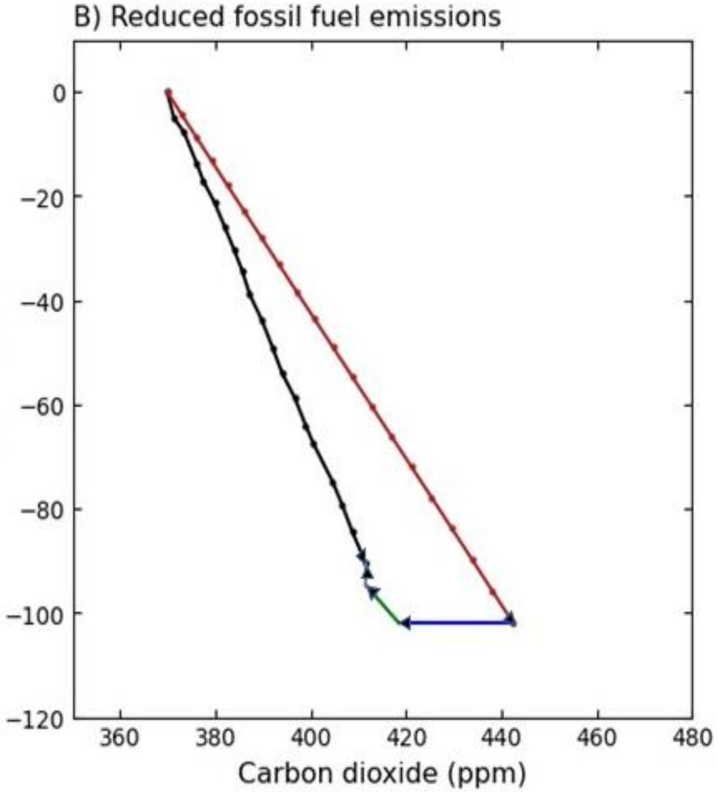


GCP Fossil Fuel Flux



Land sink: 1.6 Pg C/y
Ocean sink: 2.4 Pg C/y

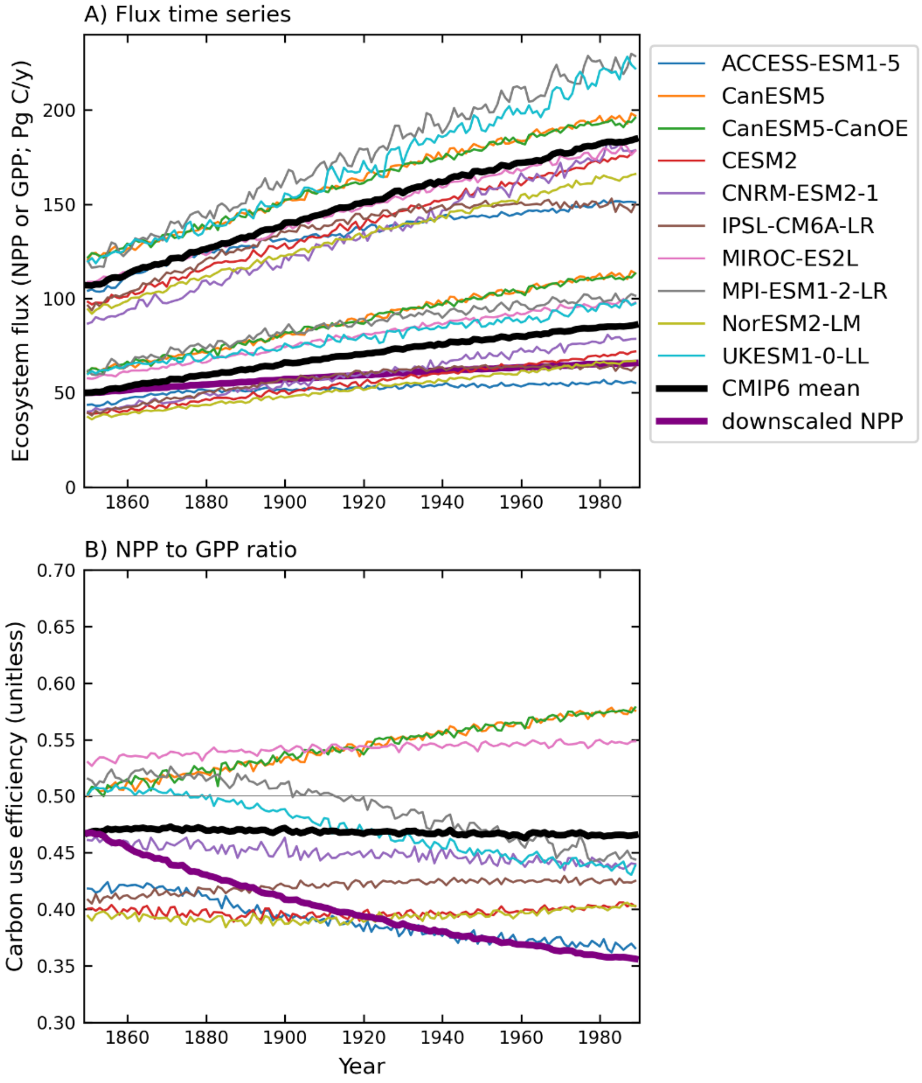
6% Reduction in FF Flux



Land sink: 0.8 Pg C/y
Ocean sink: 2.7 Pg C/y

Data from Ralph Keeling at SIO (MLO Station)

Why do many CMIP6 models accumulate too much C?
They are not capturing increasing disturbance trends, decoupling of GPP and NPP, and limits to soil carbon uptake from microbial feedbacks and mineral stabilization

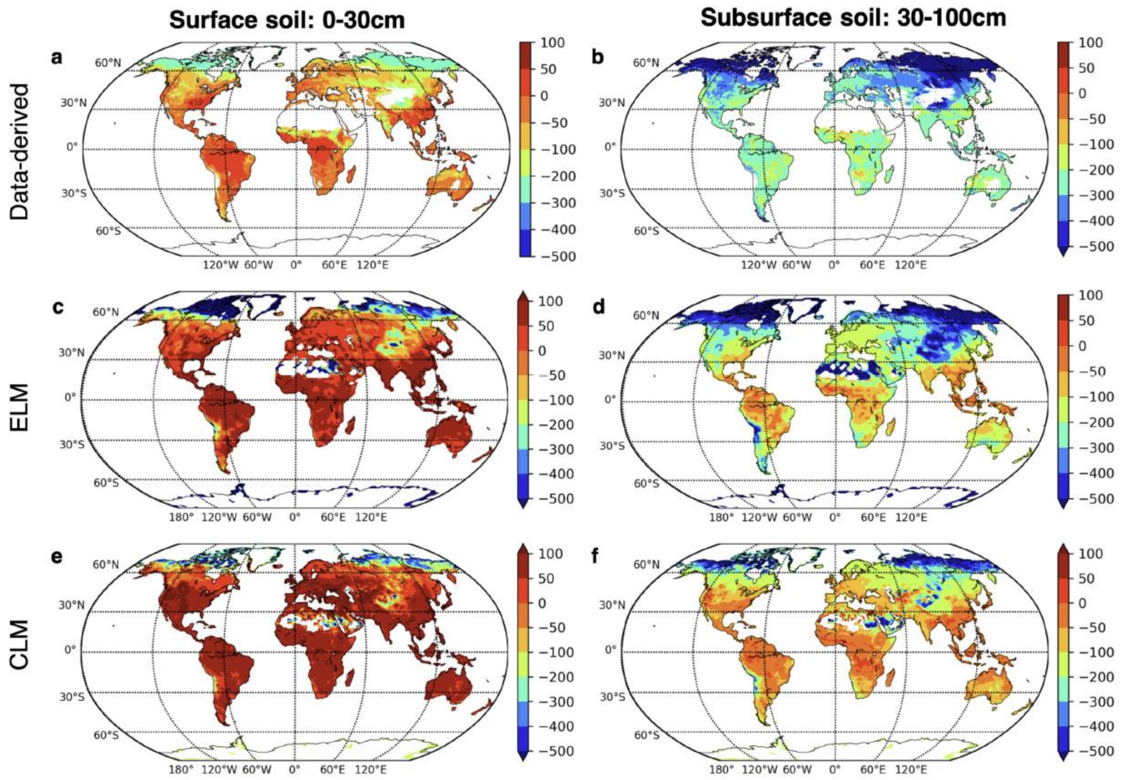


Effect:	CMIP6 Models:	Observations: Ainsworth and Long (2005), Norby et al. (2005)
GPP enhancement	27%	32%
NPP enhancement	29%	18%

Could it be in the soil instead of aboveground biomass?

- The answer is unlikely for mineral soils because they are too old, and the carbon flows in a steady state are too small to influence a change on a 100-year time scale
- Also, likely carbon storage is limited by mineral stabilization, which reflects long-term weathering rates – this is unlikely to change quickly.
- Models represent soil carbon flows with turnover times that too fast; this means they draw in too much C from NPP changes (e.g., CO_2 fertilization) on century timescales

Radiocarbon content (del 14C)



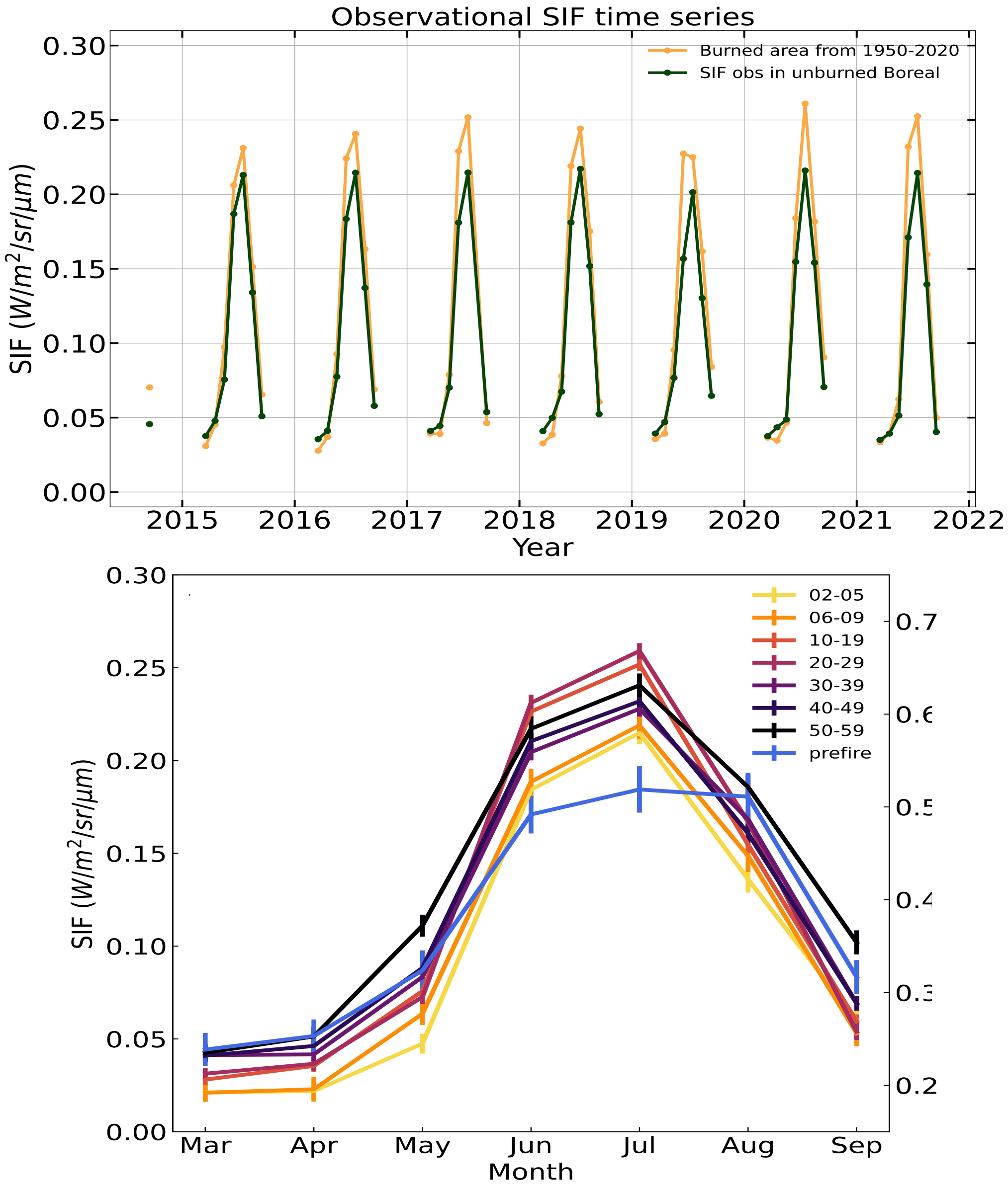
He, Y., S.E. Trumbore, M.S. Torn, J.W. Harden, L.J.S. Vaughn, S.D. Allison, and J.T. Randerson. 2016. Radiocarbon constraints imply reduced carbon uptake by soils during the 21st century. Science. 353:1419-1424. doi: 10.1126/science.aad4273.

Shi, Z., S.D. Allison, Y. He, P.A. Levine, A.M. Hoyt, J. Beem-Miller, W. Wieder, Q. Zhu, S.E. Trumbore, and J.T. Randerson. 2020. The age distribution of global soil carbon inferred from radiocarbon measurements. Nature Geosciences. 13: 555–559. doi: 10.1038/s41561-020-0596-z.

How to make the weak sink compatible with other carbon cycle constraints?

- A decoupling of GPP from NPP and NPP from woody biomass responses to atm. CO_2 can help explain changes in the annual cycle of atmospheric CO_2

- Changes in plant functional types following disturbance can partly explain global greening trends



J.E. Kim et al. Global Change Biology (2024)

Conclusions and Implications:

- Major advances in satellite remote sensing now enable direct estimation of the land carbon sink

- Fossil fuel emissions may have a small systematic positive bias and larger uncertainties than currently assumed. These emissions are largely self-reported to the IEA and the UN. A possible conflict of interest may arise in that currency valuation, capital investment, and trade negotiation are all tied to the projection of growth.
  - Did the Kyoto Protocol incentivize overreporting for Annex B countries?
  - Should the COP strengthen the review system for fossil fuel emissions?

- The potential for improved forest management may be overestimated in some situations (e.g., Coffield et al., 2022)

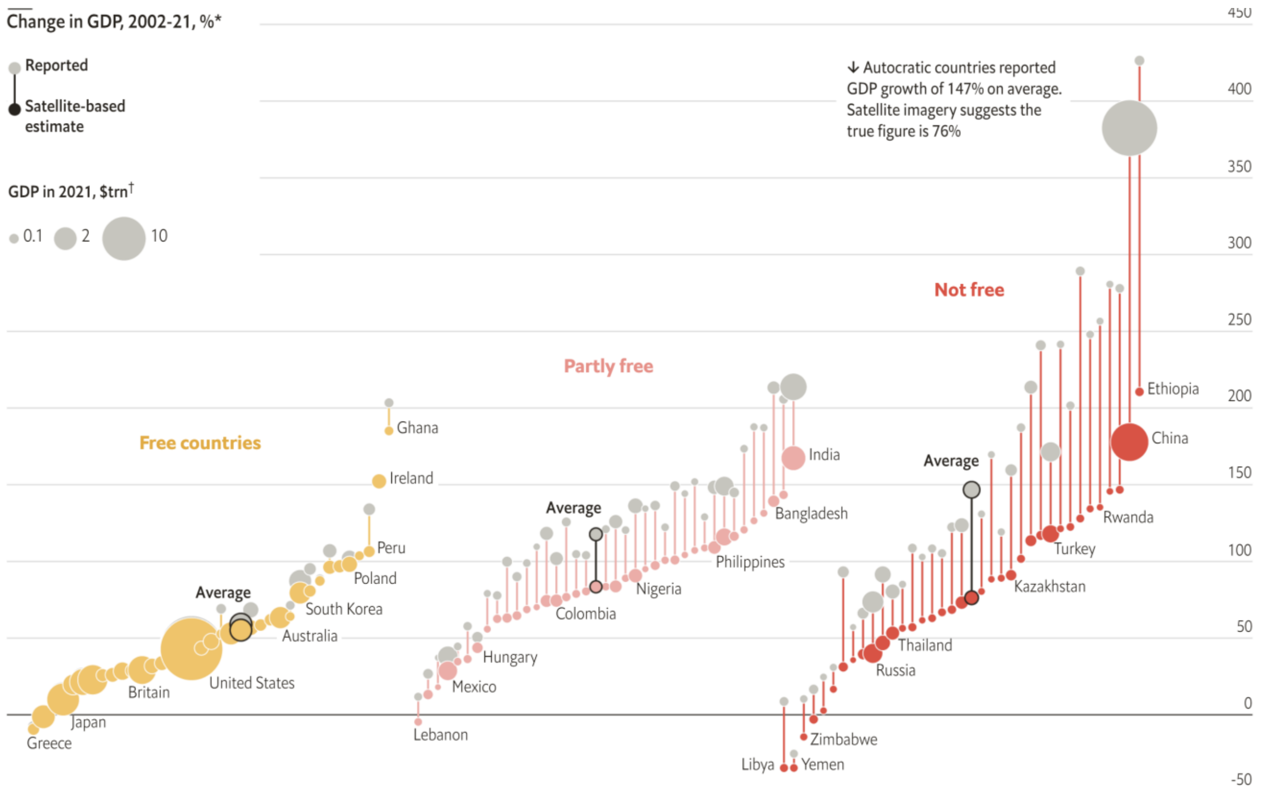
- Could we implement a stock change approach across Ameriflux using in-situ lidar and inventory protocols?

- Use of aboveground biomass time series from lidar/Landsat will be a critically important emergent constraint for the land carbon sink in CMIP7

Backup Slides

Is there be a high bias in the fossil inventory, and why?

Emissions are often self-reported, and often closely connected to energy and GDP statistics



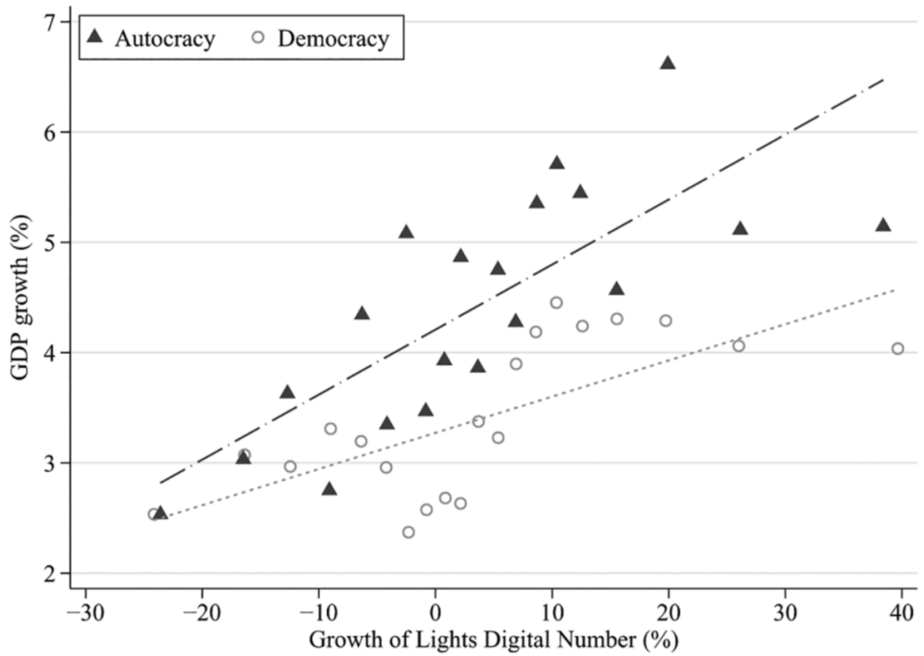
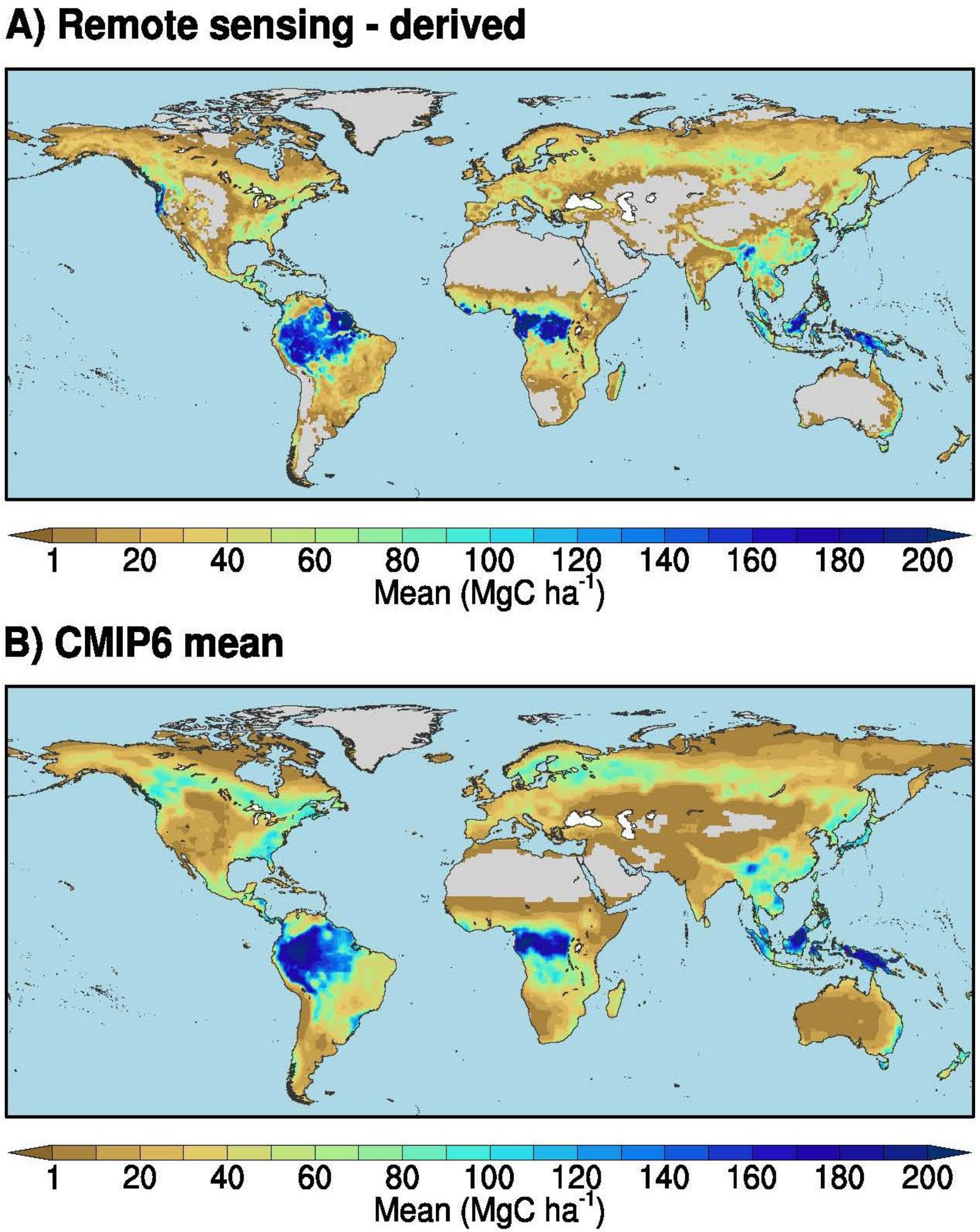


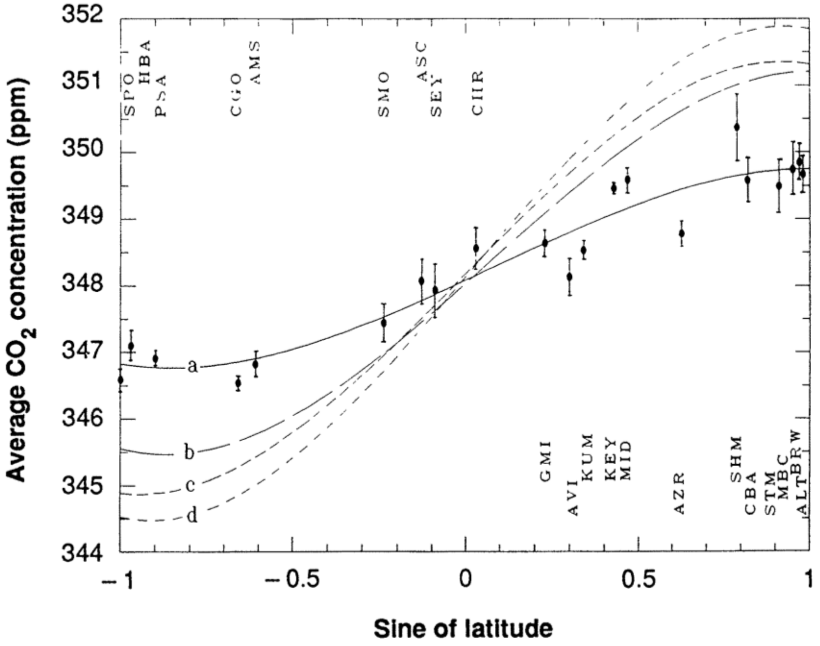
Figure from the Economist

Martinez, J.R. How Much Should We Trust the Dictator's GDP Growth Estimates?, Journal of Political Economy, volume 130, number 10, October 2022.

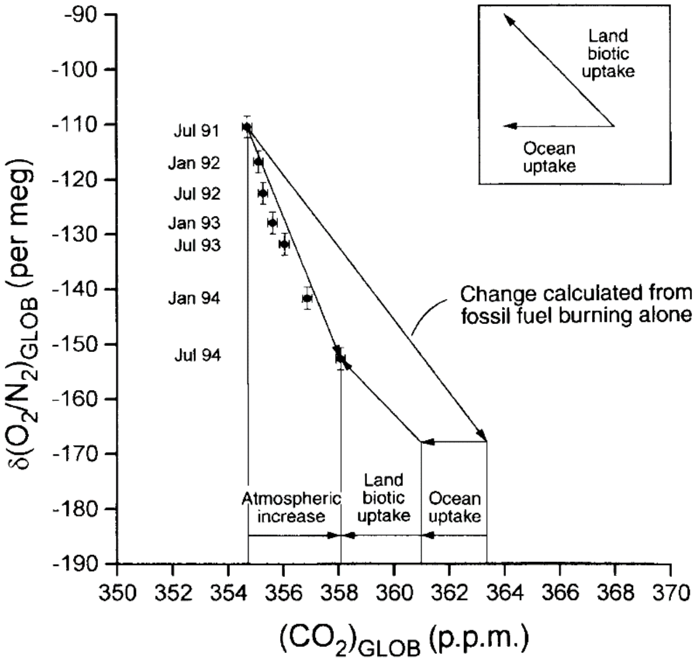

BOSCH


A) Remote sensing - derived
1
20
40
60
80
100
120
140
160
180
200
Mean (MgC ha^{-1})
B) CMIP6 mean
1
20
40
60
80
100
120
140
160
180
200
Mean (MgC ha^{-1})

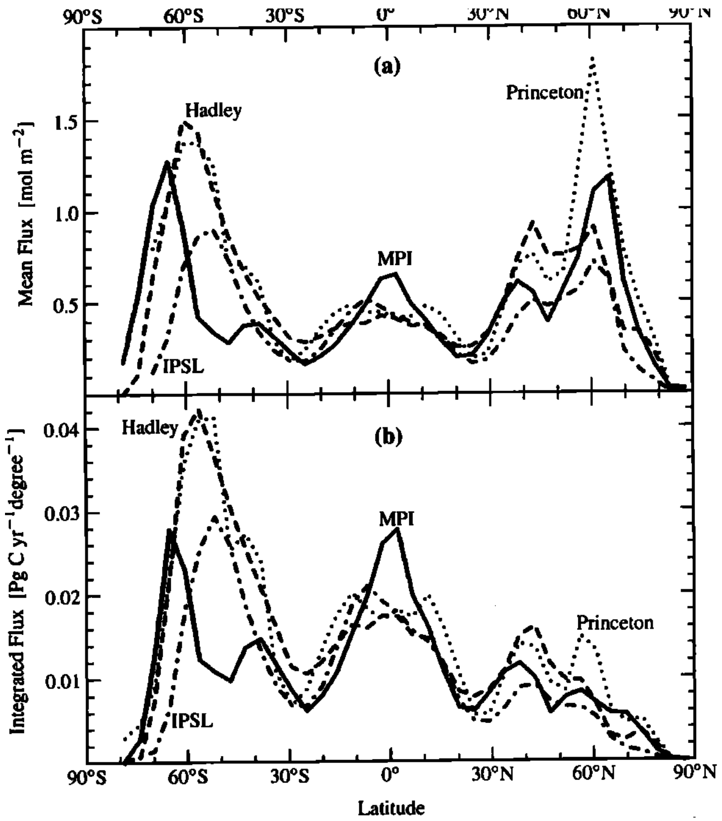
Primary Evidence for a Strong Terrestrial Carbon Sink: Interhemispheric Gradient of CO_2, O_2/N_2, and Data-constrained Ocean Models



Tans et al. (1990)



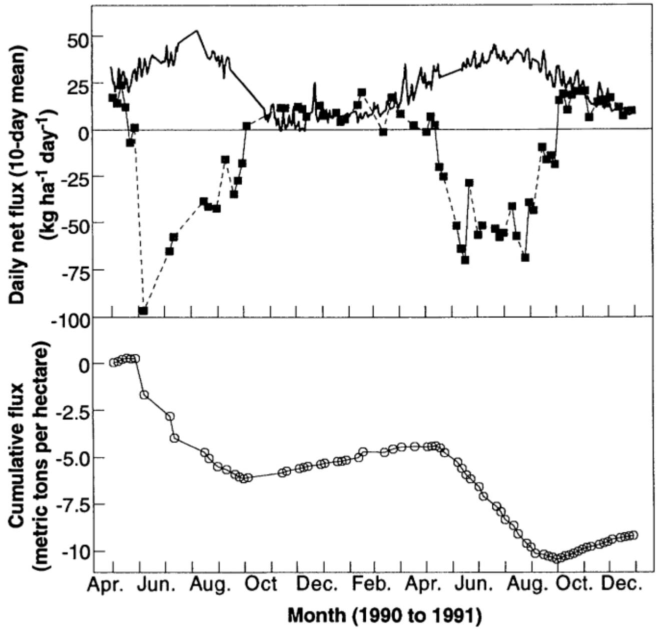
Keeling et al. (1996)



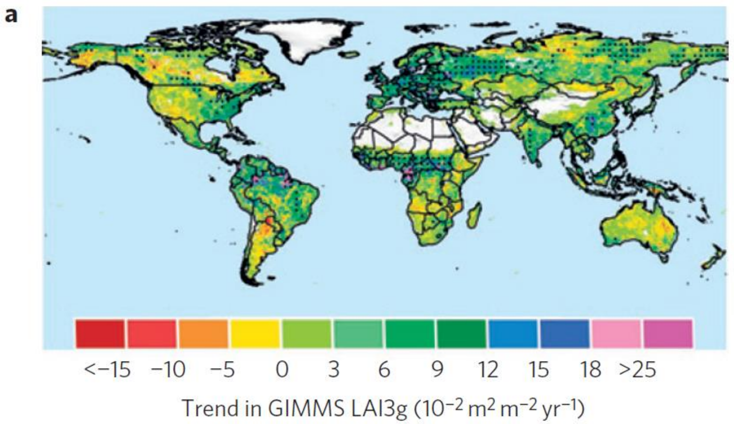
Orr et al. (2001)

Supporting evidence:

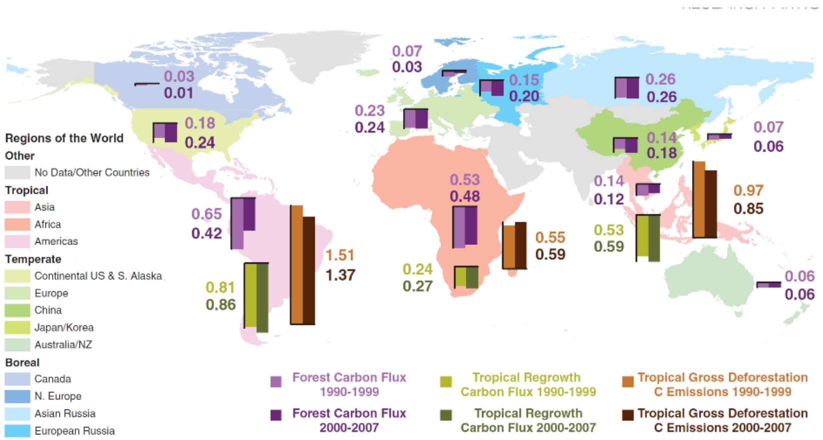
- Eddy covariance towers revealed large carbon sinks at many mid-latitude temperate forest sites (Wofsy, et al. 1993)
- A global greening trend inferred from long-term satellite records (including AVHRR NDVI)
- Syntheses of global forest inventories that show a large aboveground terrestrial carbon sink (2.3 Pg C/y from 1990-2007)



Wofsy, Goulden, et al. (1993)



Zhu et al. (2017)



Pan et al. (2011)

IPCC Third Assessment (2001)
Global 1990s Carbon Budget

Budget component:	**Flux: (Pg C/y)**
Fossil fuel emissions:	6.3 ± 0.4
Atmospheric increase:	3.2 ± 0.1
Ocean uptake:	1.7 ± 0.5
Net Land flux:	1.4 ± 0.7

- Fossil fuel emissions uncertainty is assumed to be about 5% with a Gaussian distribution
- Net land flux is often computed as a residual in budgets, as the difference between fossil emissions and accumulation in the atmosphere and oceans
- O_2 measurements confirm the presence of a large terrestrial sink
- Net land flux often decomposed into a positive tropical deforestation flux and a residual terrestrial sink

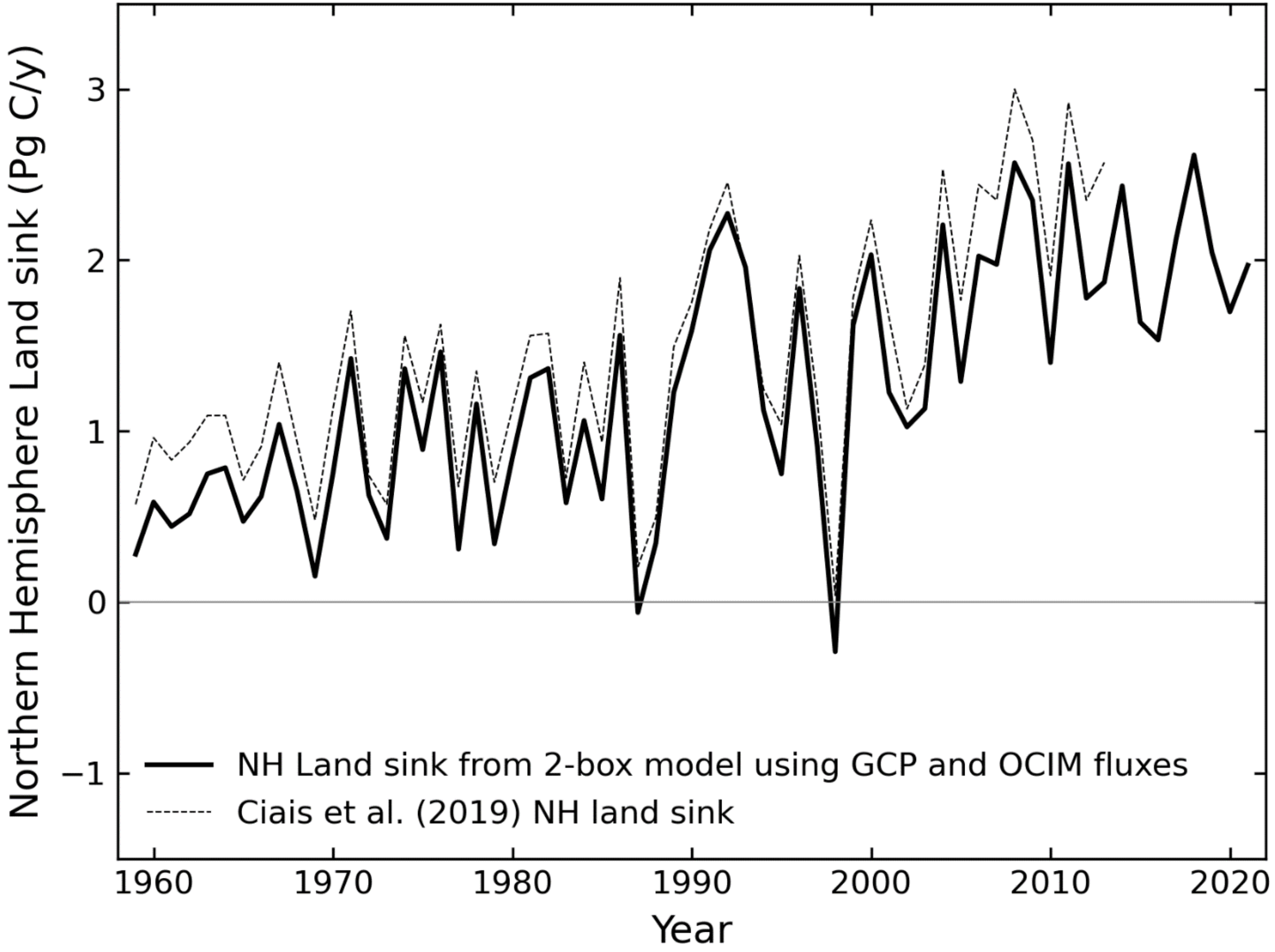
Mechanisms for a terrestrial carbon sink

- CO_2 fertilization
- Lengthening growing season from warming
- Nitrogen deposition
- Aerosol-driven enhancements of diffuse light
- Decreases in O_3 exposure (in some regions)
- Land use change from forest expansion (China) and recovery (Eastern US)

DeLucia et al. (1999) Science Duke FACE

See recent review of mechanisms by Sophie Ruehr in Nature Reviews

The northern hemisphere land carbon sink from 1959-2021 derived from a 2-box atmospheric model



- We extended the methodology of Ciais et al. (2019) using more recent atmospheric CO_2 data from Mauna Loa and the South Pole through 2021

- Small adjustments for the ocean biological pump, the river carbon loop, the atmospheric reduced chemistry pump, and the biosphere rectifier effect

- The integral of carbon uptake in the NH from 1959 to 2021 is:
- **81 ± 25 Pg C**

How do the carbon sink integrals compare with vegetation carbon pool sizes?

Global budget: 1959-2021

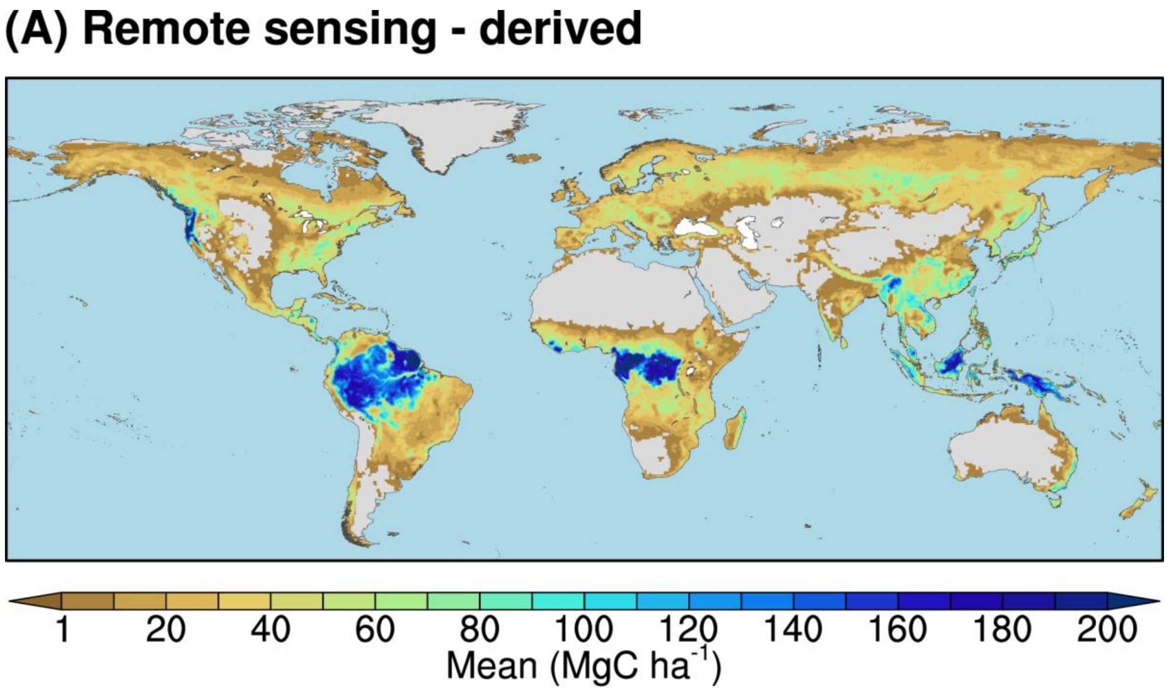
C_{veg} = 408 Pg C
ΔC_{land} = 55 Pg C

Percent change: 16%

NH budget: 1959-2021

C_{veg} = 261 Pg C
ΔC_{land} = 81 Pg C

Percent change: 45%

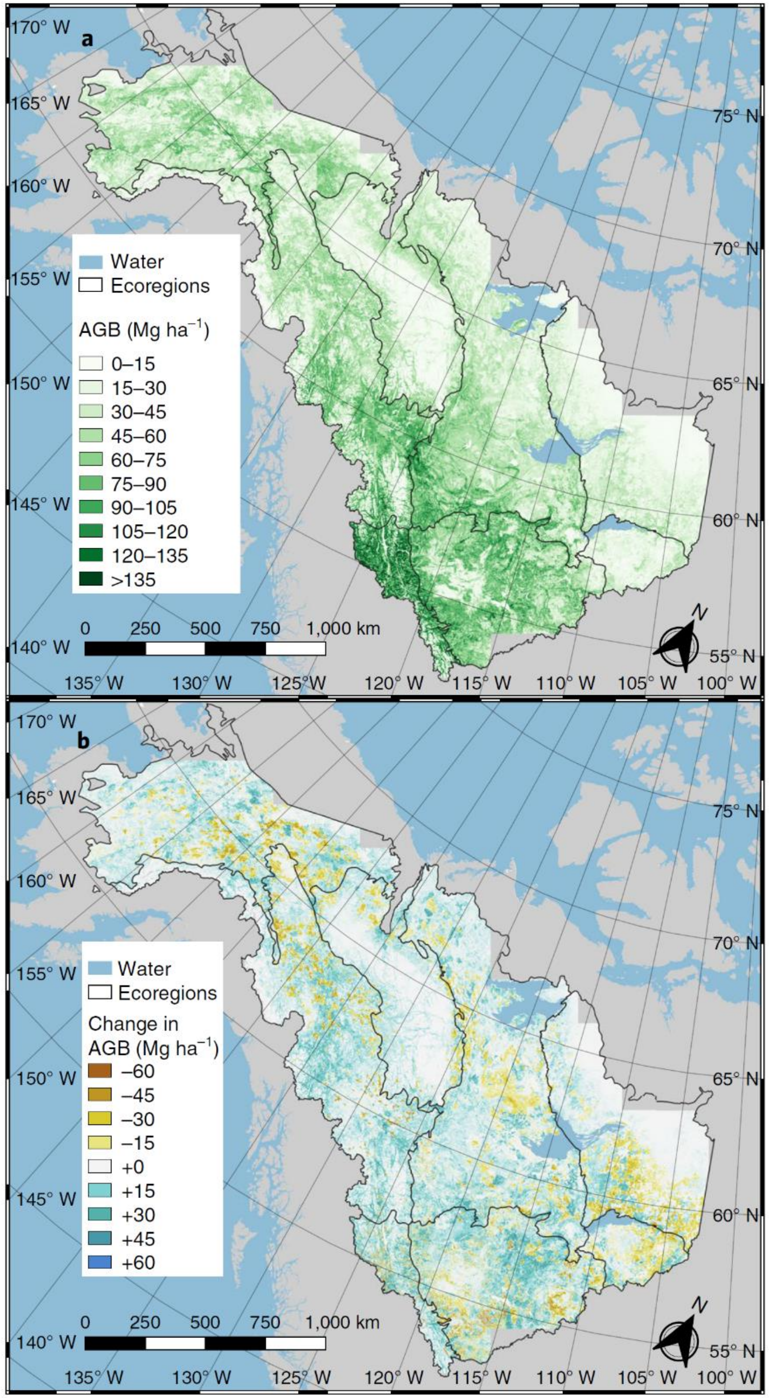


Observations from:

Xu, Saatchi, et al. (2021) Science Advances

And Baccini et al. (2017) Science

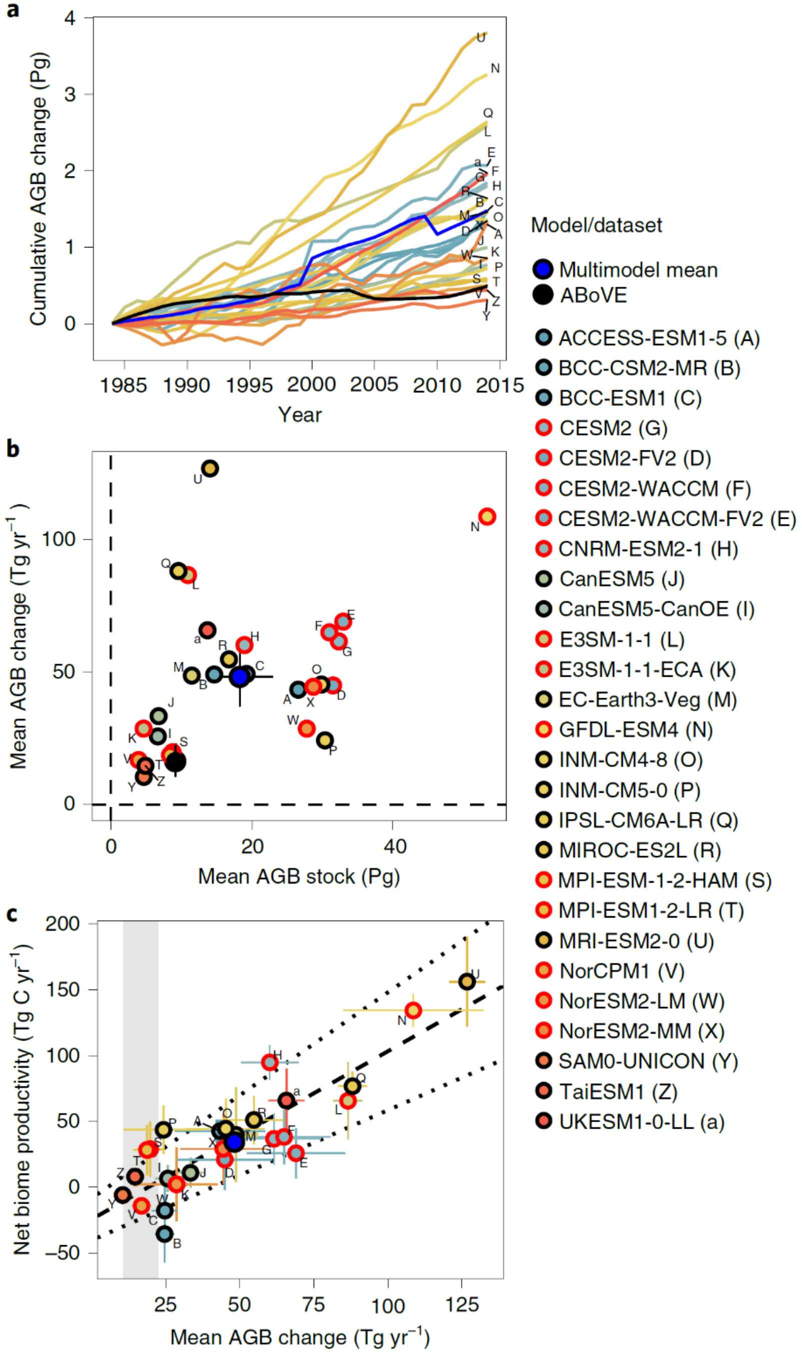
Yue Li



Aboveground biomass change in NASA's ABoVE study region from 1985-2014

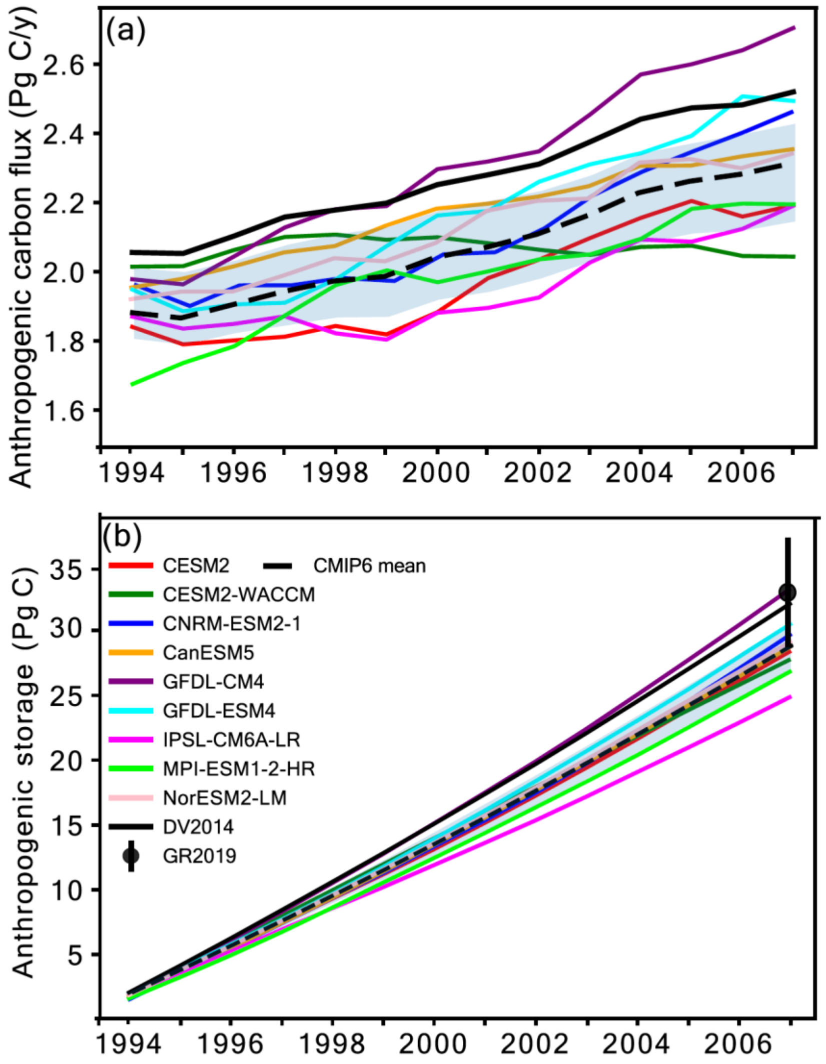
AGB accumulation from remote sensing was 430 Tg, a factor of 3 lower than CMIP6 models (1520 Tg) over 31 years

Jonathan A. Wang, Alessandro Baccini, Mary Farina, James T. Randerson, and Mark A. Friedl (2021) Nature Climate Change. Disturbance suppresses the aboveground carbon sink in North American boreal forests.

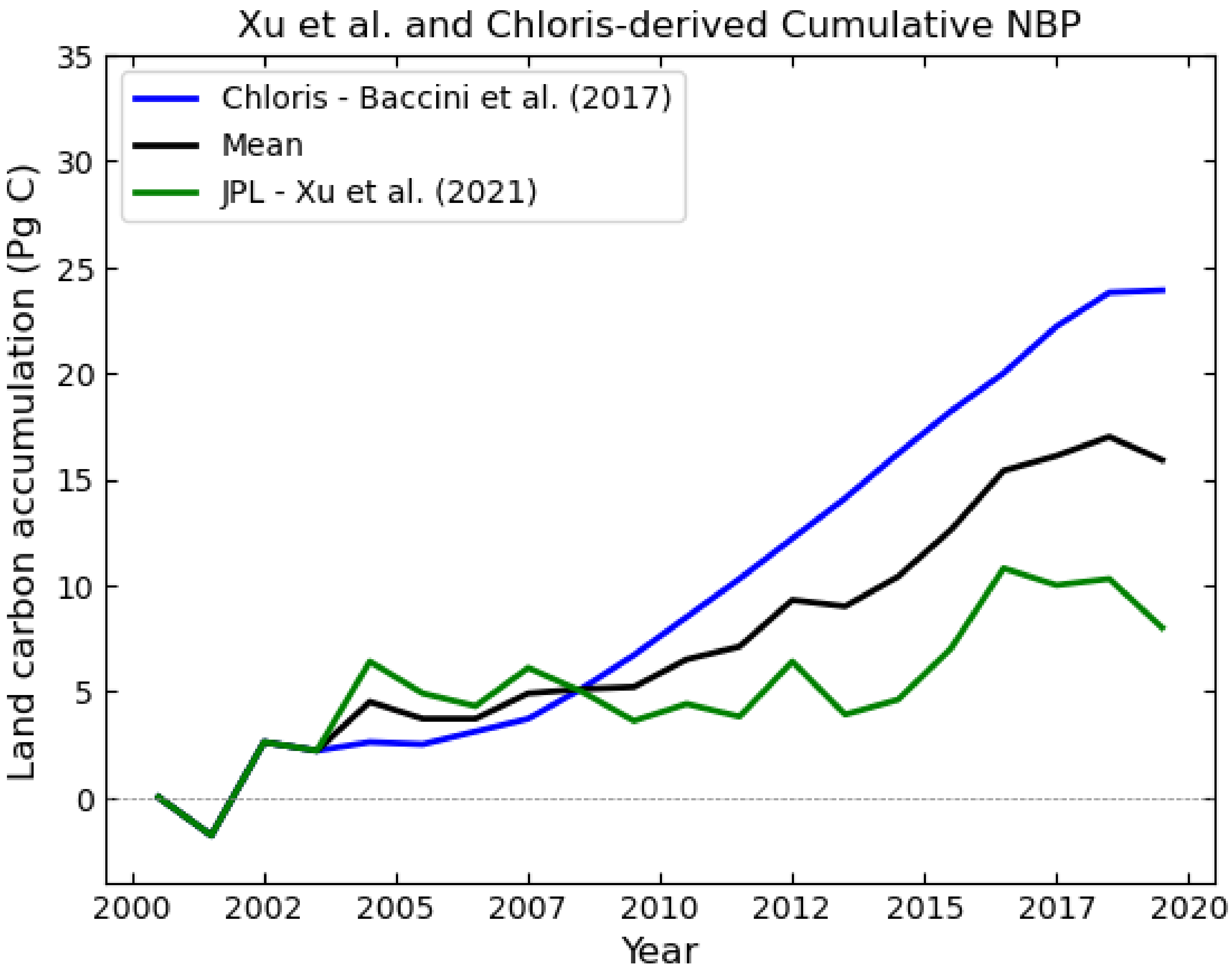


Ocean sinks in the GCP budget may be somewhat low relative to observation-constrained estimates

We adjust the GCP ocean flux estimate to match the Gruber et al. (2019) anthropogenic inventory from 1994-2007 and further adjust for the natural outgassing from ocean heat uptake using the estimates from Fu et al. (2022)



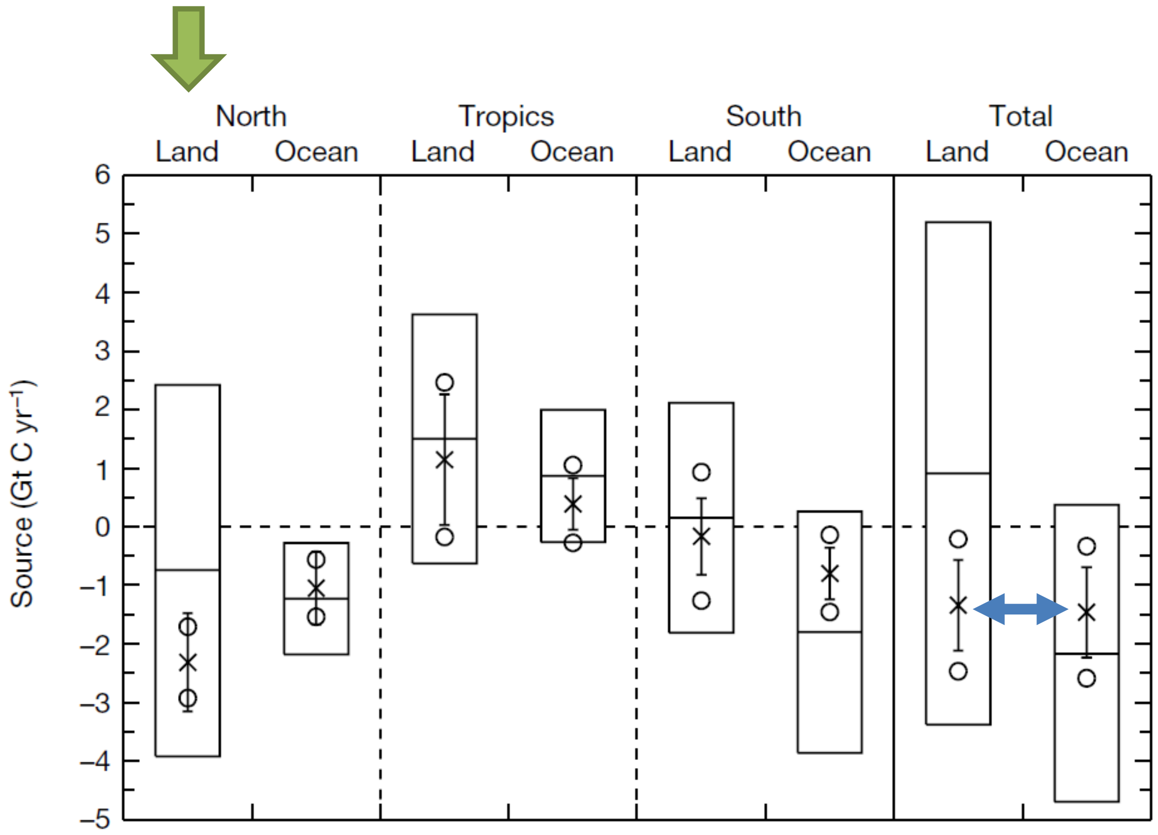
Fu W., J.K. Moore, F. Primeau, N. Collier, O.O. Ogunro, F.M. Hoffman, and J.T. Randerson. 2022. Evaluation of ocean biogeochemistry and carbon cycling in CMIP earth system models with the International Ocean Model Benchmarking (IOMB) software system. Journal of Geophysical Research-Oceans. 127(10): e2022JC018965.



Xu et al. and Chloris-derived Cumulative NBP
Chloris - Baccini et al. (2017)
Mean
JPL - Xu et al. (2021)
Land carbon accumulation (Pg C)
Year
0
5
10
15
20
25
30
35
2000
2002
2005
2007
2010
2012
2015
2017
2020

TRANSCOM Project Confirms a NH Land Carbon Sink

- 16 different atmospheric models
- Terrestrial carbon sinks estimated for temperate North America, Europe, and temperate Asia
- Robust with respect to consideration of a rectifier effect from seasonal terrestrial biosphere CO_2 exchange
- 1992-1996 period



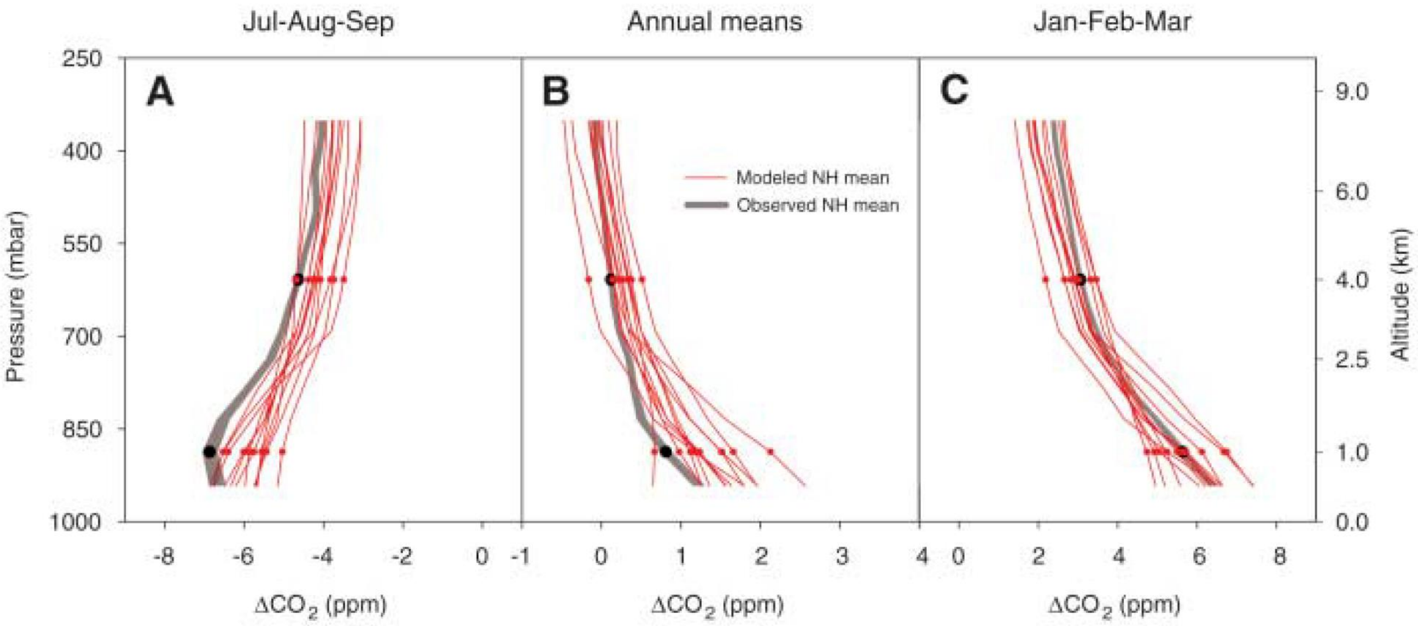
Gurney et al. (2002) Nature

Vertical mixing must be accurately simulated for the atmospheric inversions to work

Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO_2

Britton B. Stephens,[1]* Kevin R. Gurney,[2] Pieter P. Tans,[3] Colm Sweeney,[3] Wouter Peters,[3] Lori Bruhwiler,[3] Philippe Ciais,[4] Michel Ramonet,[4] Philippe Bousquet,[4] Takakiyo Nakazawa,[5] Shuji Aoki,[5] Toshinobu Machida,[6] Gen Inoue,[7] Nikolay Vinnichenko,[8]† Jon Lloyd,[9] Armin Jordan,[10] Martin Heimann,[10] Olga Shibistova,[11] Ray L. Langenfelds,[12] L. Paul Steele,[12] Roger J. Francey,[12] A. Scott Denning[13]

Measurements of midday vertical atmospheric CO_2 distributions reveal annual-mean vertical CO_2 gradients that are inconsistent with atmospheric models that estimate a large transfer of terrestrial carbon from tropical to northern latitudes. The three models that most closely reproduce the observed annual-mean vertical CO_2 gradients estimate weaker northern uptake of −1.5 petagrams of carbon per year (Pg C year^{-1}) and weaker tropical emission of +0.1 Pg C year^{-1} compared with previous consensus estimates of −2.4 and +1.8 Pg C year^{-1}, respectively. This suggests that northern terrestrial uptake of industrial CO_2 emissions plays a smaller role than previously thought and that, after subtracting land-use emissions, tropical ecosystems may currently be strong sinks for CO_2.



Budget estimate (1992-1996):	NH Land Flux	Tropical Land Flux
Previous consensus:	**-2.4 Pg C/y**	**1.8 Pg C/y**
Stephens et al. (2007):	**-1.5 Pg C/y**	**0.1 Pg C/y**

Radiocarbon constraints imply reduced carbon uptake by soils in CMIP Models during the 21st century.

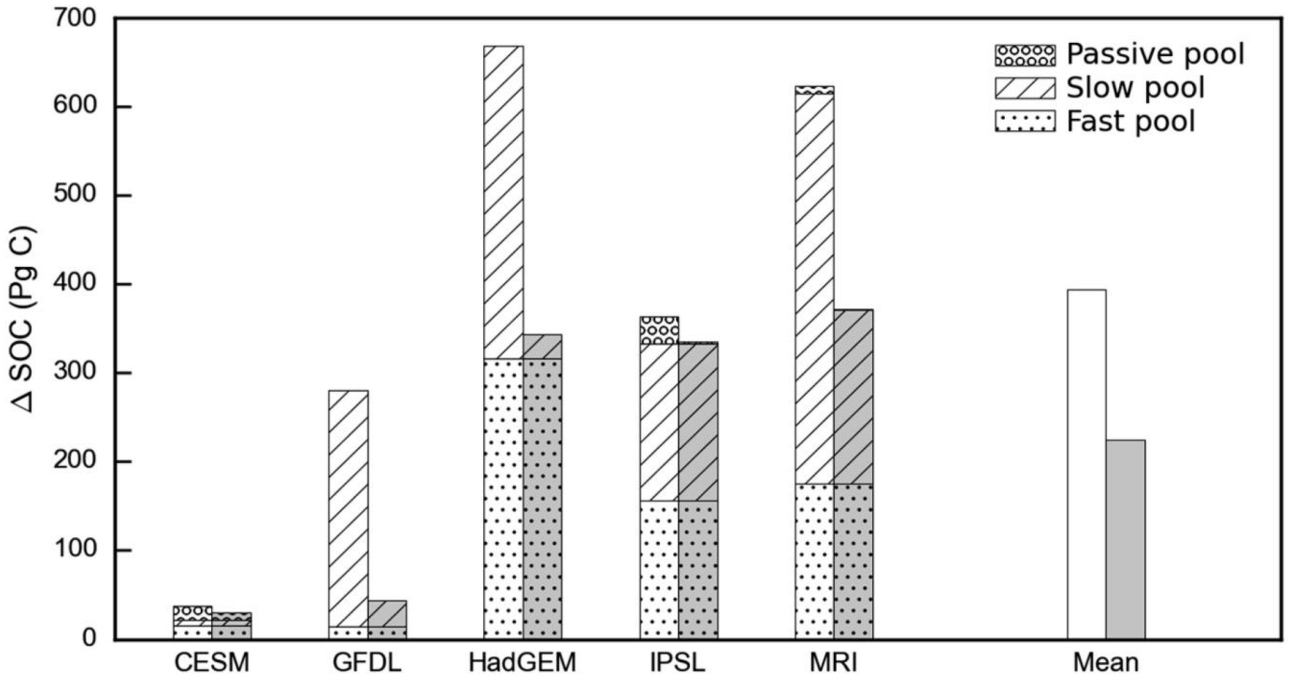
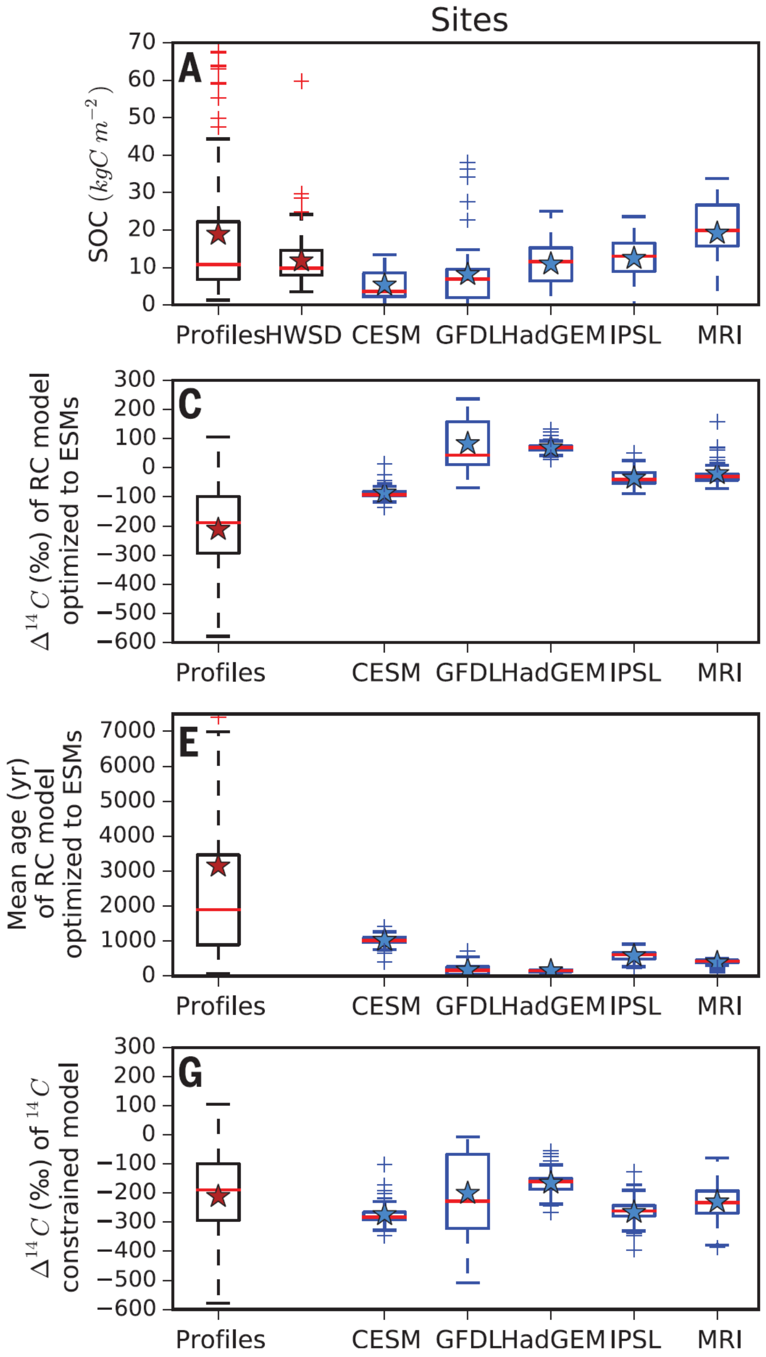


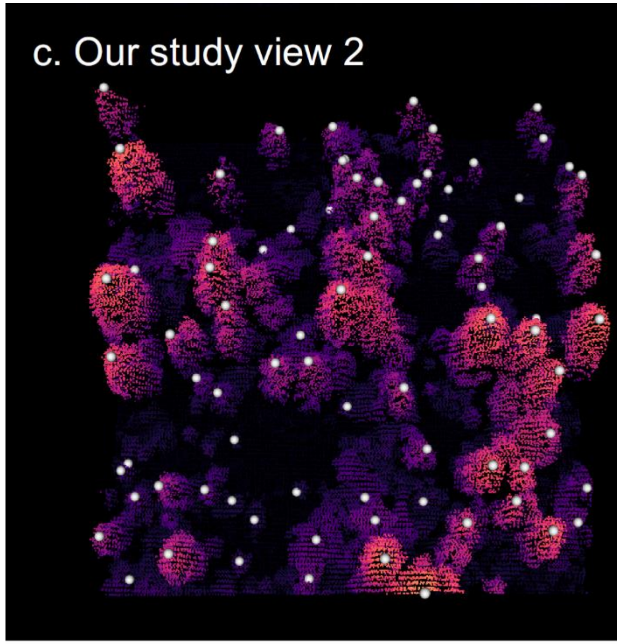
Fig. 3. Absolute change in SOC content from the reduced complexity model fit to the original ESM (bars with white background) and the estimate obtained by applying the ^{14}C constraint to the reduced complexity model (bars with gray background). The estimates on the right side show the total carbon content (sum of fast, slow, and passive) averaged across all the models, before and after applying the radiocarbon constraint.

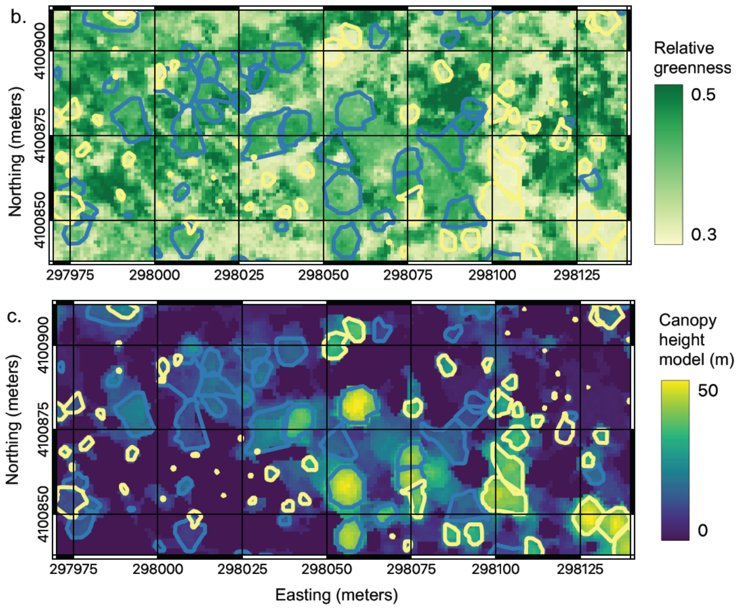


He, Y., S.E. Trumbore, M.S. Torn, J.W. Harden, L.J.S. Vaughn, S.D. Allison, and J.T. Randerson. 2016. Radiocarbon constraints imply reduced carbon uptake by soils during the 21st century. Science. 353:1419-1424. doi: 10.1126/science.aad4273.

How this hypothesis could be wrong:

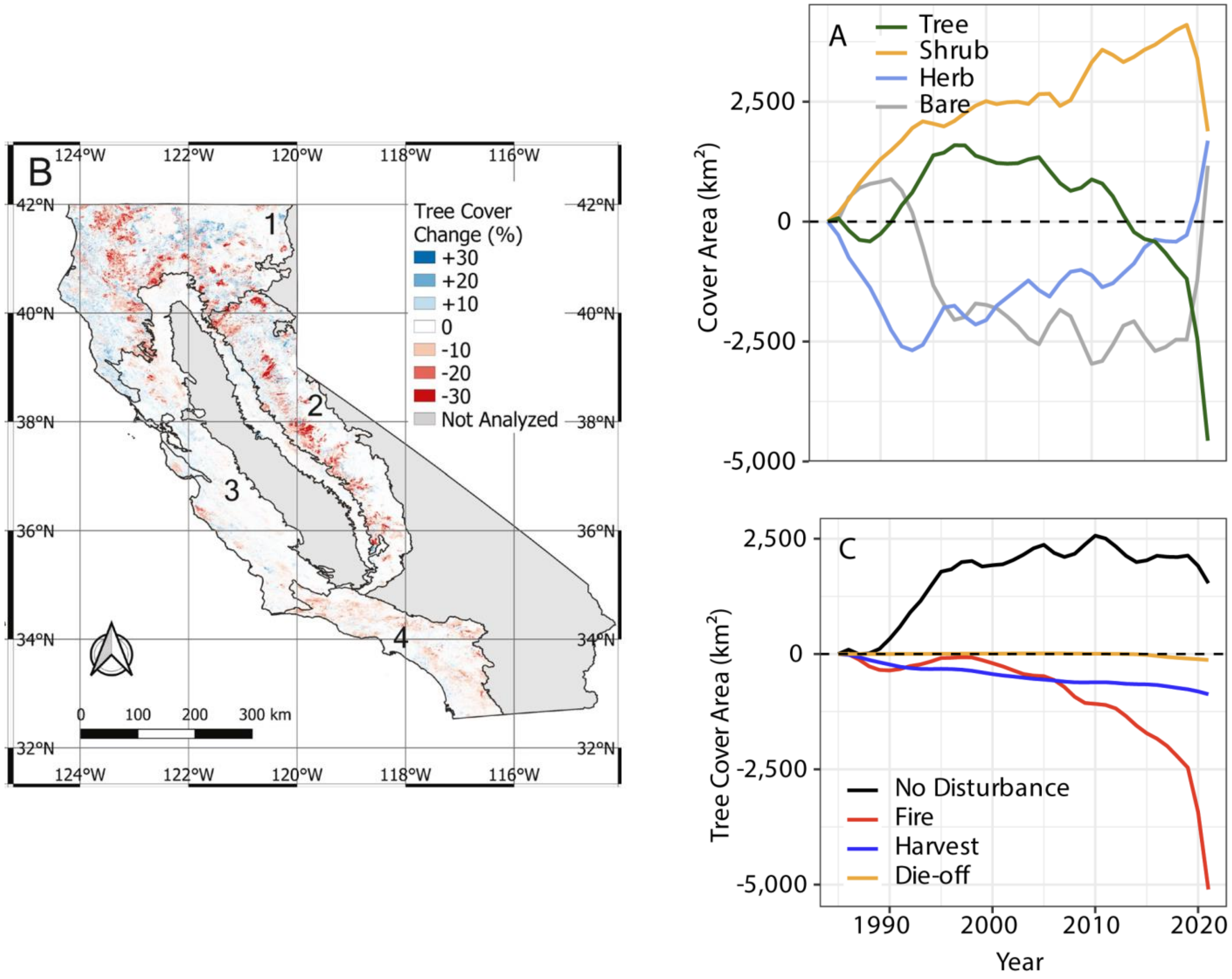
- We need more time to refine satellite-derived AGB trends
- There is a significant ocean organic carbon sink in coastal shelf sediments and in the open ocean, driven by increasing nutrient delivery and accelerating ocean NPP
- There is probably a small but important carbon sink in cities (0.1-0.2 Pg C/y)
- We have underestimated accumulation in litter and coarse woody debris





Hemming-Schroeder et al. (2023)

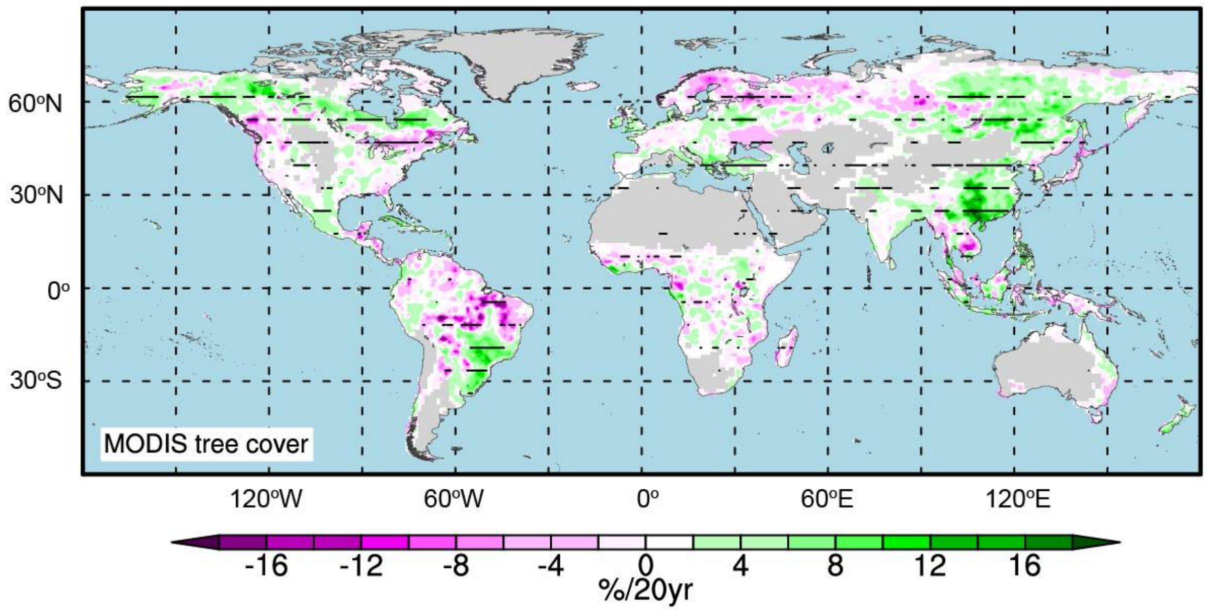
Analysis of Landsat time series reveals loss of tree cover in California

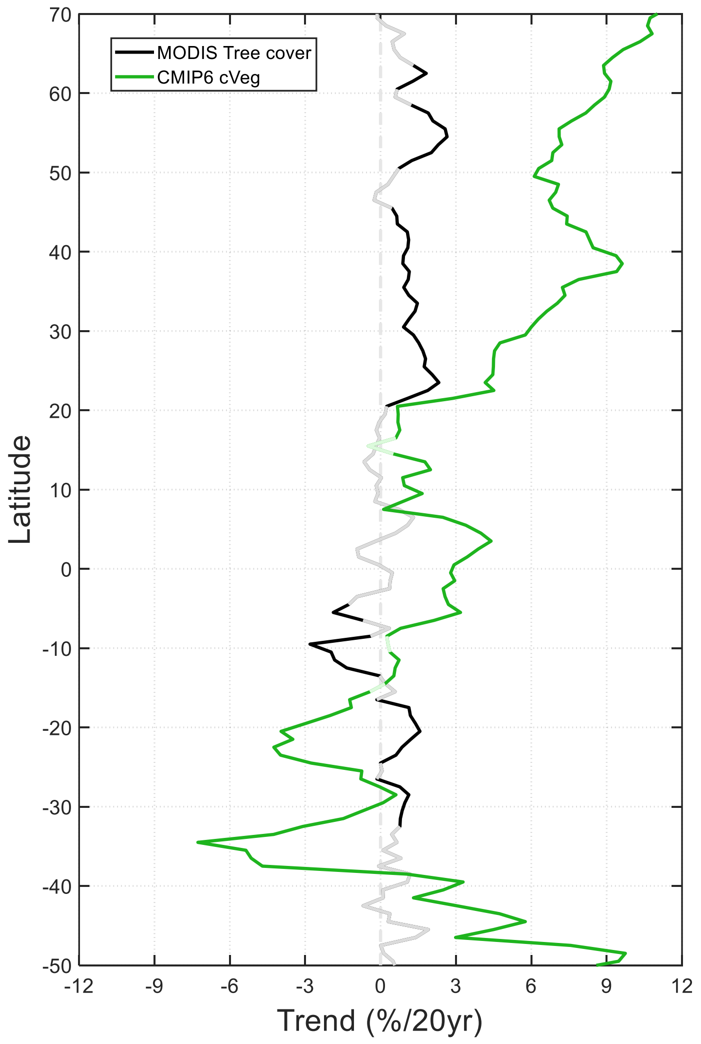


- California lost about 7% of its tree cover from 1984 through 2020
- Losses in Southern California Mountains are greater than the state-wide average (over 13%)
- Fire is the dominant driver of tree cover loss
- Recovery of forests after fire cannot keep pace with increasing levels of annual burned area
- Shrubs are replacing forests in many areas; this may be making wildfires worse

Wang, Randerson, Goulden et al. (2022) AGU Advances

NASA MODIS fractional tree cover changes provide evidence for a lower rate of forest expansion

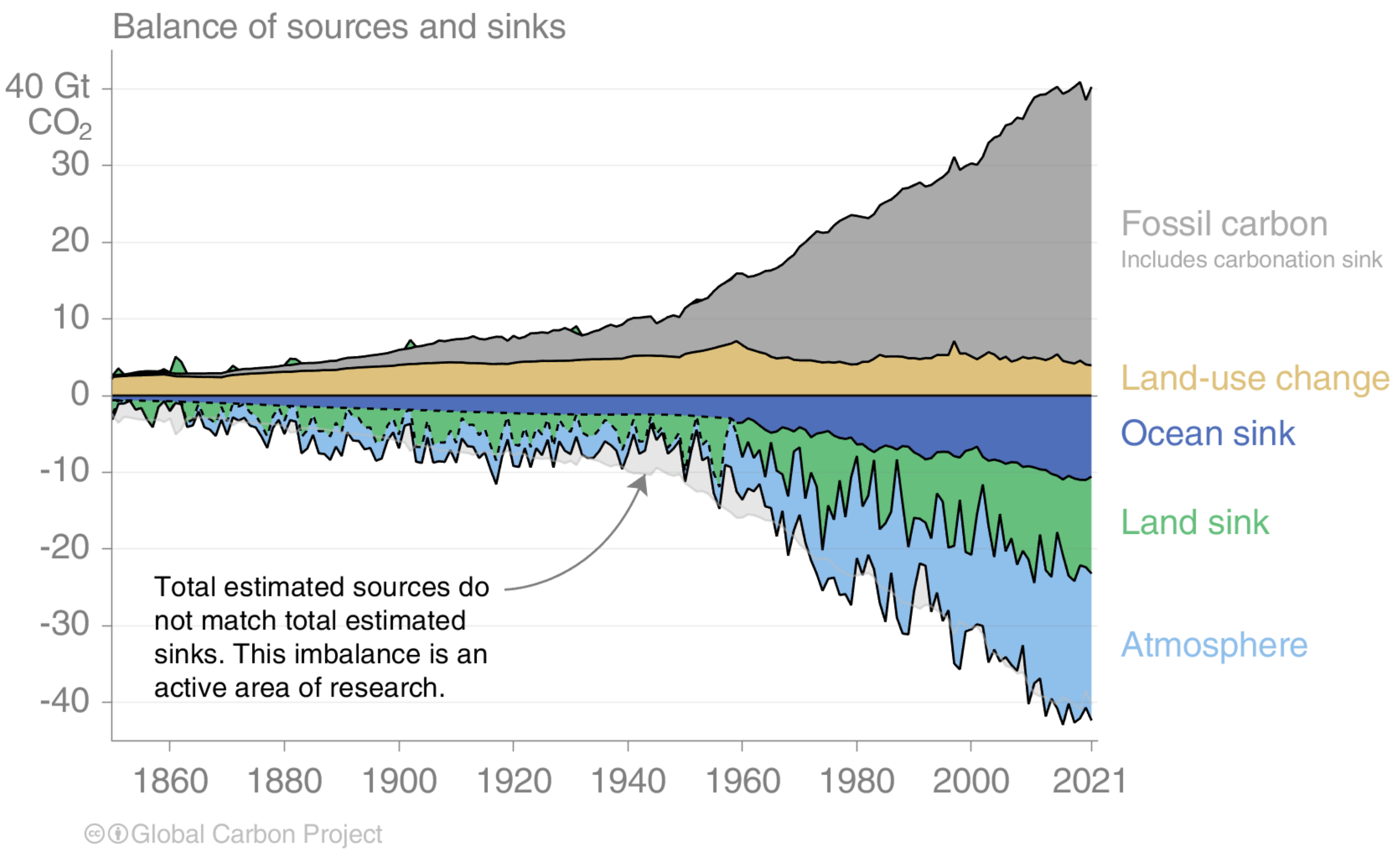




Yue Li (in preparation)

Global Carbon Project budget

Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean
The “imbalance” between total emissions and total sinks is an active area of research



Source: Friedlingstein et al 2022; Global Carbon Project 2022