CO_2 fertilization of terrestrial photosynthesis inferred from site to global scales

Chi Chen[1,2*] (presenter), William J. Riley[1], I. Colin Prentice[3], Trevor F. Keenan[1,2*]

[1]Lawrence Berkeley National Laboratory; [2]UC Berkeley; [3]Imperial College London

RUBISCO Biogeochemistry Science Seminar
December 2021

The research questions

1. When and how can we detect a signal of CO_2 fertilization effect (CFE) emerge in long-term measurement of carbon flux from globally distributed networks?

FLUXNET A Global Network   AMERIFLUX   .....

2. Can we accurately constrain CFE using satellite observations / meteorological reanalysis data?

NASA   ECMWF   ......

First-order CO_2 fertilization effect

- Terrestrial photosynthesis is quantified by terrestrial Gross Primary Productivity (GPP).
- Exchange of CO_2 and water vapor fluxes between the land and the atmosphere.
- Both fluxes can be described by the Fickian gas diffusion.

Stomatal conductance

leaf intercellular CO_2 mole fraction

e.g.: $f_c = g(c_a - c_i)$

CO_2 flux

Atm. CO_2 mole fraction

- **Fertilization**: c_a is increasing @2.1 ppm yr^{-1}

Optimization: carbon-water economy

Plants adjust g and c_i to optimize the gas exchange problem!

Loss: Water flux

$$f_e = 1.6g(e_i - e_a) \approx 1.6gD$$

Stomatal conductance

leaf intercellular CO_2 mole fraction

$$f_c = g(c_a - c_i)$$

Gain: CO_2 flux

Atm. CO_2 mole fraction

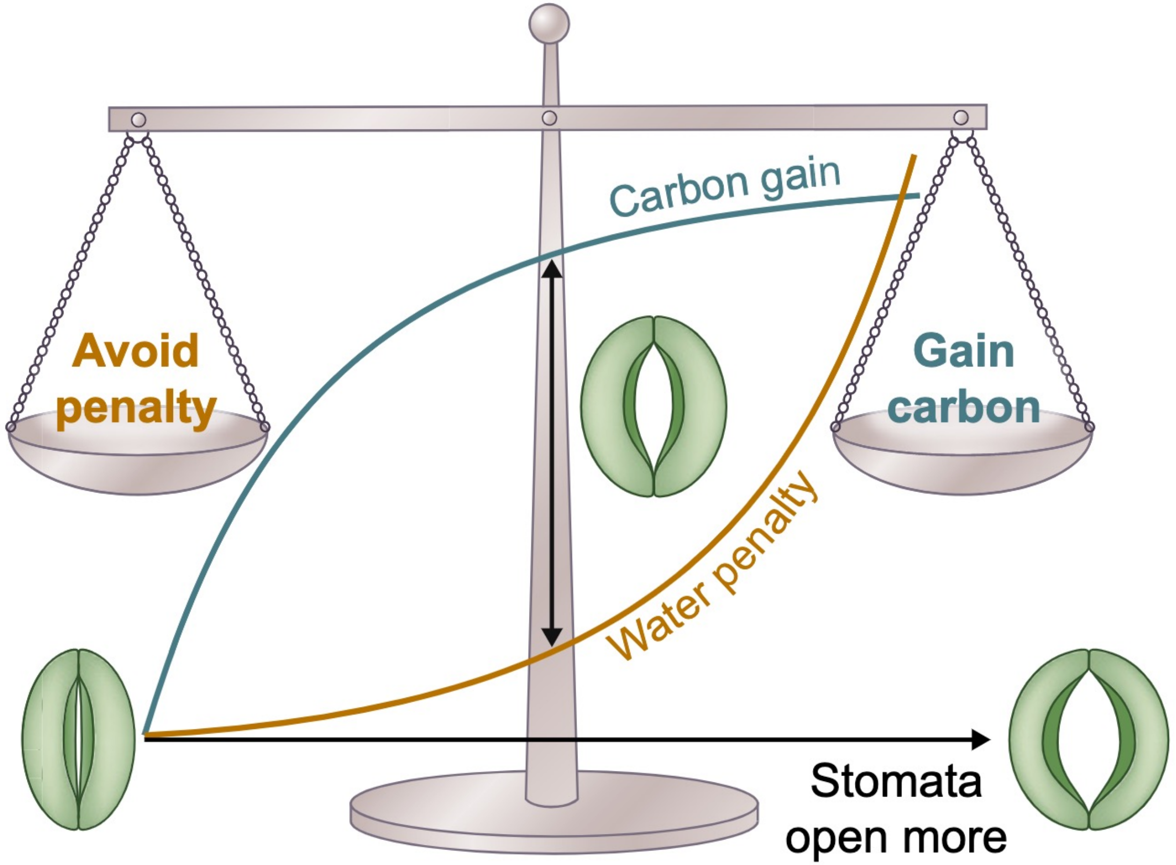


Figure credit: Wang et al. (2020)

Major challenges

The magnitude of the CO_2 fertilization effect (CFE) on terrestrial GPP is not directly observed and is subject to confounding effects of (1) climate variability & (2) model representations.

Different GPP **magnitudes**

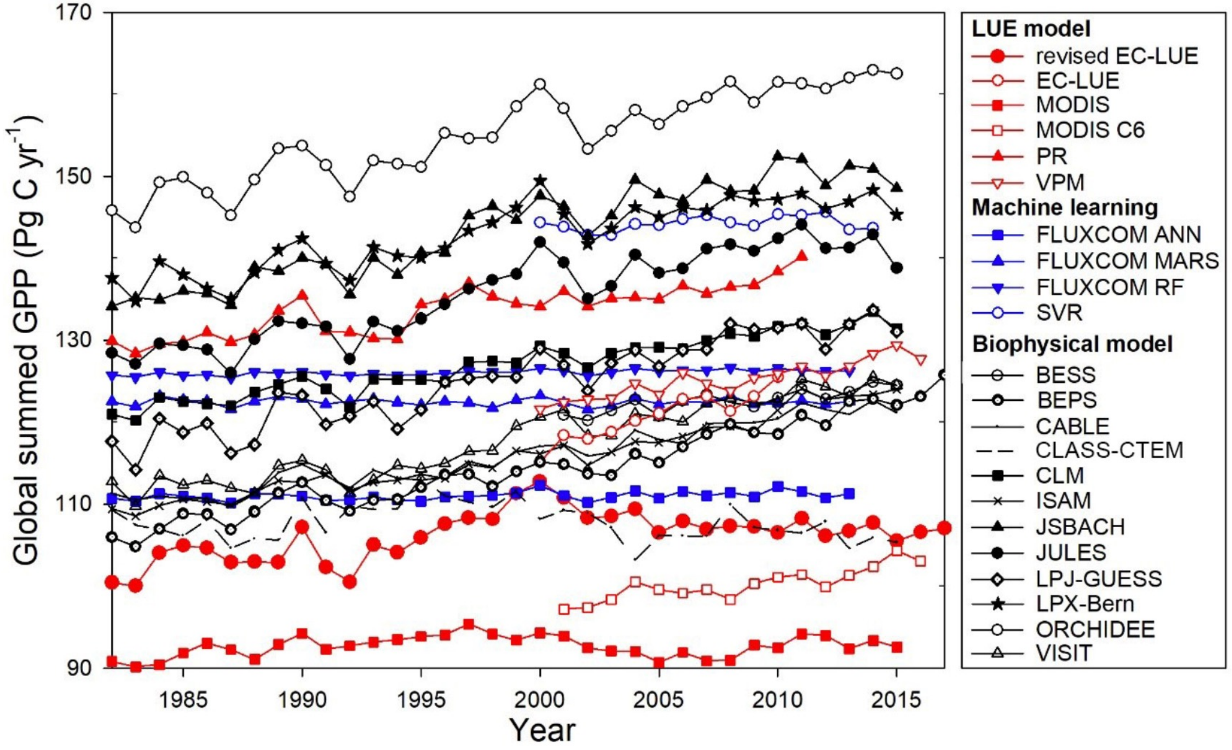


Figure credit: Zheng et al. (2020)

Different GPP **trends**

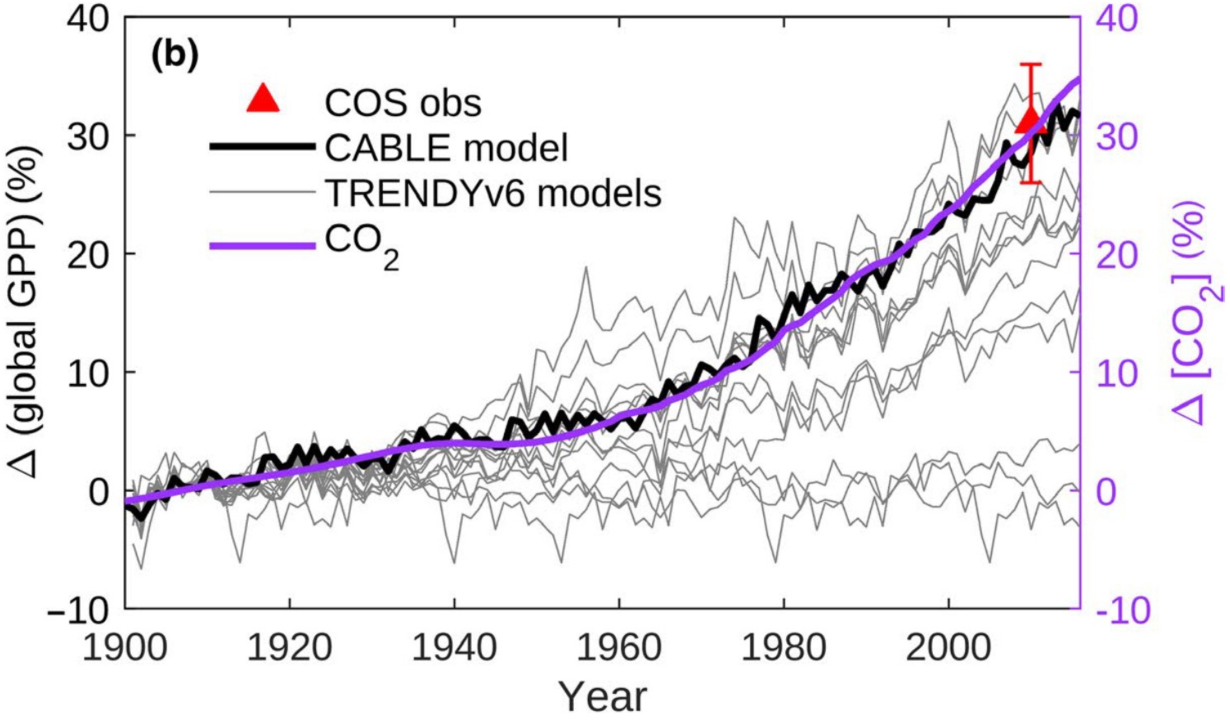


Figure credit: Harverd et al. (2020)

Constrain the CFE at the leaf level

Eco-Evolutionary Optimality (EEO) model to constrain the **partial differential** GPP sensitivity to CO_2.

$$\beta_{co2} = \frac{\partial GPP}{\partial c_a}$$

Also need the Farquhar photosynthesis model

$$f_c = g(c_a - c_i)$$

1 more eq.

1 more eq.

theory #1: Cowen-Farquhar hypothesis

$=$

theory #2: least-cost hypothesis

- Constrains the λ (marginal water use efficiency)

Constrain the photosynthetic capacity

The Farquhar photosynthesis model

- Light-saturated: $A_c = \frac{V_{cmax}(c_i - \Gamma^*)}{K + c_i} - R_d$
- Light-limited : $A_j = \frac{J(c_i - \Gamma^*)}{4(c_i + 2\Gamma^*)} - R_d$
- $f_c = \min(A_c, A_j)$

Balancing the nutrient allocation: apply the coordination hypothesis to constrain reference V_{cmax} and J_{max}

$$\overline{A_{c,peak}} = \overline{A_{j,peak}}$$

Climatological mean environment of the peak LAI month

No need about the biome type information!

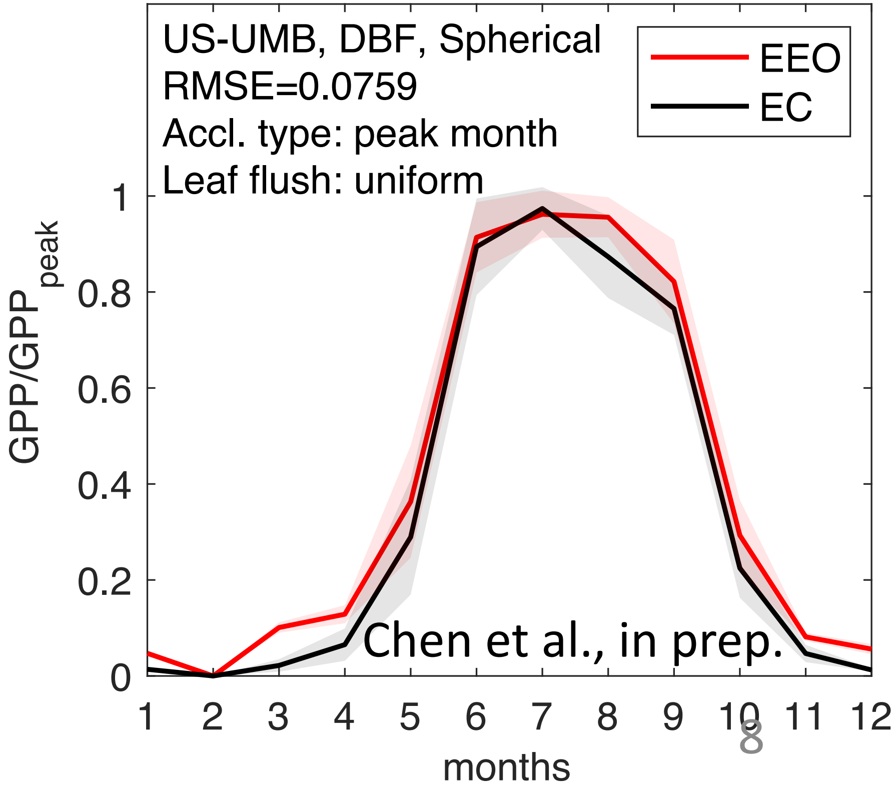
The canopy upscaling factor: $\left|\overline{\frac{G(\mu)}{\mu}}\right|$

- Big leaf
- Least square with FLUXNET
- No interannual variation

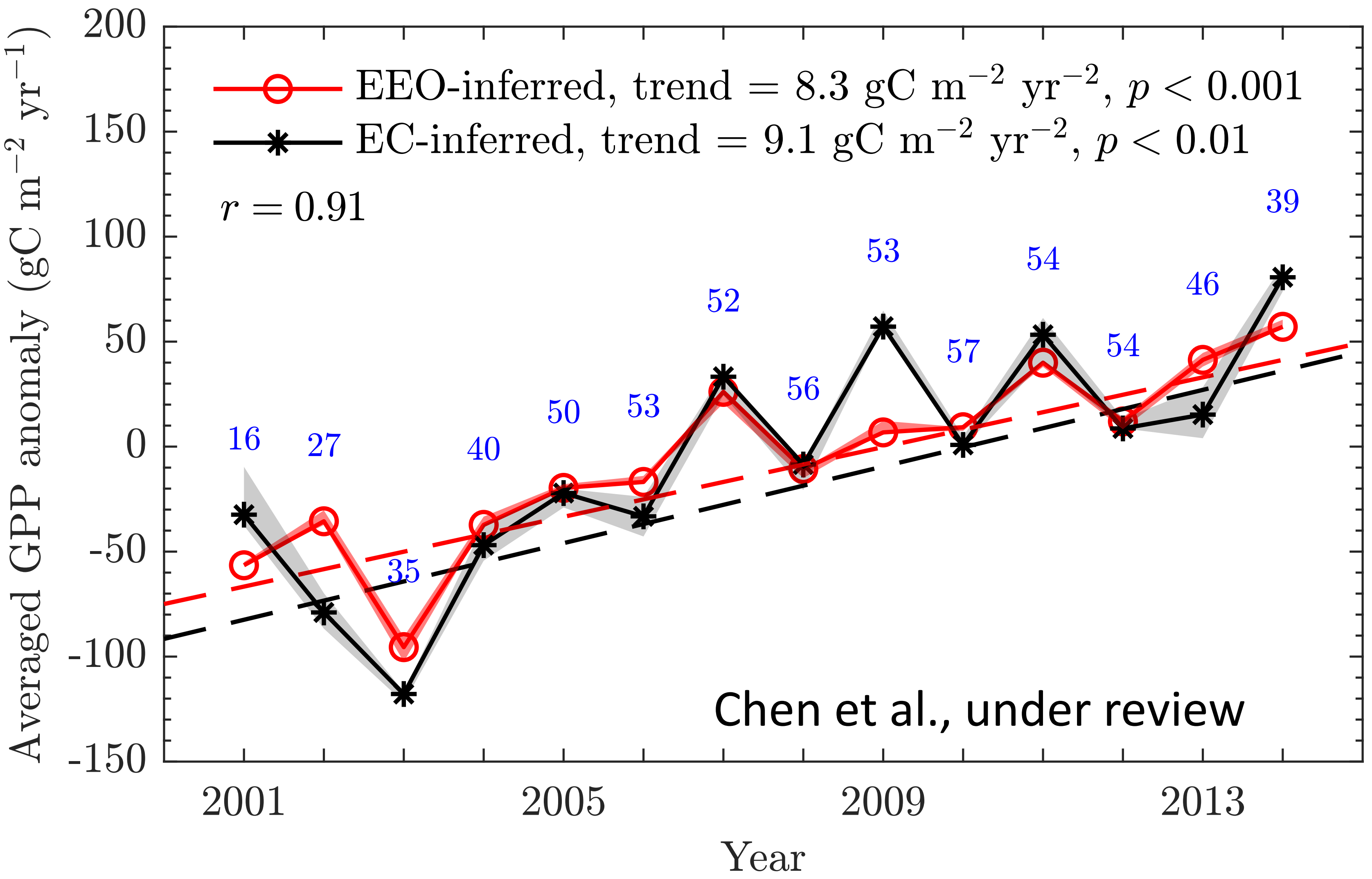
GPP and CFE are constrained by 7 variables:

- c_a
- Satellite LAI
- T_a
- SWC
- q_a
- SW_{in}
- P

A follow-up work: EEO model + a full canopy radiative transfer



Reproducing GPP trend and interannual variability (IAV)



Annual summed GPP for each site

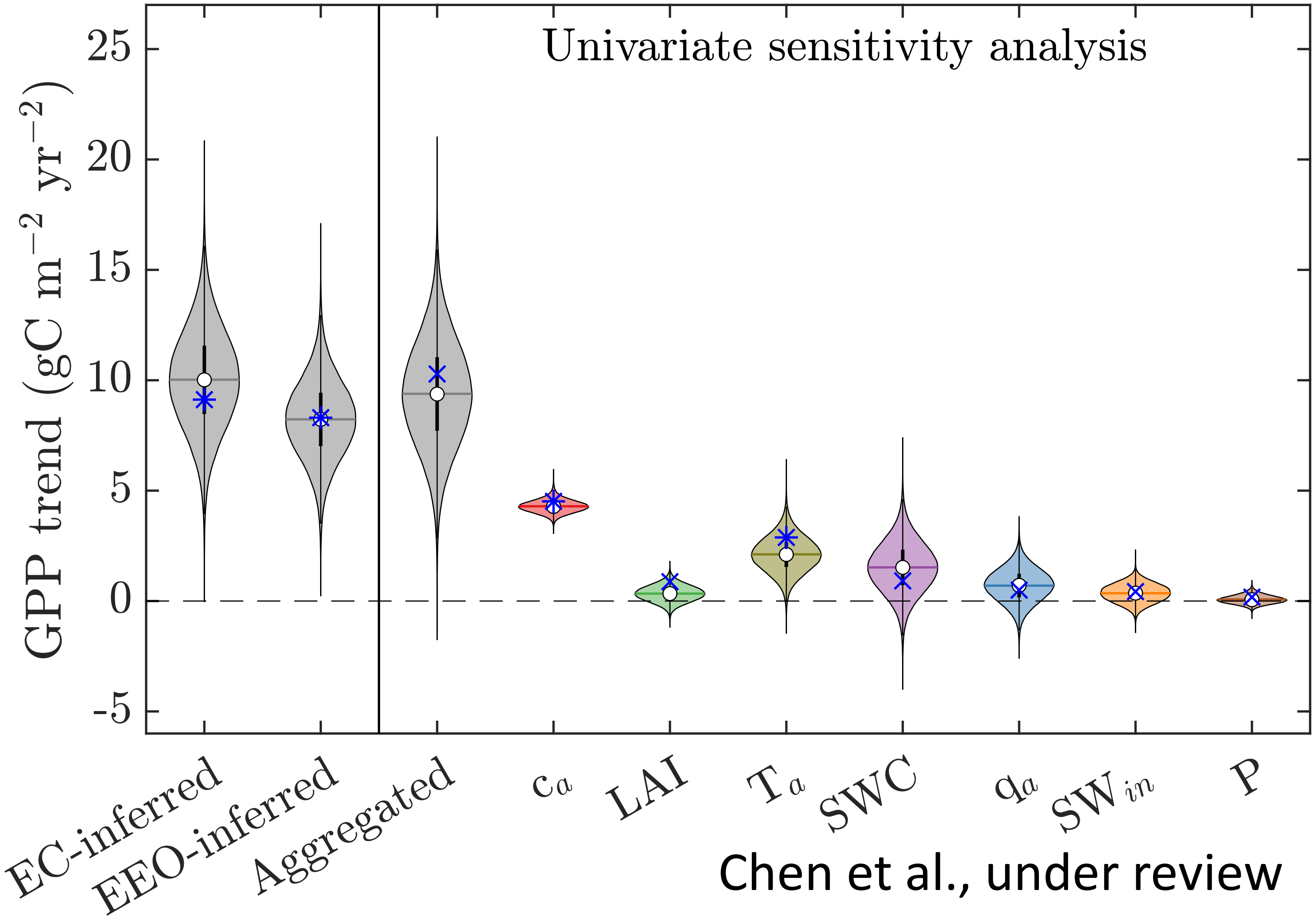
GPP annual anomaly for each site

Average the anomaly across sites

Test the trend

- EEO-inferred: Evo-Evolutionary Optimality model
- EC-inferred: FLUXNET2015

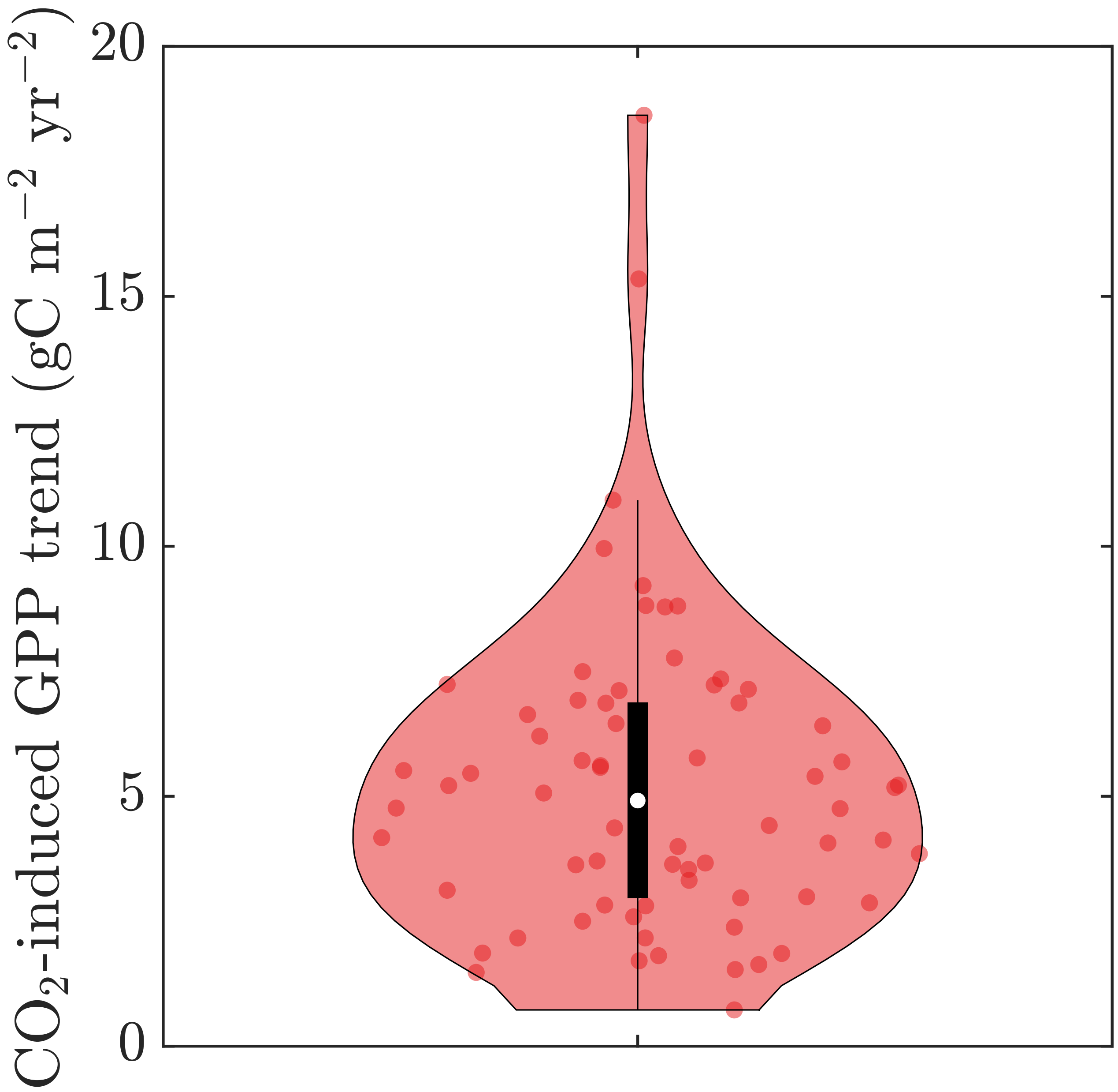
Overall trend attribution



Chen et al., under review

- >40% of the overall GPP trend across the sites is due to CO_2
- 4.5 gC m^{-2}yr^{-2}

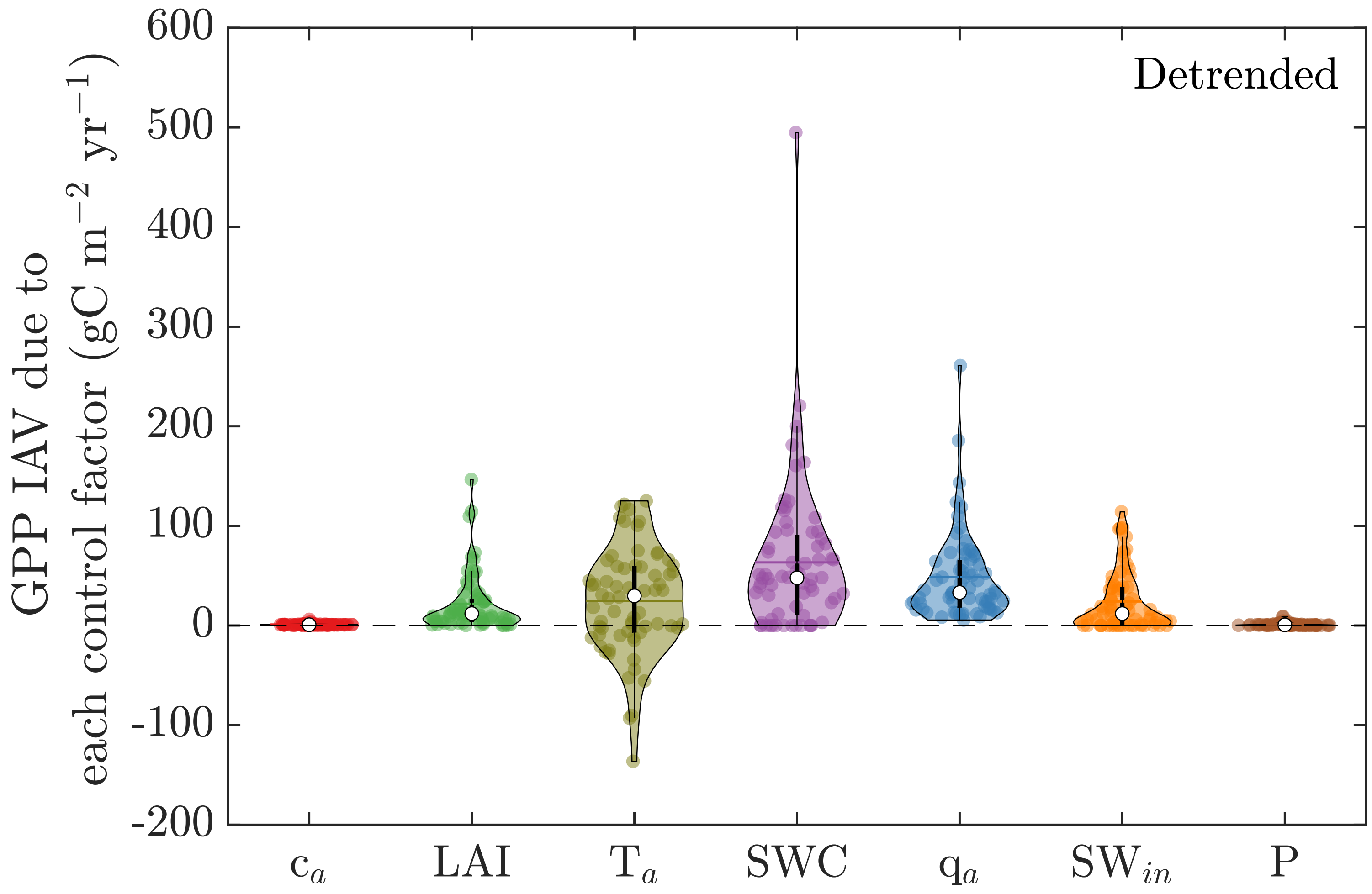
Diagnosed CFE for each site



Analytical constraints for individual sites

- $CFE = \frac{\partial GPP}{\partial c_a} \times \Delta c_a$
- Δ represents the trend
- Median CFE = 4.9 gC m^{-2} yr^{-2}
- CFE from the univariate analysis = 4.5 gC m^{-2} yr^{-2}

Diagnosed the IAV for each site

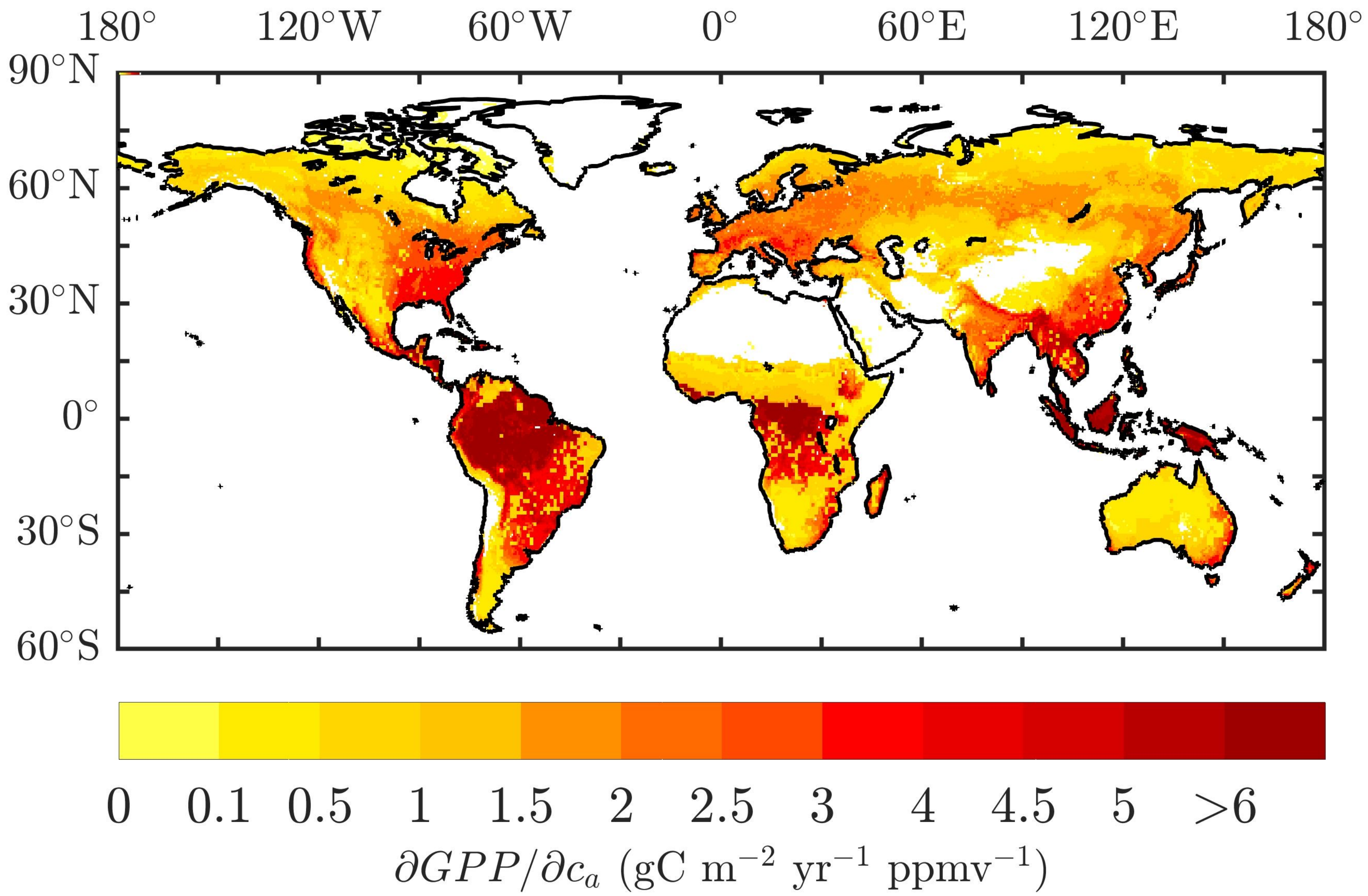


Chen et al., under review

Ability of each factor to cause GPP IAV

- $\frac{\partial GPP}{\partial X} \times Std_X$
- SWC > q_a > T_a
- c_a negligible

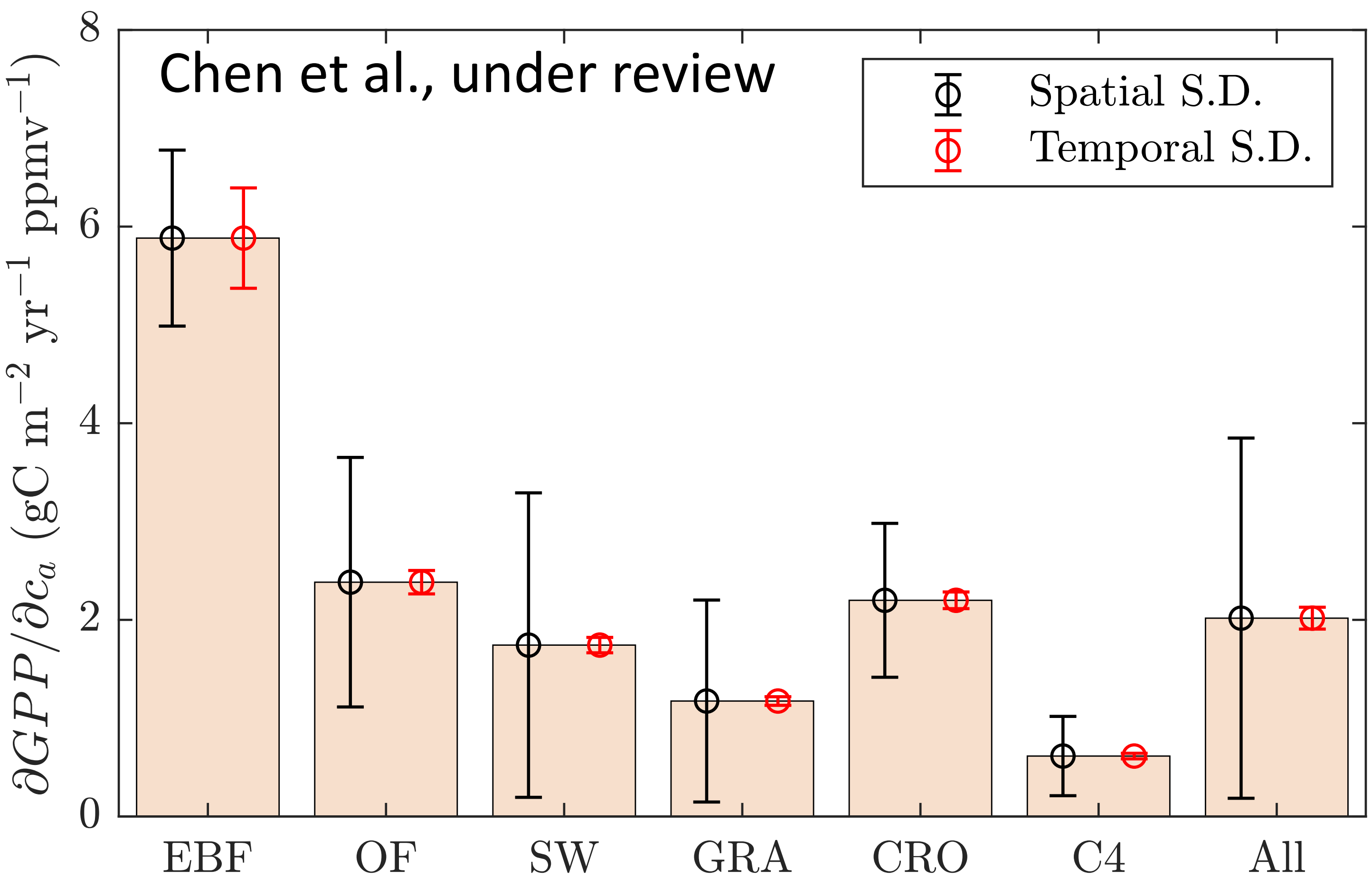
β_{co2} at the global scale



Chen et al., under review

- Inputs: ERA5 + MODIS LAI
- Canopy upscaling calibration: multiple satellite GPP products
- CO_2 trend @ ~2.1 ppm yr^{-1}
- Global average = 4.4 gC m^{-2}yr^{-1}ppmv^{-1}

Within biome β_{co2} variation driven by climate



Bars: mean β_{co2} for each biome type

- β_{co2} is a function of climate and CO_2, but CO_2 are prescribed without spatial variations
- No sig. temporal fluctuations due to climate variability

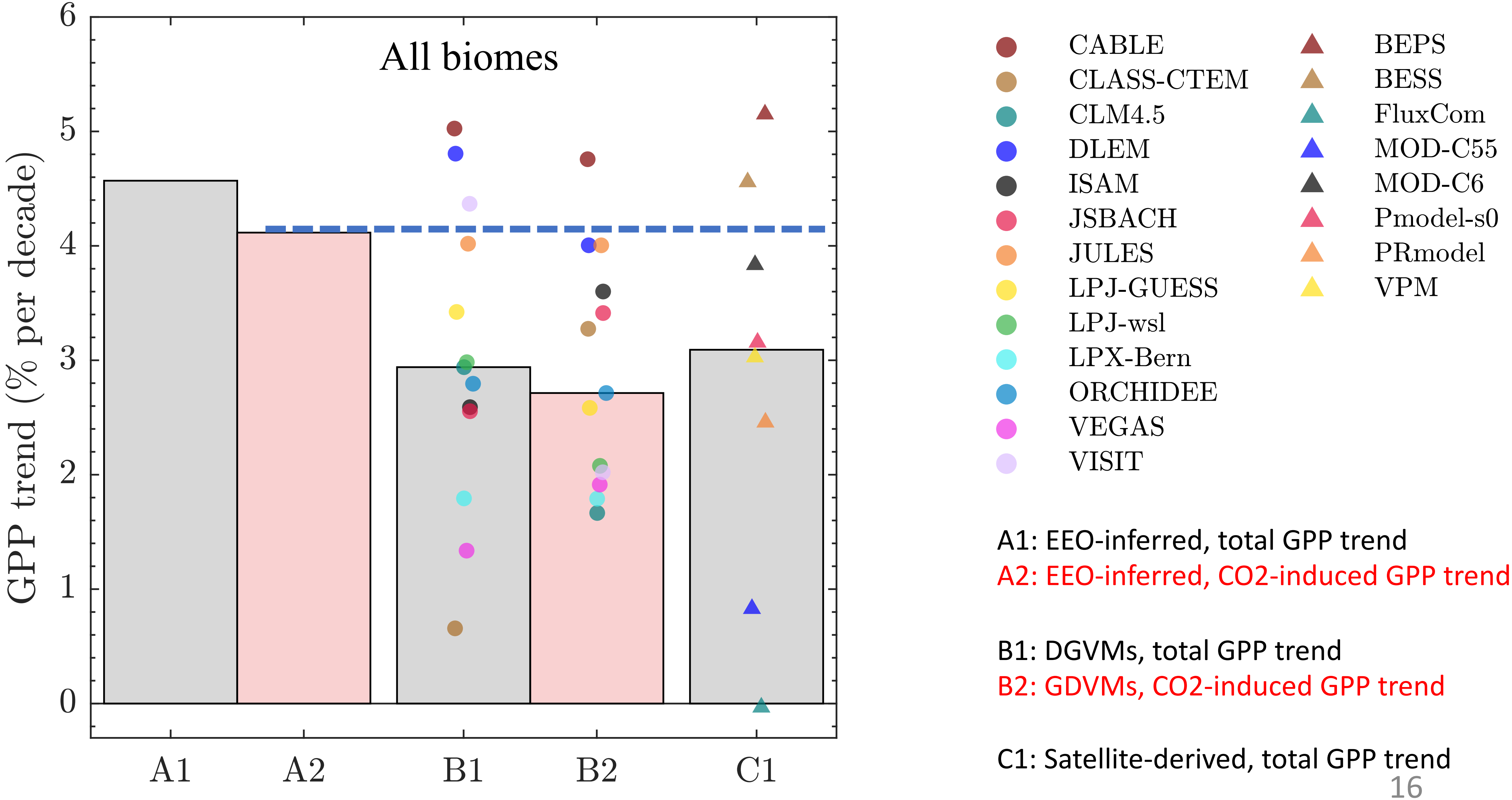
Relative CFE is conserved

GPP source used to calibrate the EEO framework	EBF	OF	SW	GRA	CRO	C4	All biomes
Ensemble mean of 8 satellite-derived GPP	4.76	4.27	4.75	5.02	5.06	1.35	4.12
BEPS	4.89	4.50	4.85	5.18	5.35	1.41	4.36
BESS	4.85	4.29	4.76	5.16	5.14	1.38	4.24
FluxCom	4.81	4.35	4.77	4.85	4.91	1.28	4.07
MOD-C55	4.76	4.37	4.88	5.19	5.12	1.37	4.20
MOD-C6	4.69	4.36	4.89	5.22	5.11	1.38	4.17
Pmodel-s0	4.71	4.06	4.52	4.66	4.71	1.25	3.91
PR-model	4.96	4.07	4.60	4.76	4.95	1.34	4.08
VPM	4.67	4.31	4.88	5.23	5.08	1.34	4.03

Chen et al., under review

- $Relative\ CFE = \frac{\Delta GPP_{co2}}{GPP} \times 100\%$
- ~4.1% GPP per decade relative to corresponding GPP climatological mean

Comparison to DGVMs and satellite GPP



A1: EEO-inferred, total GPP trend

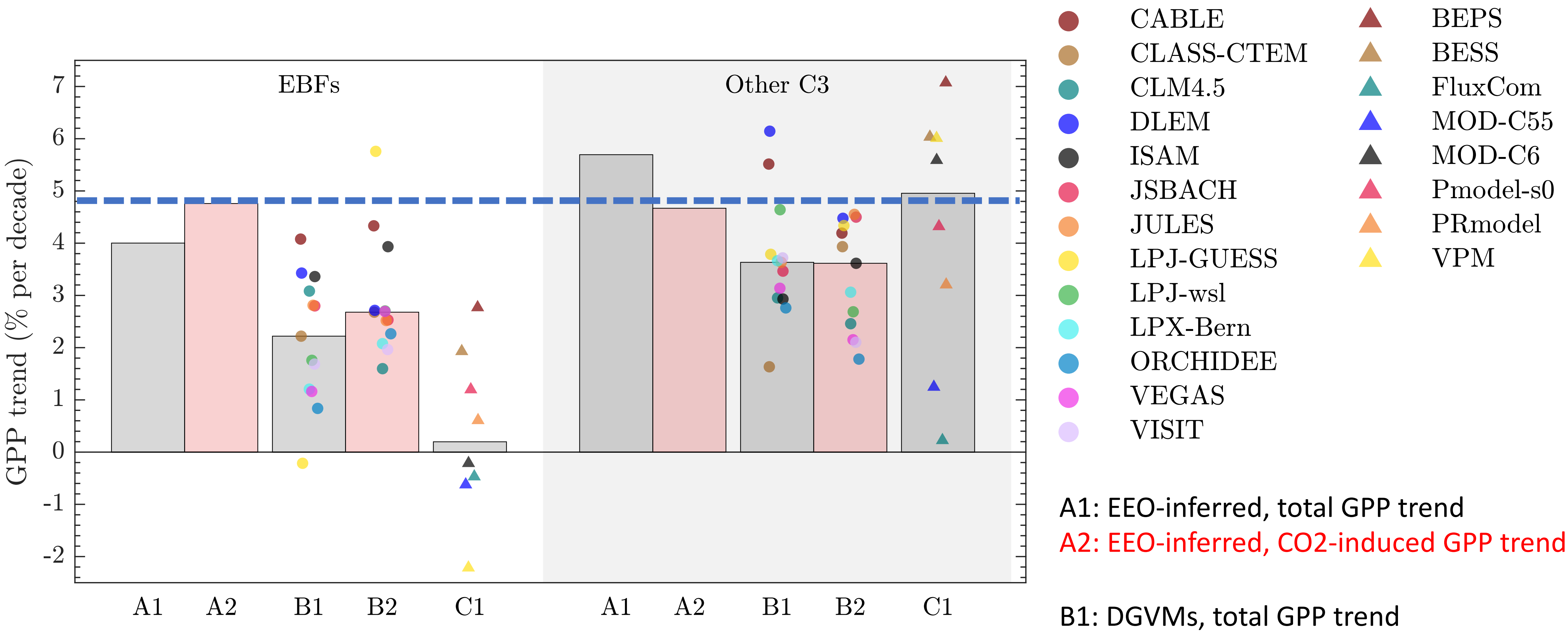
A2: EEO-inferred, CO2-induced GPP trend

B1: DGVMs, total GPP trend

B2: GDVMs, CO2-induced GPP trend

C1: Satellite-derived, total GPP trend

Comparison to DGVMs and satellite GPP



A1: EEO-inferred, total GPP trend

A2: EEO-inferred, CO2-induced GPP trend

B1: DGVMs, total GPP trend

B2: GDVMs, CO2-induced GPP trend

C1: Satellite-derived, total GPP trend

Take home messages

- A strong CO_2 fertilization effect is detectable in the eddy covariance networks
- CO_2 fertilization effect can also be constrained at the global scale
- Our framework further provides the opportunity to diagnose the sensitivity of GPP to multiple factors

Thank you!

Questions -> (chenchi@lbl.gov)