Deforestation fire impacts on atmospheric composition as a constraint on the magnitude of annual carbon emissions

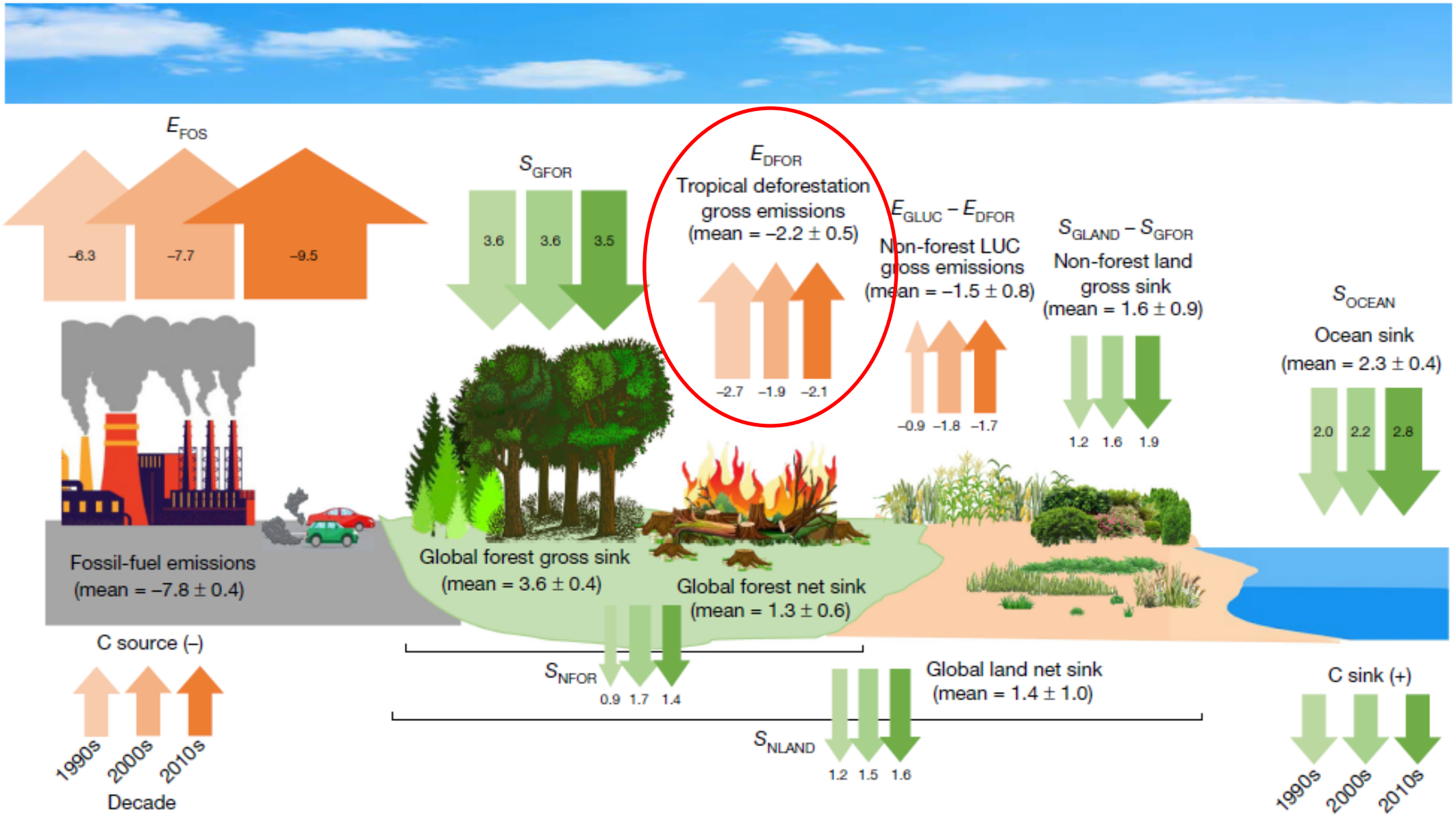
James Randerson and Li Xu

June 10, 2025

CESM 30th Annual Meeting
Boulder Colorado

U.S. DEPARTMENT OF ENERGY
Office of Science

NSF

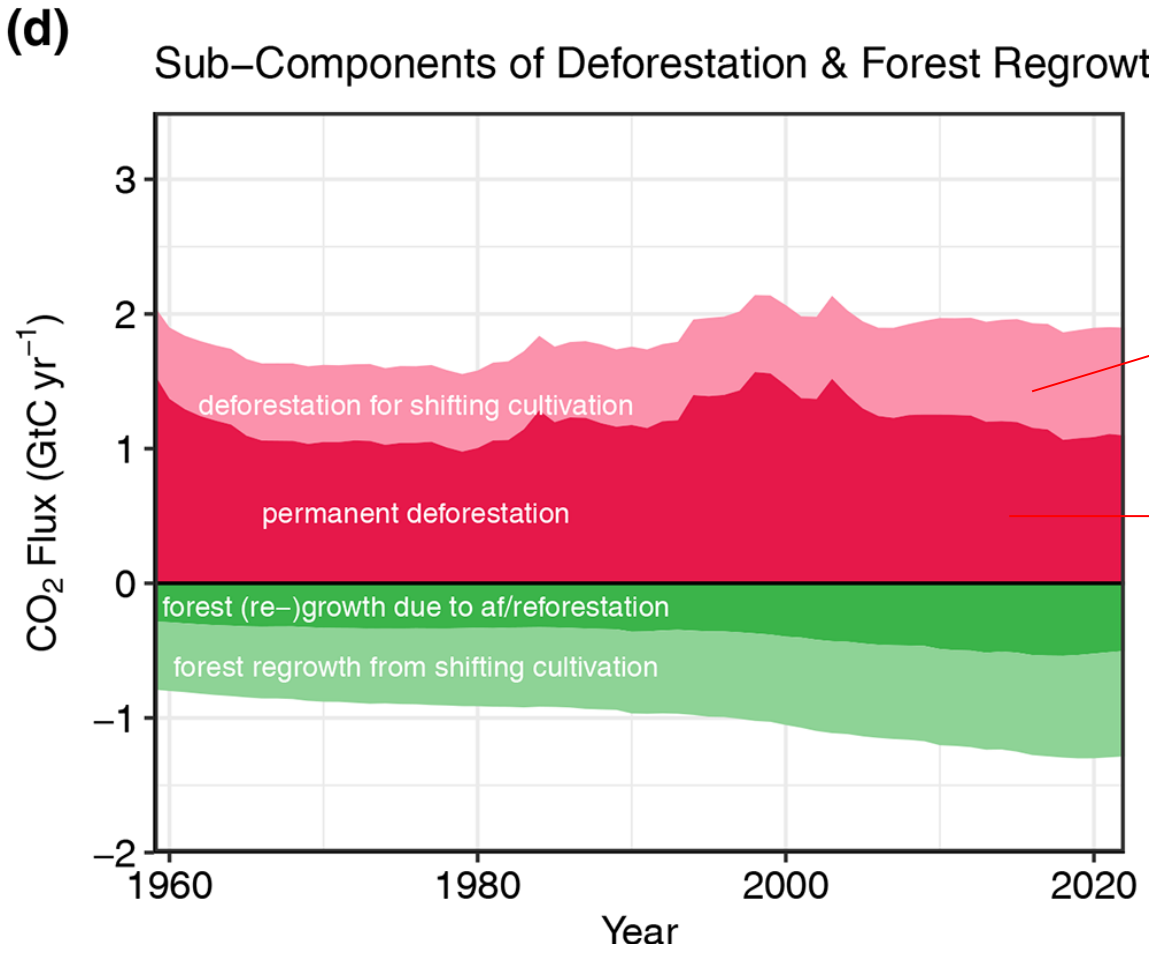


$$F_{LAND} = S_{GFOR} - E_{DFOR} + F_{NONFOR}$$

$$1.6 = 3.6 - 2.1 + 0.2 \text{ (units: Pg C/y)}$$

Pan et al. (2024) Nature

GCP (2023) and Pan et al. (2024) estimates of gross deforestation are similar



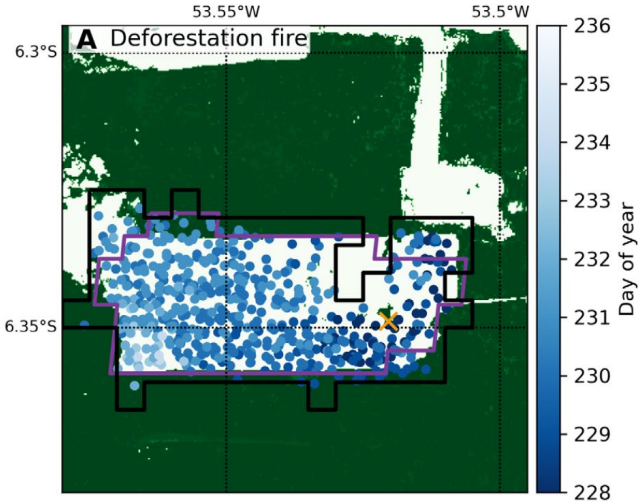
About 600-800 Tg C/y of deforestation for shifting cultivation

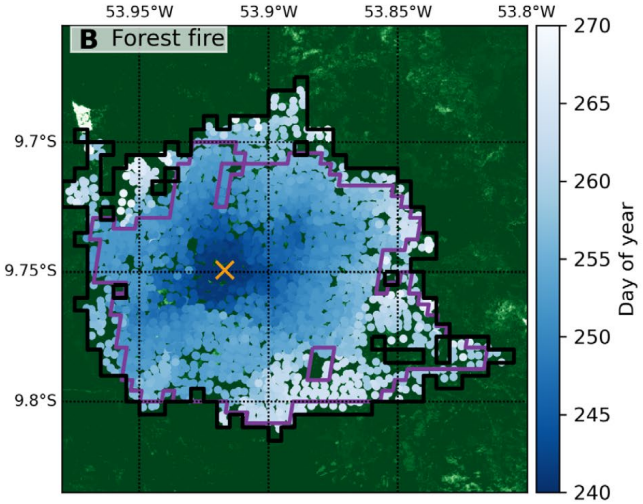
About 1000-1300 Tg C/y of permanent deforestation

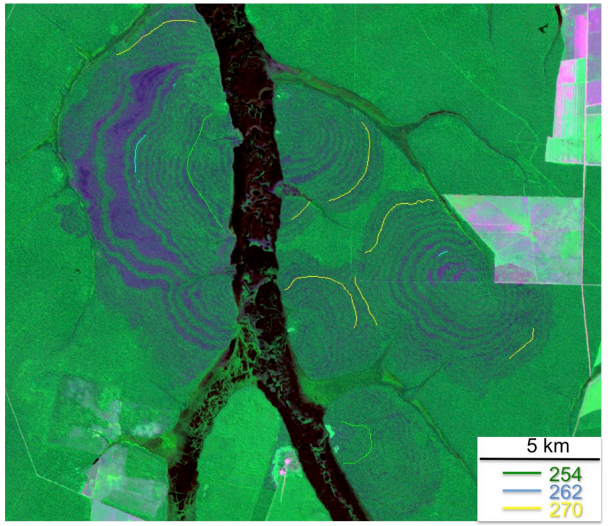
Nearly all of this should be combusted – about 2.0 Pg C/y during 2000-2020

Friedlingstein et al. (2023)
The 2023 Global Carbon Project budget

Fire is used extensively as a tool in tropical deforestation and is a key driver of forest degradation







Photos and imagery – Doug Morton

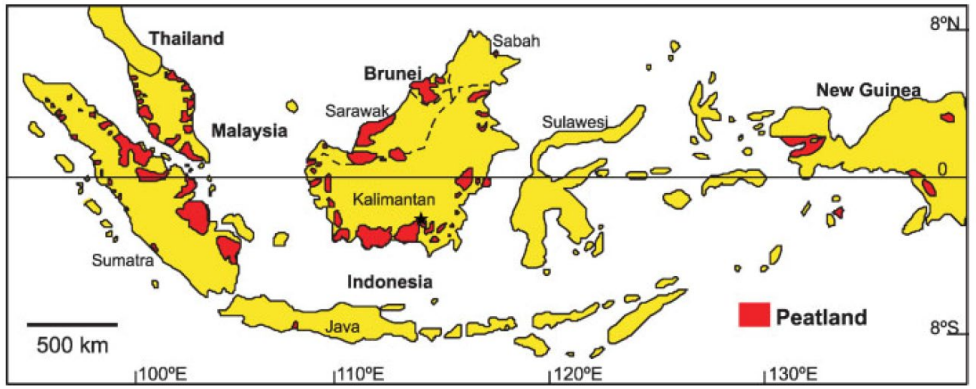
NASA MODIS August 2019

Andela et al. (2022) Science Advances. Tracking and classifying Amazon fire events in near real-time

Brando, Paulo M., et al. Science Advances. The gathering firestorm in southern Amazonia.

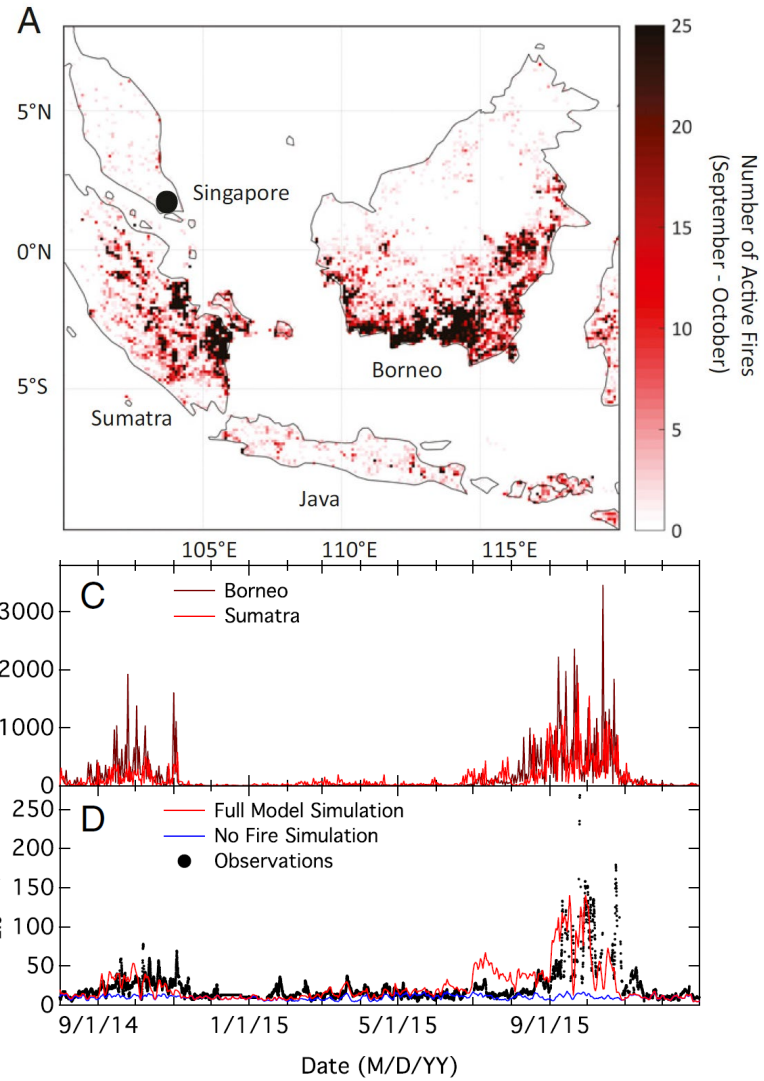
Alencar, Ane A., et al. (2015) Ecological Advances. Landscape fragmentation, severe drought, and the new Amazon forest fire regime

Fire is a critical tool in peatland conversion in Southeast Asia



[Susan Page et al., 2004]

NASA MODIS 9/24/15



Wiggins et al. (2019) PNAS

Deforestation and drainage

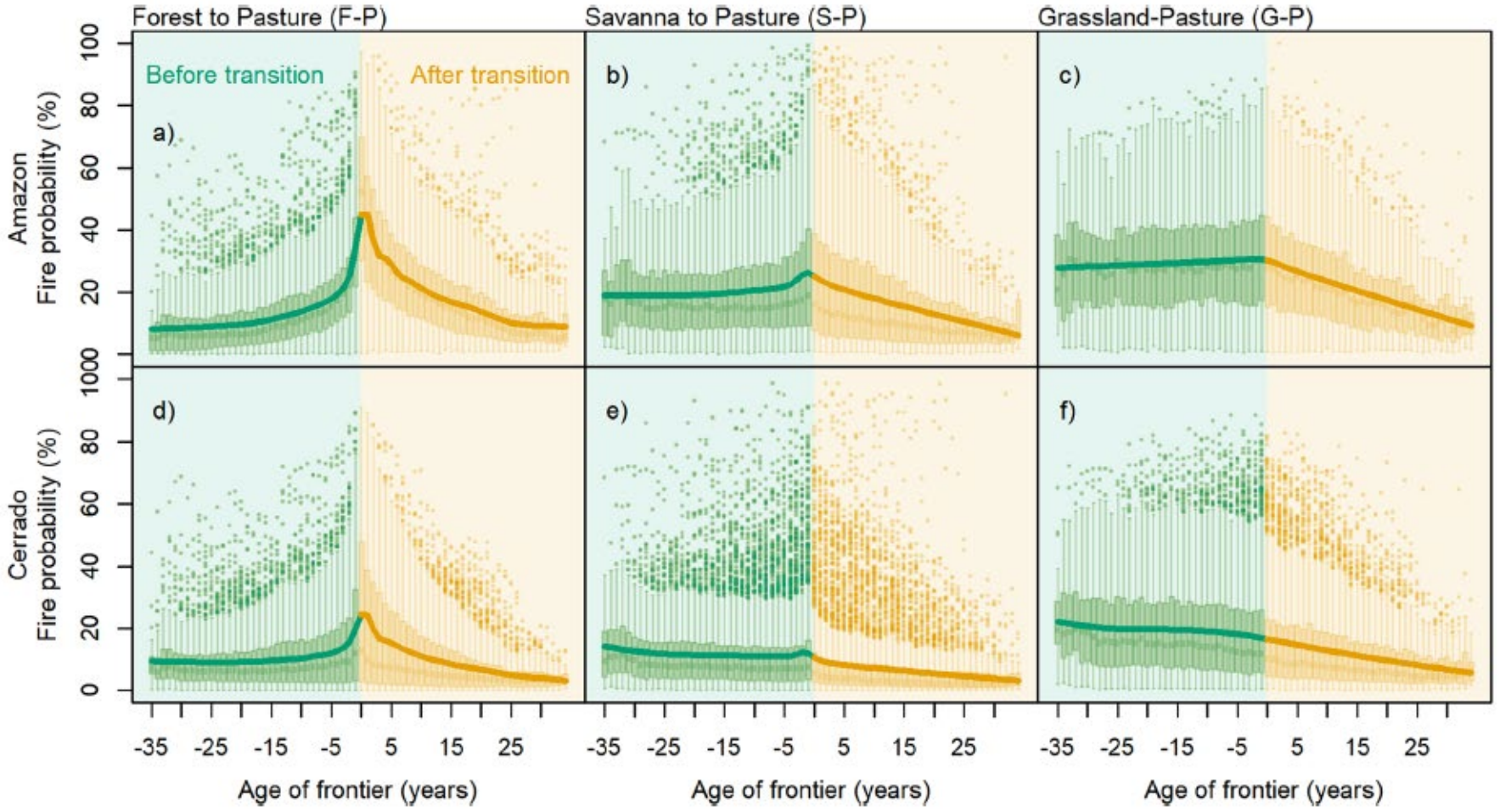
Source: © *Kemal Jufri Mongabay News*

Oil palm plantation drainage canal

Source: https://phys.org/news/2015-07-tropical-peatland-carbon-lossesoil.html

The time since land-use transition drives changes in fire activity in the Amazon-Cerrado region

Andreia F. S. Ribeiro[1,2], Lucas Santos[3], James T. Randerson[3], Maria R. Uribe[4], Ane A. C. Alencar[5], Marcia N. Macedo[5,6], Douglas C. Morton[7], Jakob Zscheischler[2,8], Rafaella A. Silvestrini[5], Ludmila Rattis[5,6], Sonia I. Seneviratne[1] & Paulo M. Brando[4,5]



Ribeiro et al. (2024)

Does deforestation carbon flow into harvested wood product pools? Yes, but it's a relatively small amount

Article

The enduring world forest carbon sink

https://doi.org/10.1038/s41586-024-07602-x

Received: 22 May 2023

Accepted: 24 May 2024

Published online: 17 July 2024

Yude Pan[1]✉, Richard A. Birdsey[2], Oliver L. Phillips[3], Richard A. Houghton[2], Jingyun Fang[4], Pekka E. Kauppi[5,6], Heather Keith[7], Werner A. Kurz[8], Akihiko Ito[9], Simon L. Lewis[3,10], Gert-Jan Nabuurs[11,12], Anatoly Shvidenko[13], Shoji Hashimoto[9,14], Bas Lerink[11], Dmitry Schepaschenko[13], Andrea Castanho[2] & Daniel Murdiyarso[15,16]

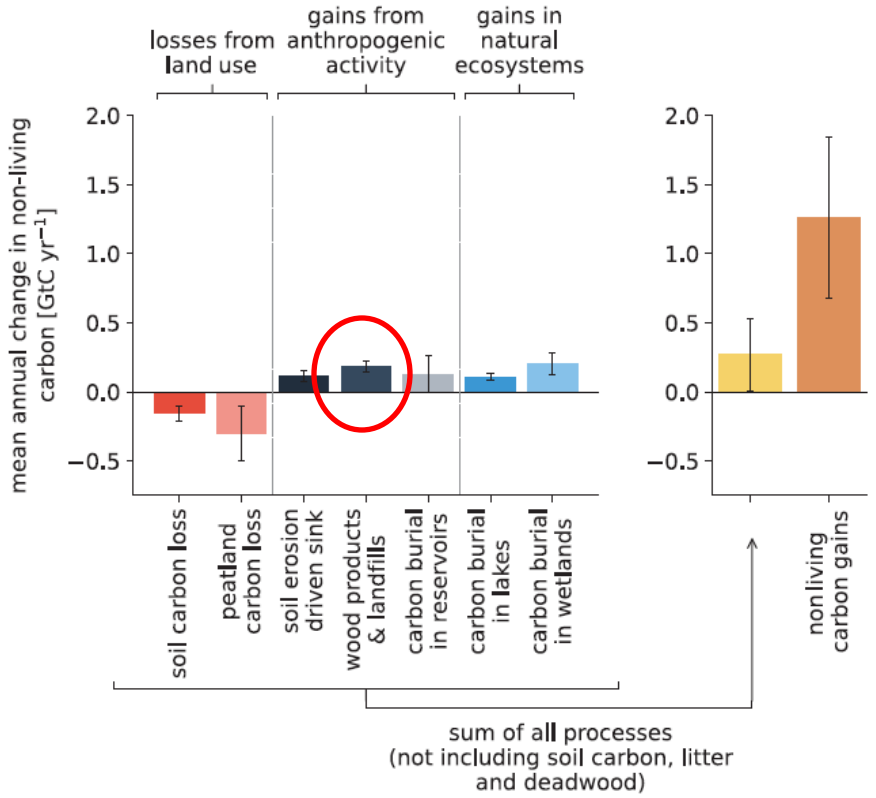
Extended Data Table S2 from Pan et al. (2024) product pool fluxes

	1990s	2000s	2010s
Intact tropical forests	0.090 Pg C/y	0.092 Pg C/y	0.102 Pg C/y
Regrowing tropical forests	0.0 Pg C/y	0.0 Pg C/y	0.0 Pg C/y
All tropical forests	0.090 Pg C/y	0.092 Pg C/y	0.102 Pg C/y

CARBON CYCLE

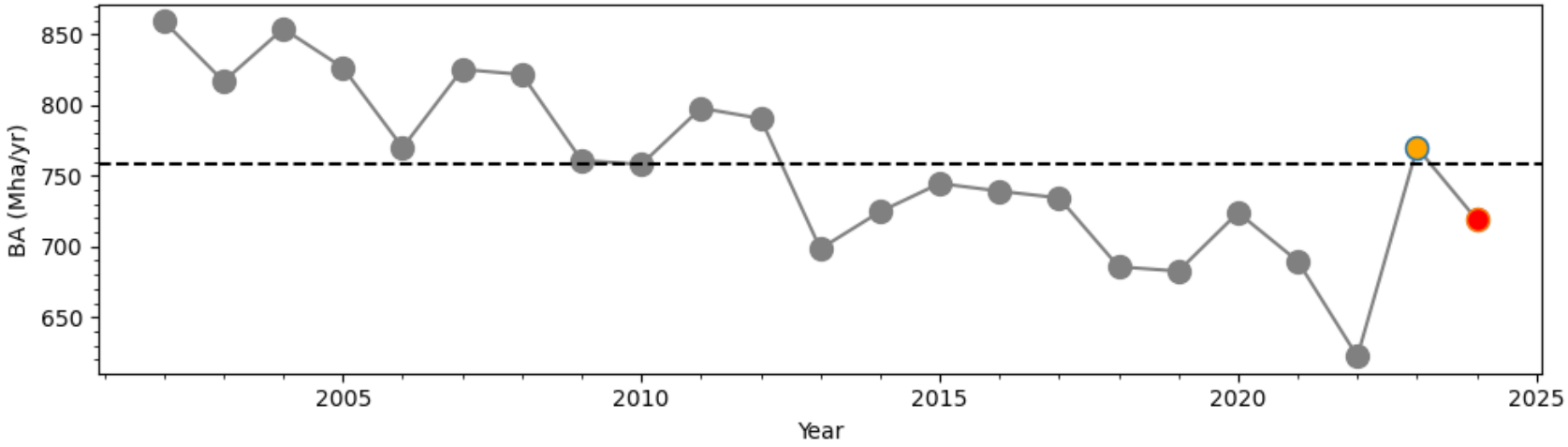
Recent gains in global terrestrial carbon stocks are mostly stored in nonliving pools

Yinon M. Bar-On[1,2]*, Xiaojun Li[3,4], Michael O'Sullivan[5], Jean-Pierre Wigneron[3], Stephen Sitch[5], Philippe Ciais[6], Christian Frankenberg[1,7], Woodward W. Fischer[1]

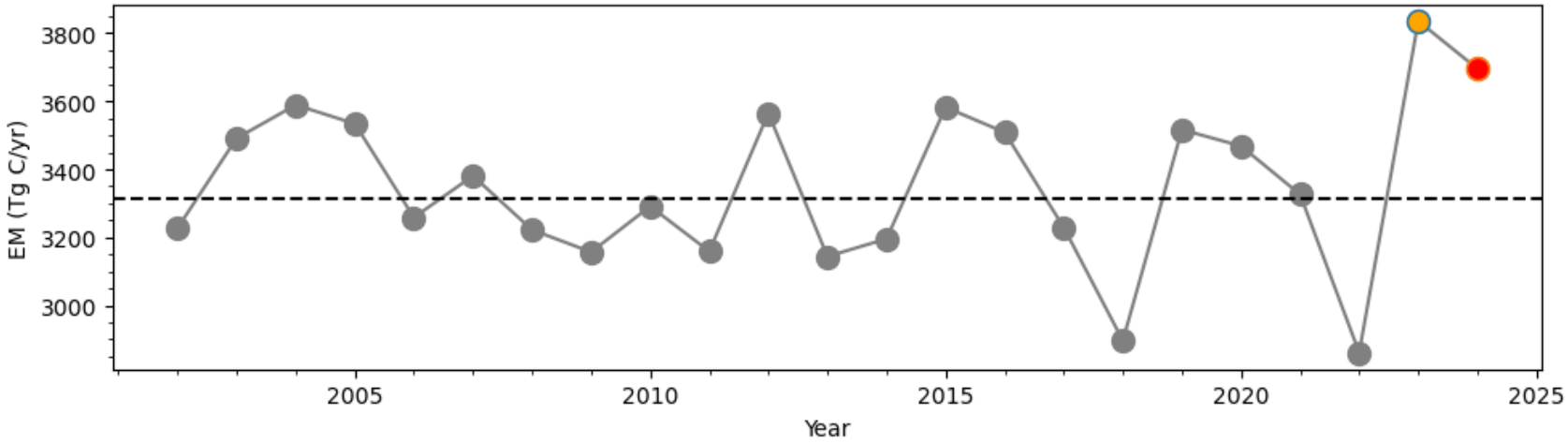


Global burned area and fire emissions trends from GFED5

Annual burned area:
(Mha/y)



Carbon emissions:
(Tg C/y)



van der Werf et al. (In review, Scientific Data), Yang Chen et al. (In prep.)

GFED5 fire carbon emissions from tropical regions are considerably lower than estimates from the GCP and Pan et al. for gross deforestation

Source:	Emissions (Tg yr^{-1})		
	Carbon	CO	POM
GFED5 total	3269.6	461.7	46.3
GFED5 sum of tropical forest, deforestation, and peat components:	420.5	102.5	6.1

Source:	Emissions (Tg yr^{-1})		
	Carbon	CO	POM
Tropical Forest	201.9	41.0	2.2
Deforestation	135.9	32.0	1.5
Peat	82.7	29.5	2.4

The carbon cycle assessments are between a factor of 4-5 higher than the satellite-derived fire estimates from GFED5!

van der Werf et al. (in review)

Can we use VIIRS fire radiative power obs. to assess whether the ratio between tropical forest fire emissions (TDP) and total global emissions from GFED5 is ok? And correct for cloud cover?

CF correction	Region/Type	2015	2017	2015+2017
Before	Globe (MW x 1e6)	196.88	186.82	383.70
	TDP (MW x 1e6)	31.01	24.63	55.64
	TDP/Global	0.158	0.132	0.145
After	Globe (MW x 1e6)	413.35	355.70	769.05
	TDP (MW x 1e6)	82.97	53.17	136.14
	TDP/Global	0.200	0.149	0.177

GFED5 C emissions ratio:

420/3269 = 13%

Monthly gridded cloud fractions ($CF_{m,i}$, 0.25 deg) from EUMETSATs CM SAF CLARA datasets are used to do the correction:

$$FRP_{corr,m,i} = FRP_{m,i} / (1 - CF_{m,i})$$

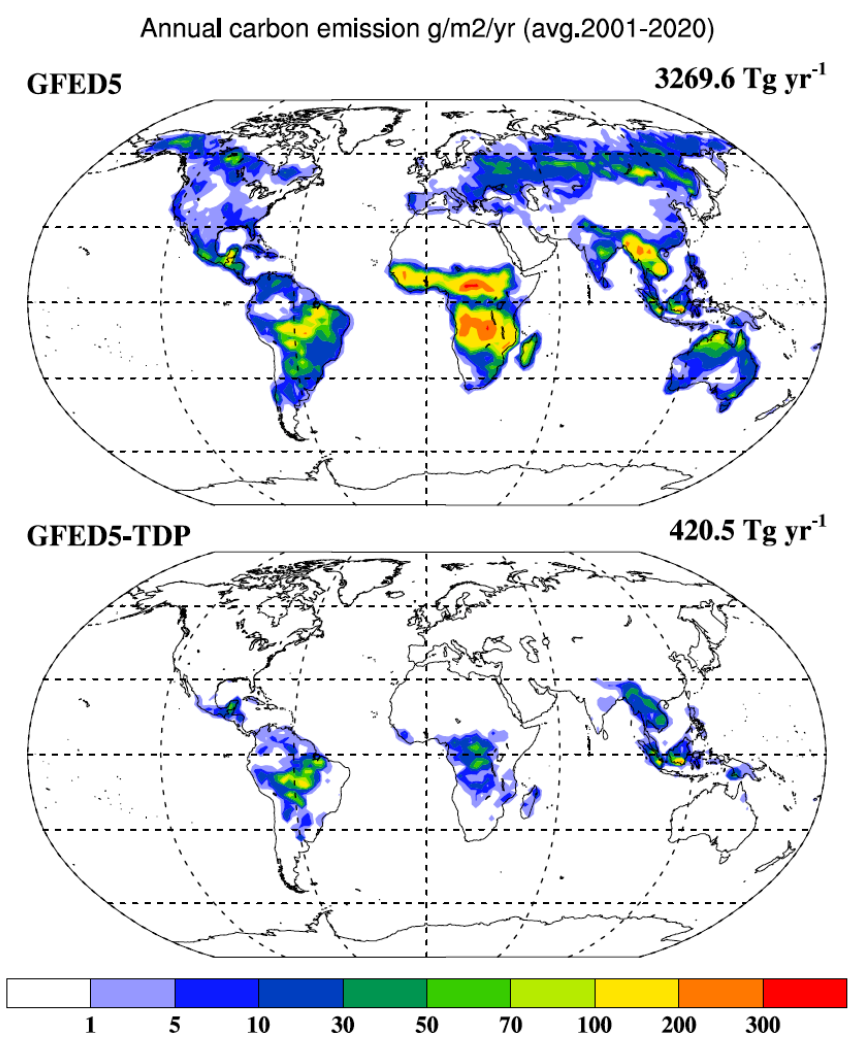
Science question:

- If most of the permanent and shifting cultivation components of deforestation are combusted, is the amount of carbon monoxide and aerosol produced by contemporary carbon cycle assessments consistent with available observations?

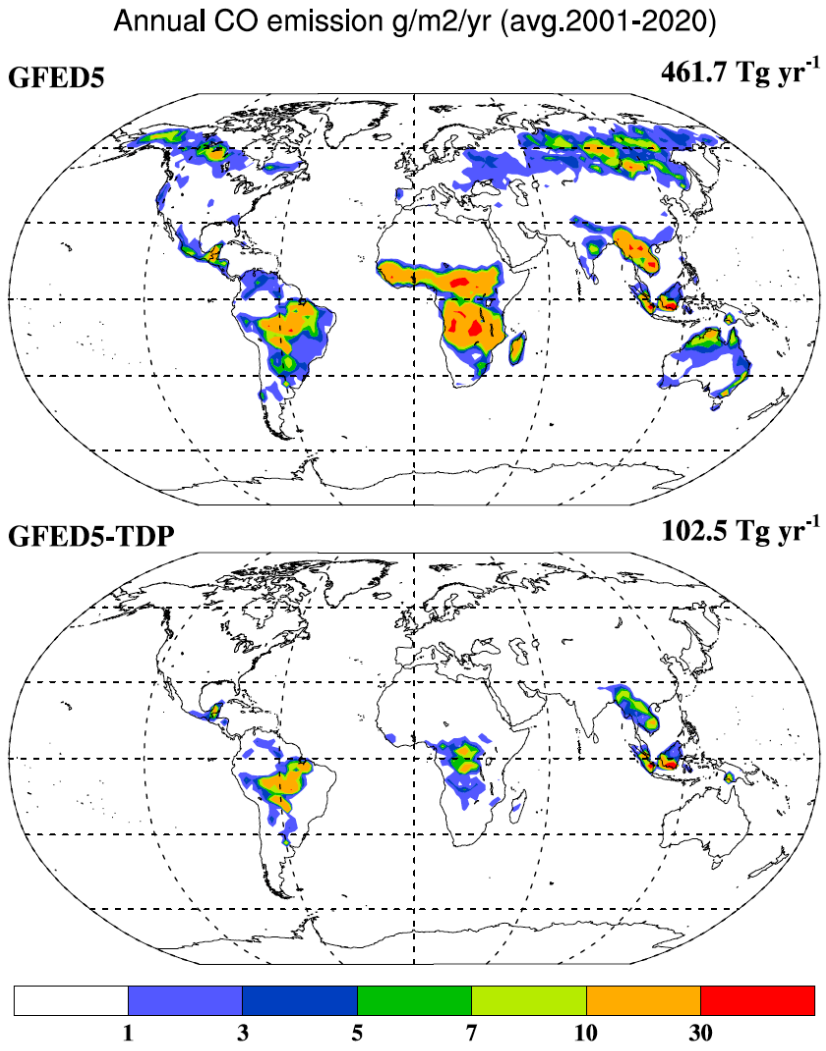
Approach:

- Assess the impact of fires on atmospheric composition in E3SM v3. Isolate GFED5 fire emissions from deforestation, tropical forests, and peat fires. Compare the baseline GFED5 simulation with one in which tropical deforestation, degradation, and peat fires are increased to match carbon cycle assessments

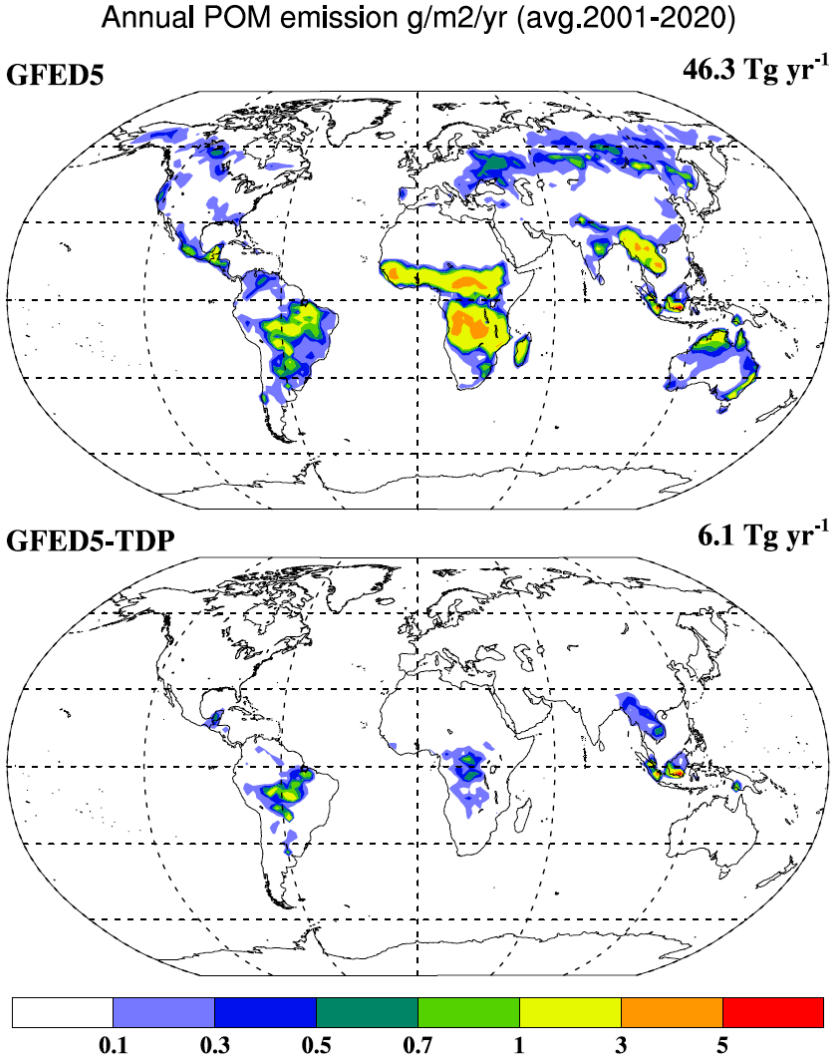
Carbon Emissions



CO Emissions



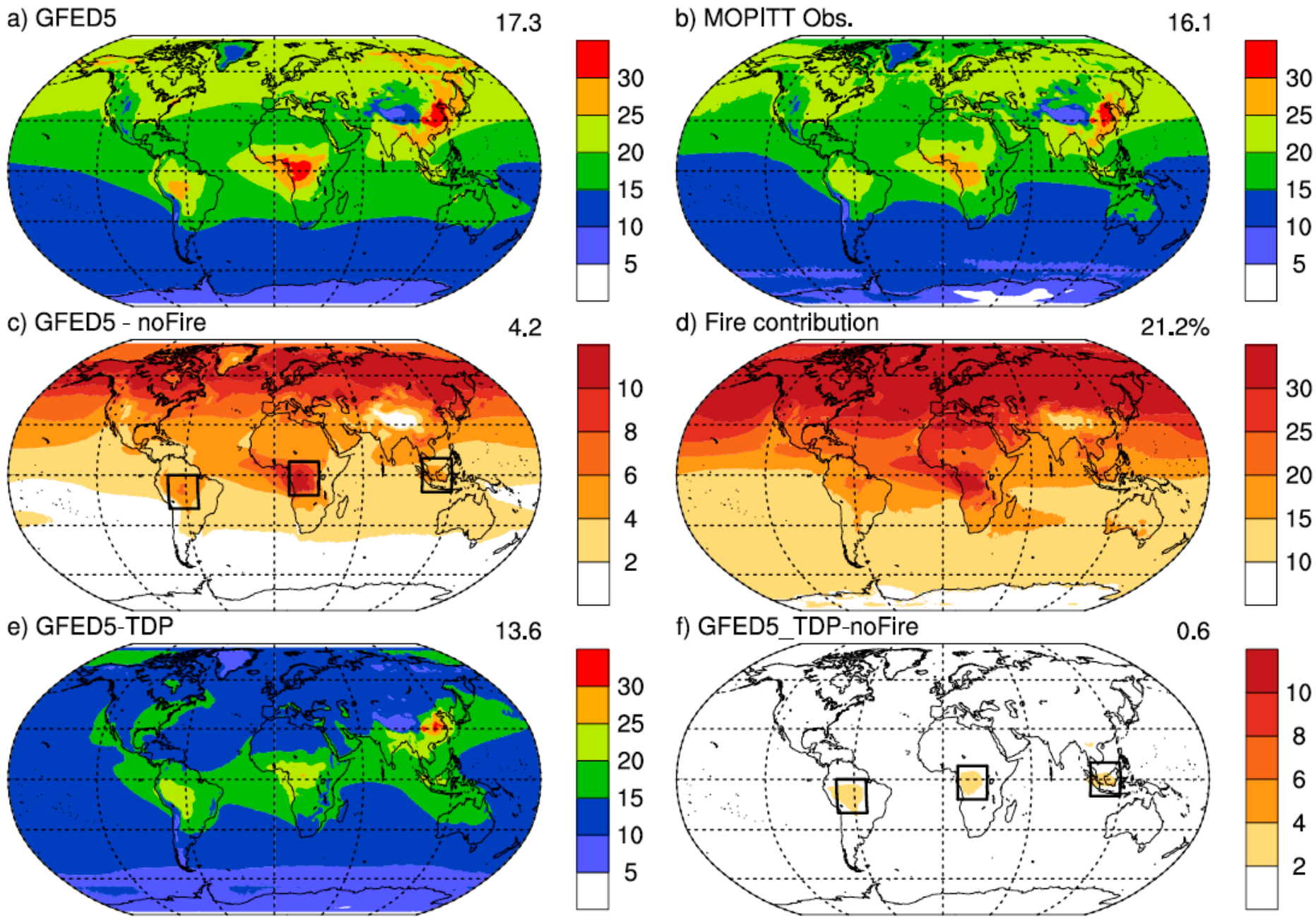
POM Emissions



E3SMv3 Experimental Design

Model run (1997-2021)	Description
GFED5	Full model simulation with GFED5 fire emissions plus all other sources from fossil fuel emissions, biogenic emissions, methane oxidation, and other sources
No fire	Same as the GFED5 simulation but global fire emissions have been set to 0 for all chemical and aerosol species
GFED5 TDP	Fire emissions only from tropical forest, deforestation, and peatland fires, plus all other non-fire sources from the GFED5 run
GFED5 + TDP x 3	Same as the GFED5 simulation plus 3 x the tropical forest, deforestation, and peatland fire emissions

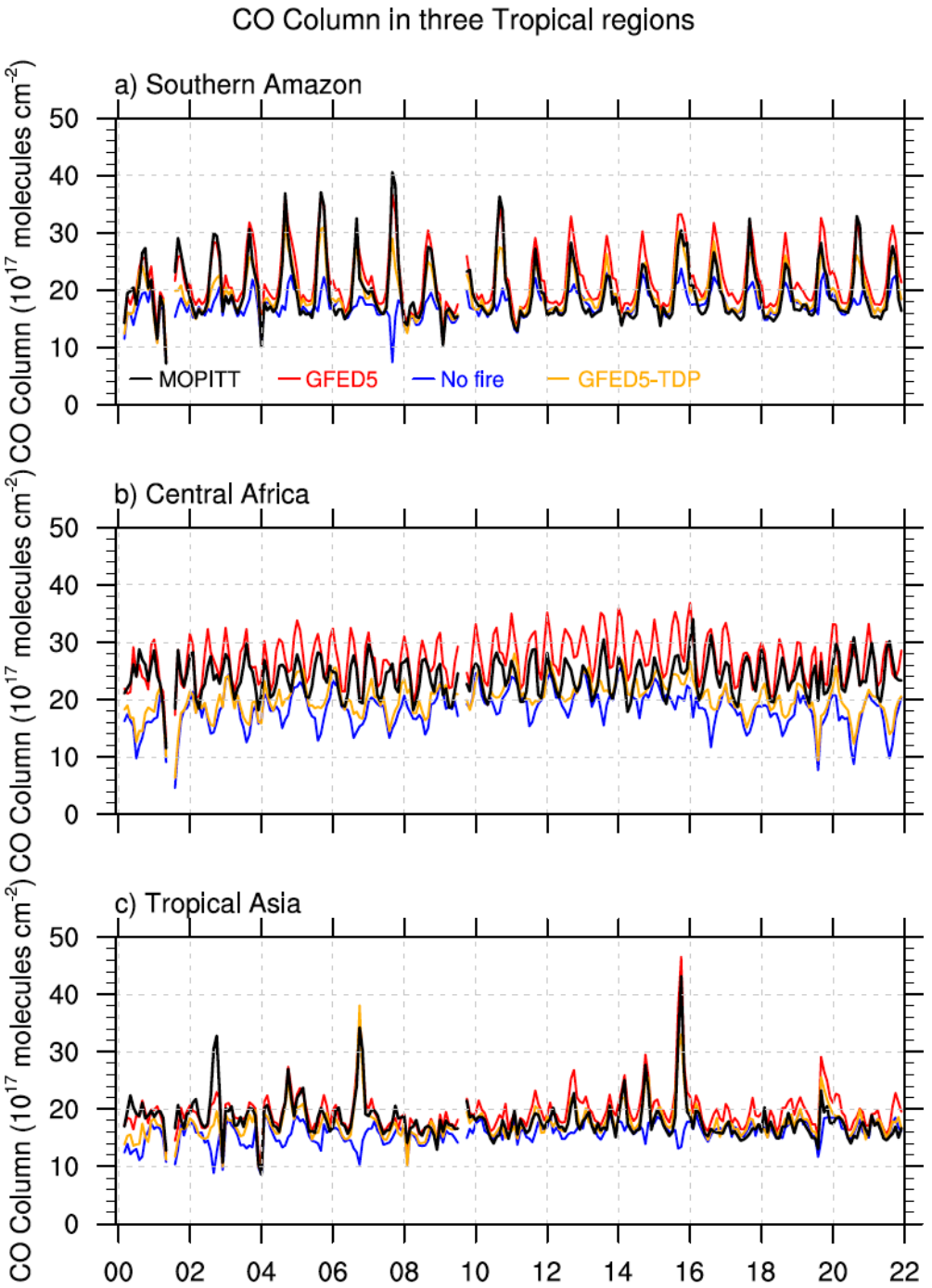
- Simulations from 1996-2021
- Uses E3SM version 3 with prescribed time varying SSTs and interactive chemistry developed by Qi Tang and colleagues at LLNL


Avg. Column CO mixing ratio (10^{17} molecules cm^{-2}) during 2000-2021
a) GFED5
17.3
b) MOPITT Obs.
16.1
c) GFED5 - noFire
4.2
d) Fire contribution
21.2%
e) GFED5-TDP
13.6
f) GFED5_TDP-noFire
0.6
30
25
20
15
10
5
10
8
6
4
2

Findings:

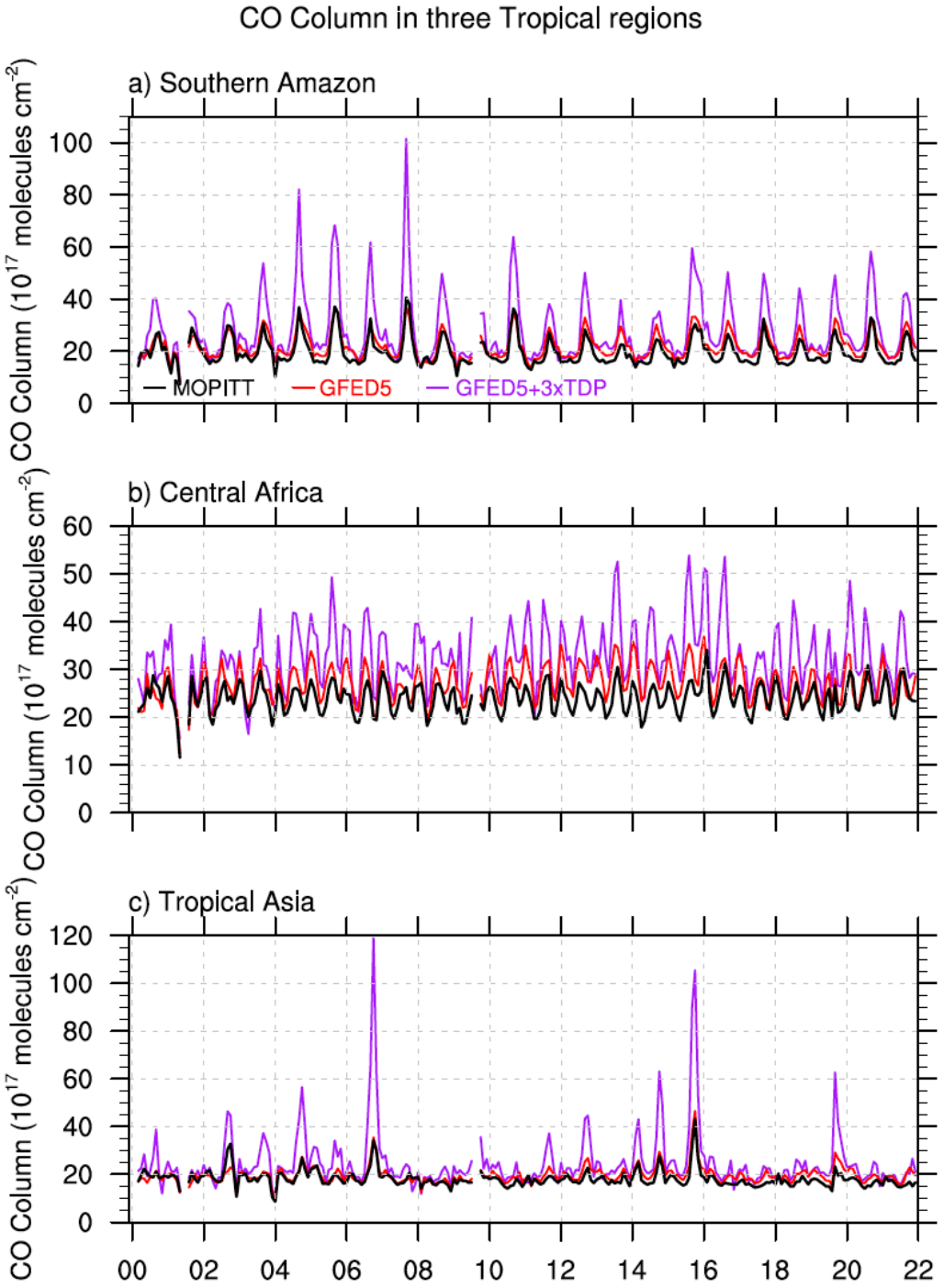
- The GFED5-E3SM3 model simulation does a reasonable job of reproducing the annual cycle of column CO in South America and Africa and interannual variability in Southeast Asia.

- Simulations without fire emissions cannot capture seasonal or interannual variability of the CO column in areas that are currently experiencing high levels of land use change in the tropics

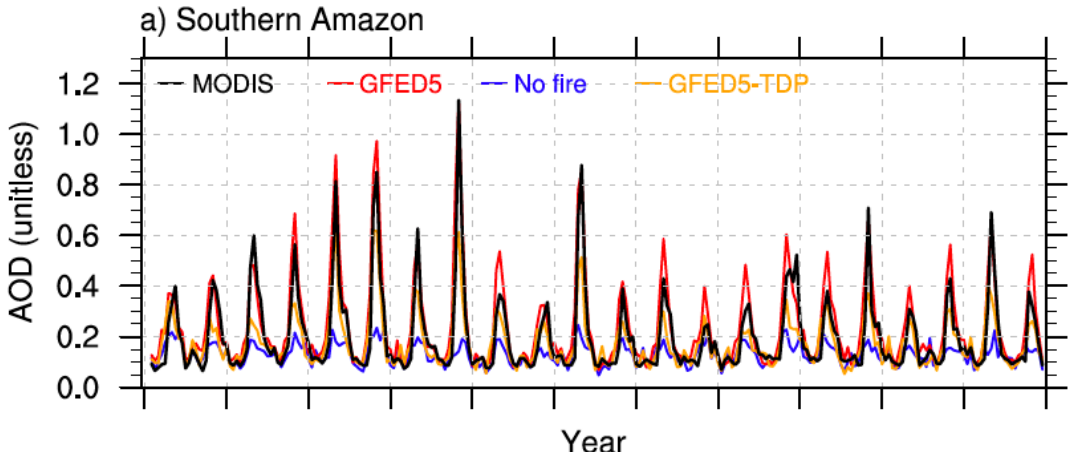


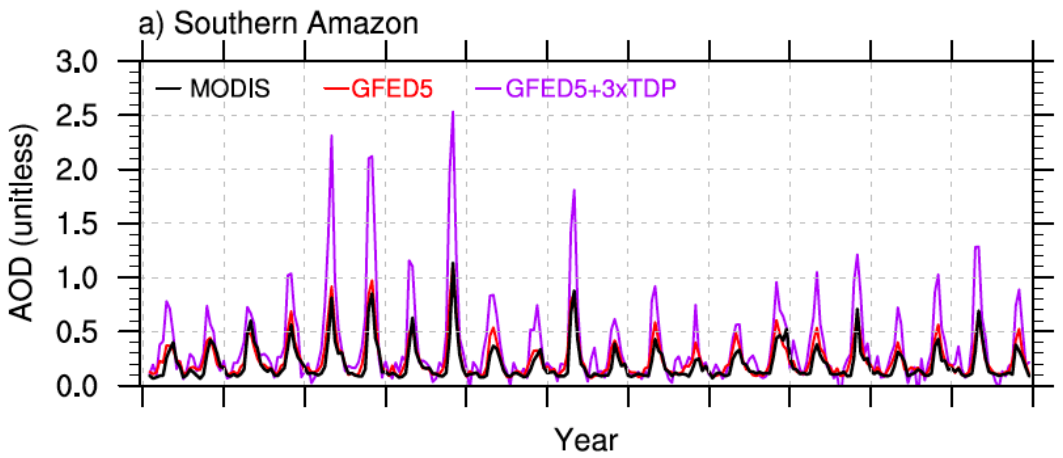
What happens when the tropical land use fire flux is increased four-fold to about 1.7 Pg C/y (i.e., the GFED5 + 3 x TDP simulation)?

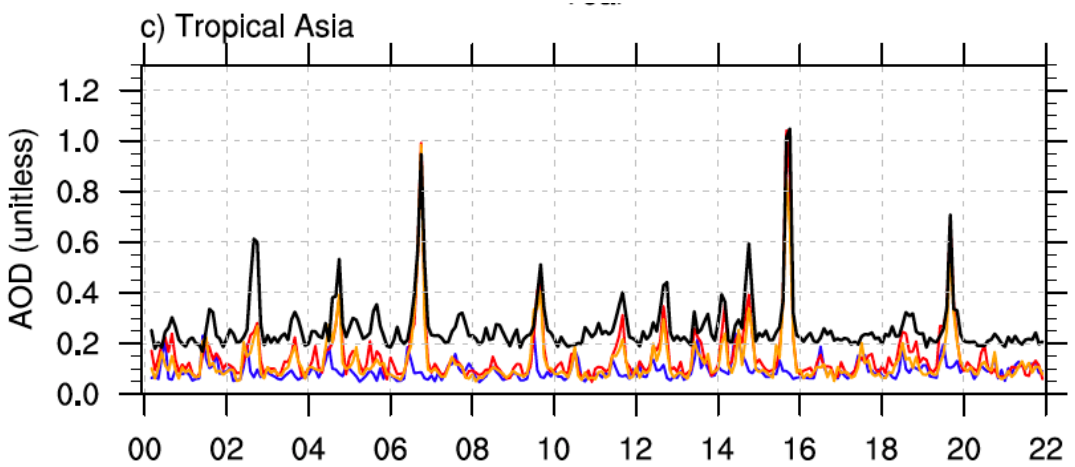
- Across the southern Amazon, peak CO concentrations are about 2-4 fold higher than the observed column CO
- Emissions during El Nino years are 3-8 times higher than the observations in tropical Asia
- The phase of CO annual cycle remains correct – the amplitude and dry-season values are too high!

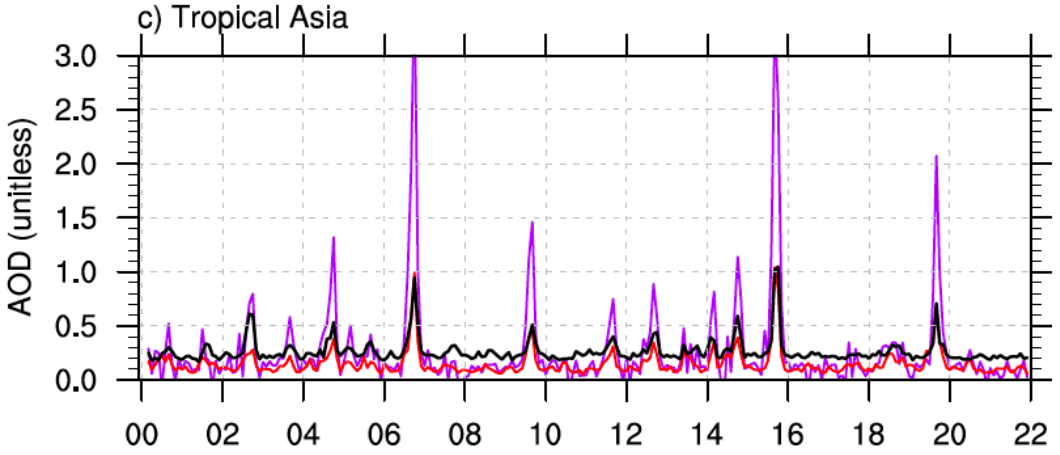


Simulated AOD from GFED5 is reasonable in many high fire regions and critical for explaining seasonal and interannual variability







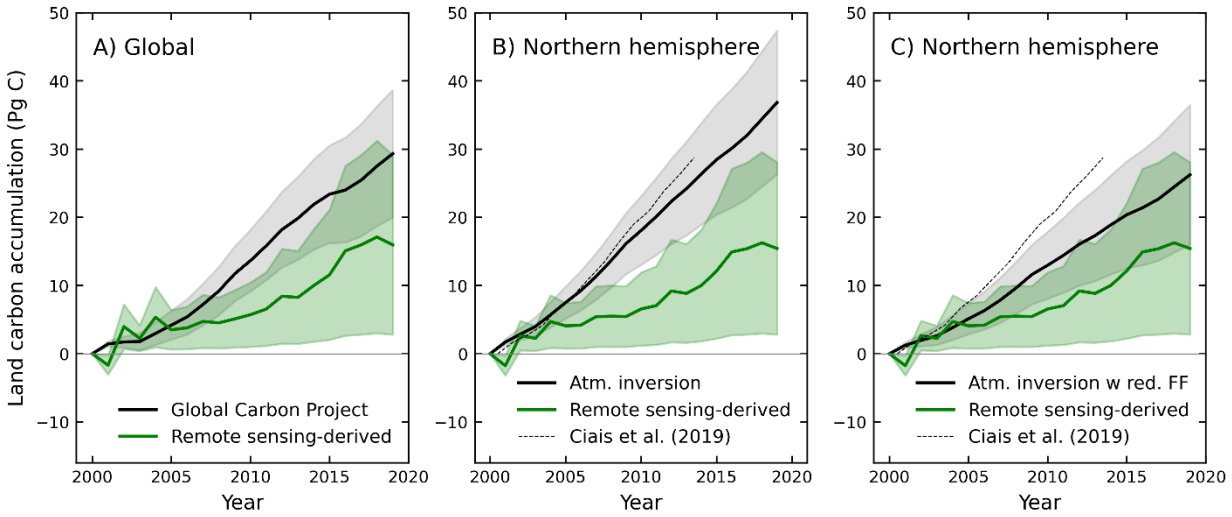


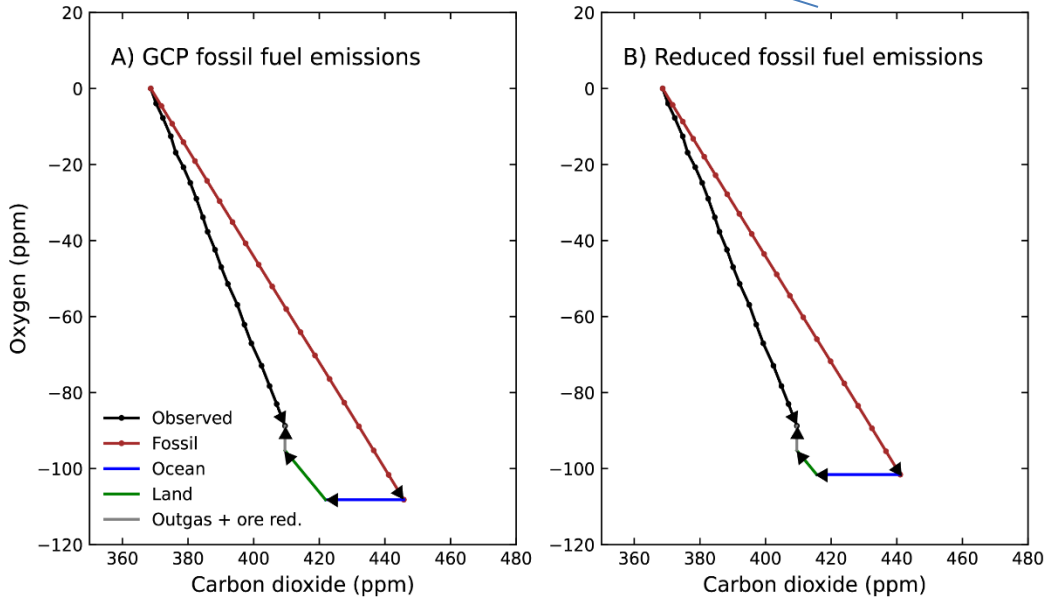
Conclusions and Future Directions

- A successful deforestation solution *needs* to match tropical chemistry and aerosol atmospheric composition observations
- GCP land use carbon emissions may be too high, and CASA-GFED5 land use fire emissions may be too low – the answer is likely somewhere in the middle …
- Wood product pools likely cannot account for the difference – this flux is about 0.2 Pg C/y globally from Pan et al.
- Key future directions:
  - Repeat with TROPOMI CO
  - Repeat with CESM v3
  - Revisit LUC product pools flows in CESM and E3SM
  - Assess uncertainties from CO emission factors for deforestation and peat burning
  - Evaluate the impact of fire-emitted aerosols using MODIS AOD and AERONET observations as a constraint
  - Evaluate clearing rates from LUH2 and Landsat-derived UMD, GLANCE, and MAPBIOMAS products

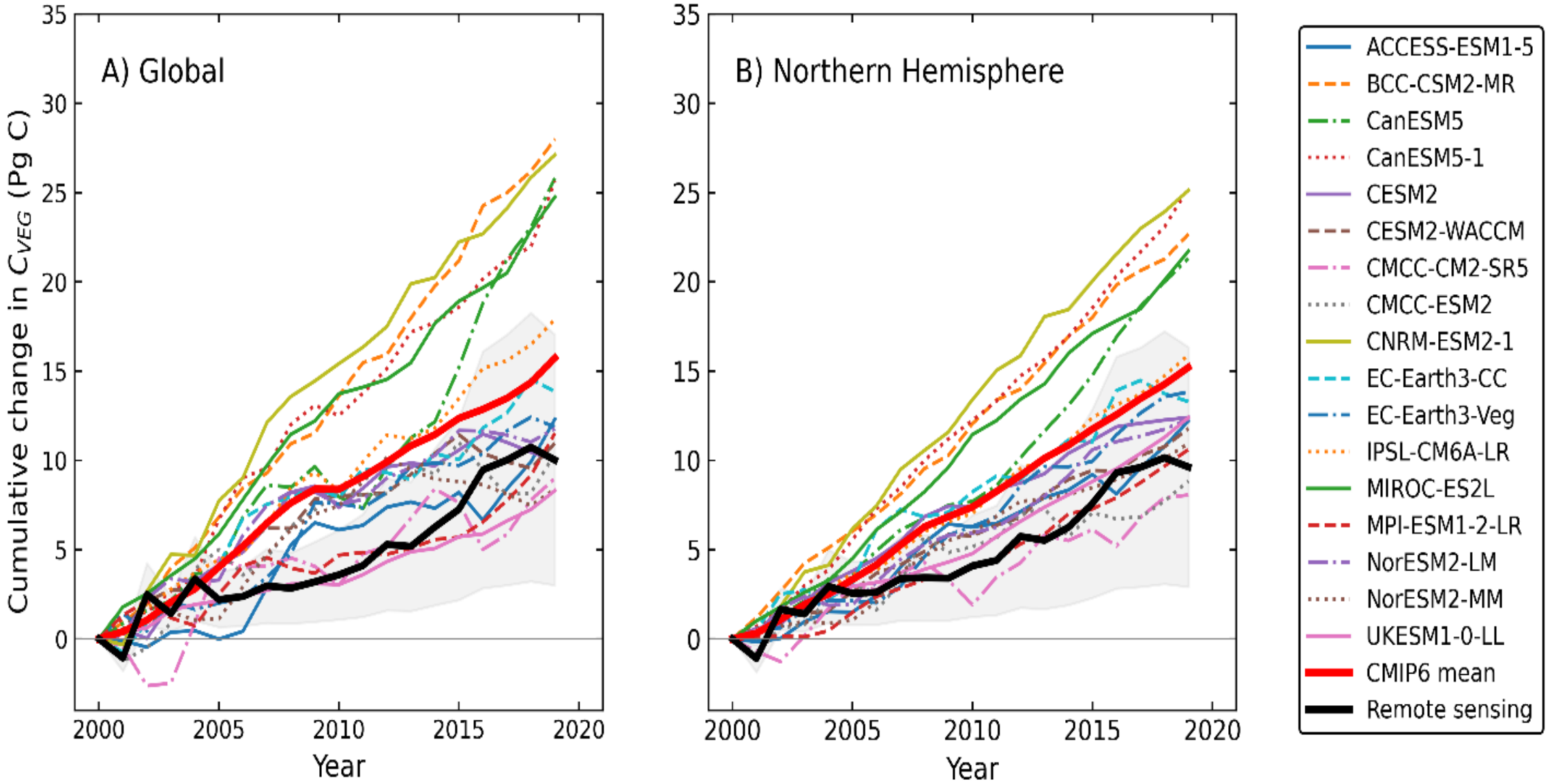
Implications for the global budget

Component (2000-2019)	GCP/Pan et al.	Proposed
Land use change	1.4	~0.7
S_{LAND} (CO_2 fertilization, climate, etc.)	3.0	1.5
Net land carbon sink:	1.6	0.8



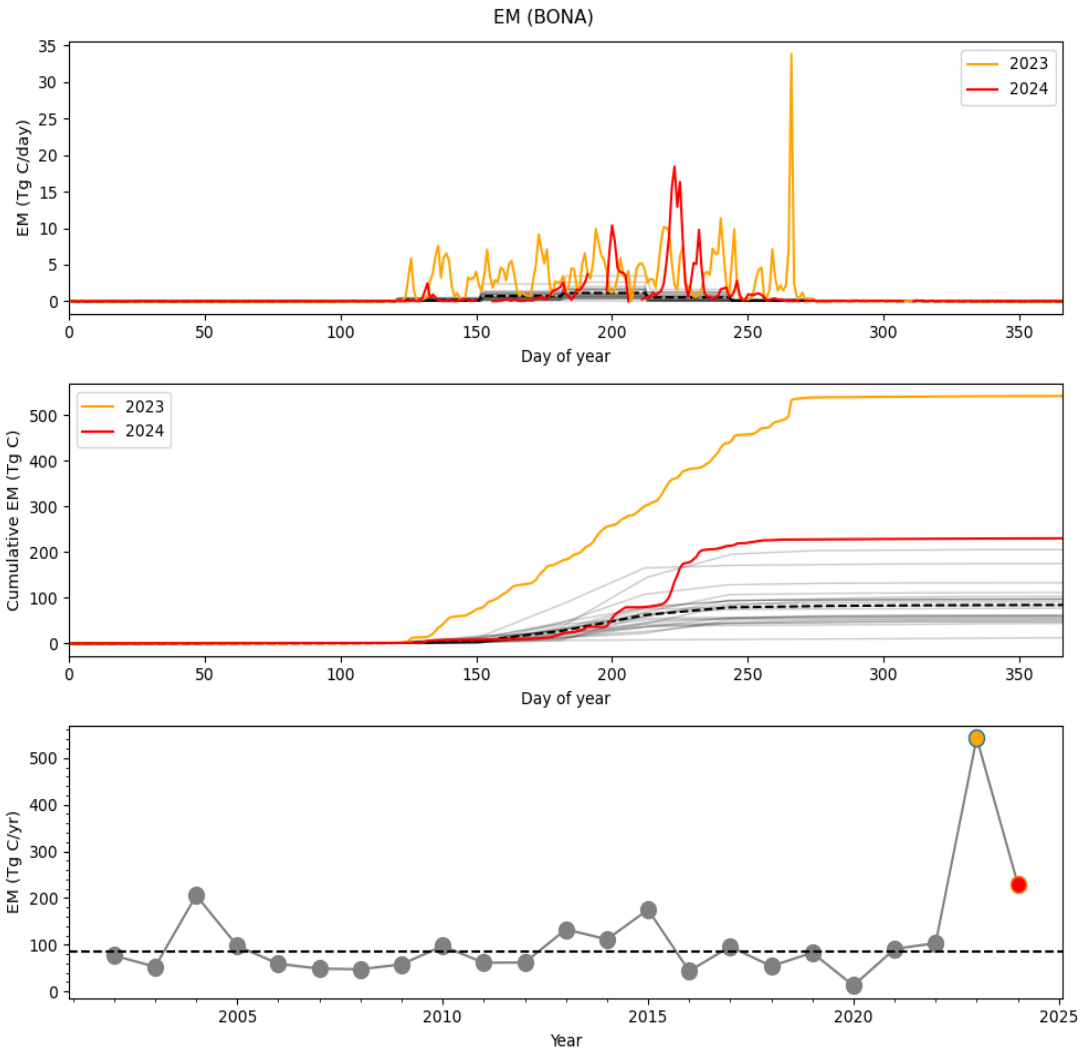


Randerson et al. (In review)

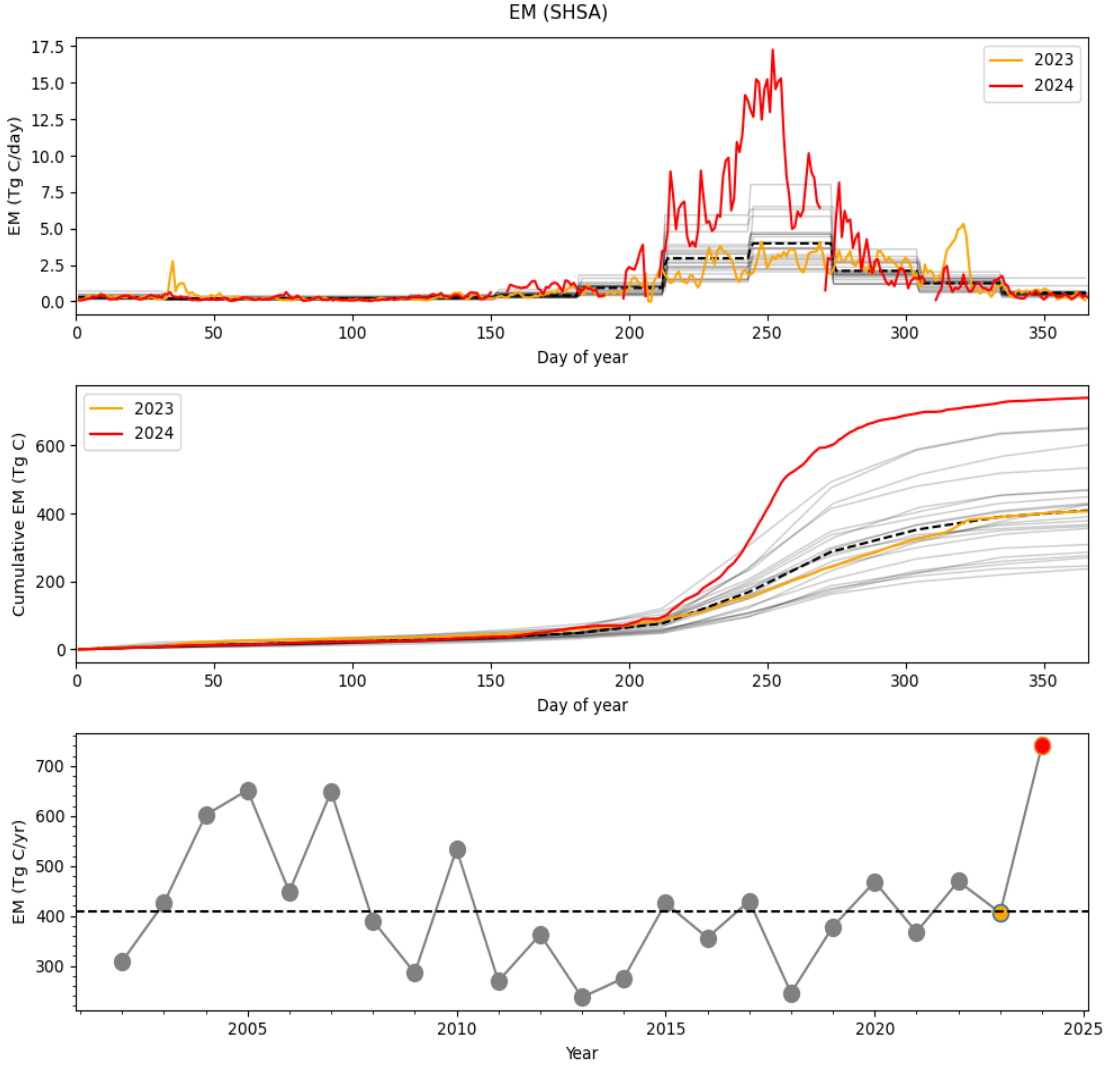

A) Global
B) Northern Hemisphere
Cumulative change in C_{VEG} (Pg C)
Year
35
30
25
20
15
10
5
0
2000
2005
2010
2015
2020
ACCESS-ESM1-5
BCC-CSM2-MR
CanESM5
CanESM5-1
CESM2
CESM2-WACCM
CMCC-CM2-SR5
CMCC-ESM2
CNRM-ESM2-1
EC-Earth3-CC
EC-Earth3-Veg
IPSL-CM6A-LR
MIROC-ES2L
MPI-ESM1-2-LR
NorESM2-LM
NorESM2-MM
UKESM1-0-LL
CMIP6 mean
Remote sensing

Why are fire emission so high in 2023 and 2024

Boreal North America



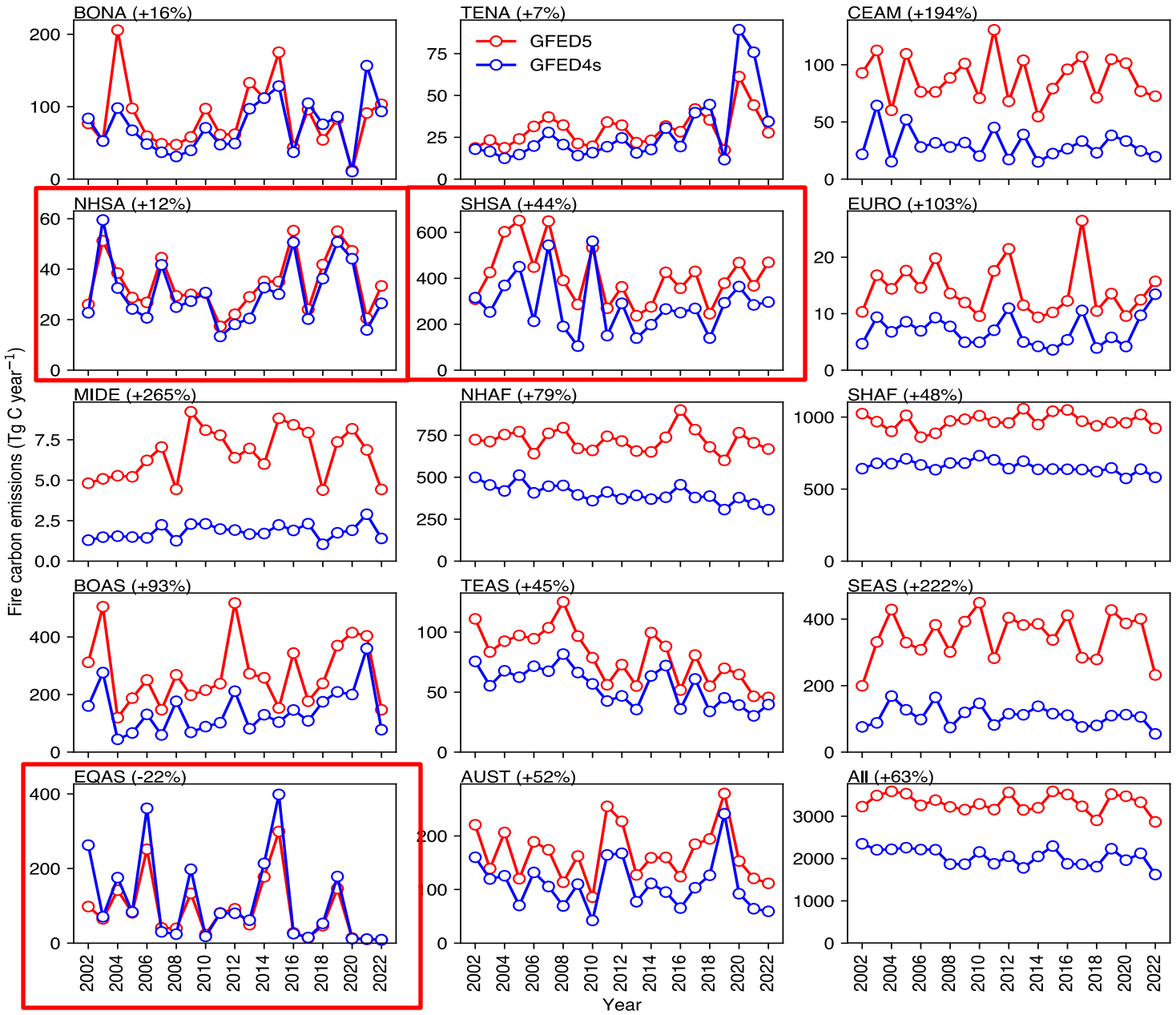
Southern Hemisphere South America



Estimating the rate of gross deforestation over the past two decades: Which is correct? About 0.4 Pg C/y from GFED5 versus about 2.0 Pg C/y from GCP LUC models?

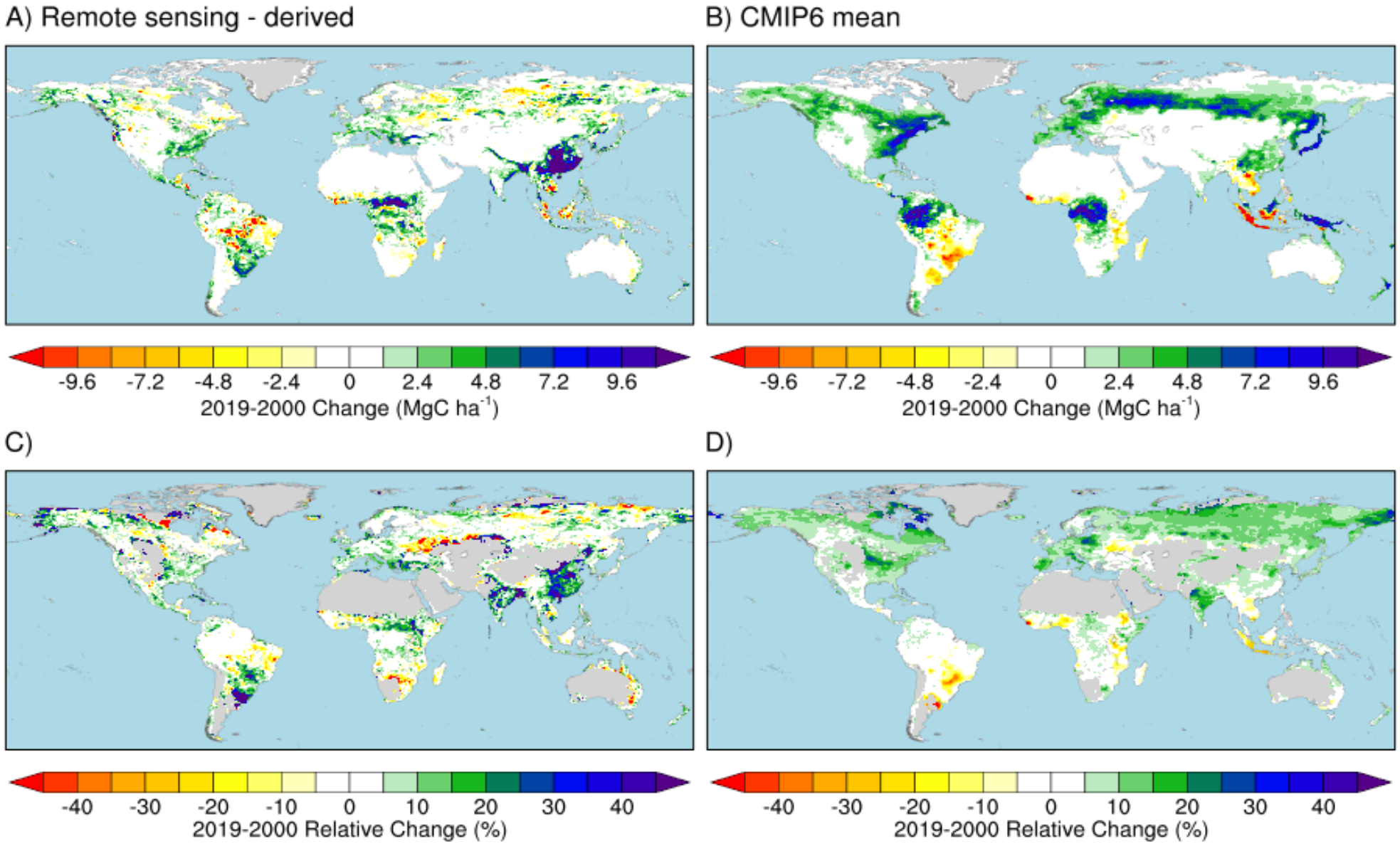
- Why GFED5 tropical forest, deforestation, and peat fire emissions could be too low:
  - Missing understory fires (Coffield et al. In review)
  - Fuel consumption in deforestation fires may be too low
  - Missing deforestation fire area estimation from cloud cover

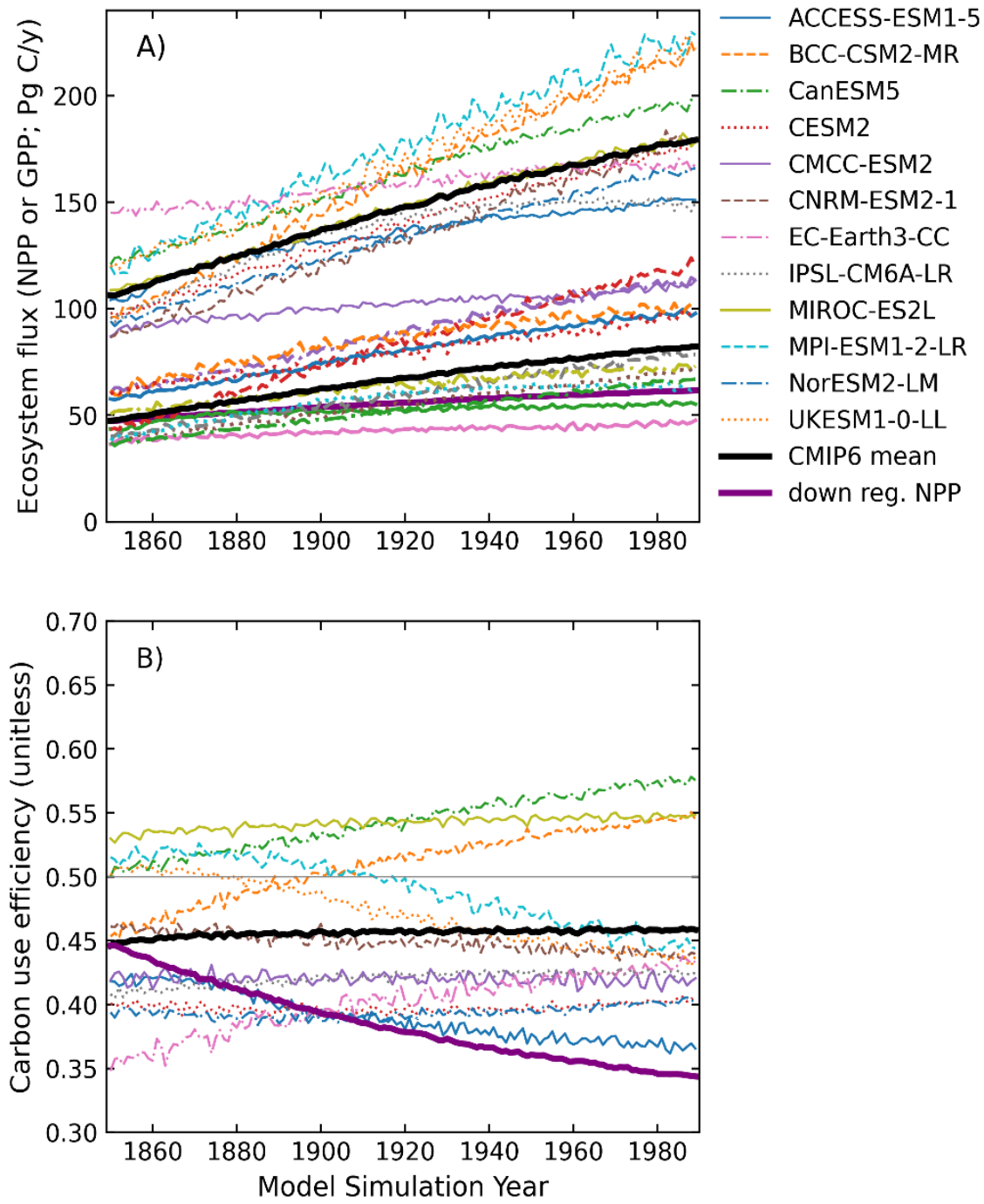
- Why GCP land use change models could be too high:
  - Shifting agriculture is overestimated, currently poorly constrained
  - Rates of gross land clearing each year are too high, and balanced by too high a rate of forest regrowth to match the same long-term (decadal) net land cover changes



van der Werf et al. (In review)

Species	GFED5	GFED4s	Difference (%)
DM	7059	4176	+69
C	3314	2037	+63
CO_2	11287	6902	+64
CO	513	334	+54
CH_4	18.2	14.6	+25
NMOC_g / NMHC	117	173	-32
H_2	14.2	8.7	+65
NO_x (as NO)	20.7	13.5	+53
N_2O	1.16	0.89	+31
PM2.5	90.7	35.0	+159
TPC	38.8	17.9	+117
OC	36.7	16.1	+128
BC	2.16	1.77	+22
SO_2	5.89	2.25	+161
NH_3	6.52	4.08	+60


A) Remote sensing - derived
B) CMIP6 mean
-9.6 -7.2 -4.8 -2.4 0 2.4 4.8 7.2 9.6
2019-2000 Change (MgC ha-1)
C)
D)
-40 -30 -20 -10 0 10 20 30 40
2019-2000 Relative Change (%)


A)
Ecosystem flux (NPP or GPP; Pg C/y)
0
50
100
150
200
1860
1880
1900
1920
1940
1960
1980
ACCESS-ESM1-5
BCC-CSM2-MR
CanESM5
CESM2
CMCC-ESM2
CNRM-ESM2-1
EC-Earth3-CC
IPSL-CM6A-LR
MIROC-ES2L
MPI-ESM1-2-LR
NorESM2-LM
UKESM1-0-LL
CMIP6 mean
down reg. NPP
B)
Carbon use efficiency (unitless)
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
1860
1880
1900
1920
1940
1960
1980
Model Simulation Year