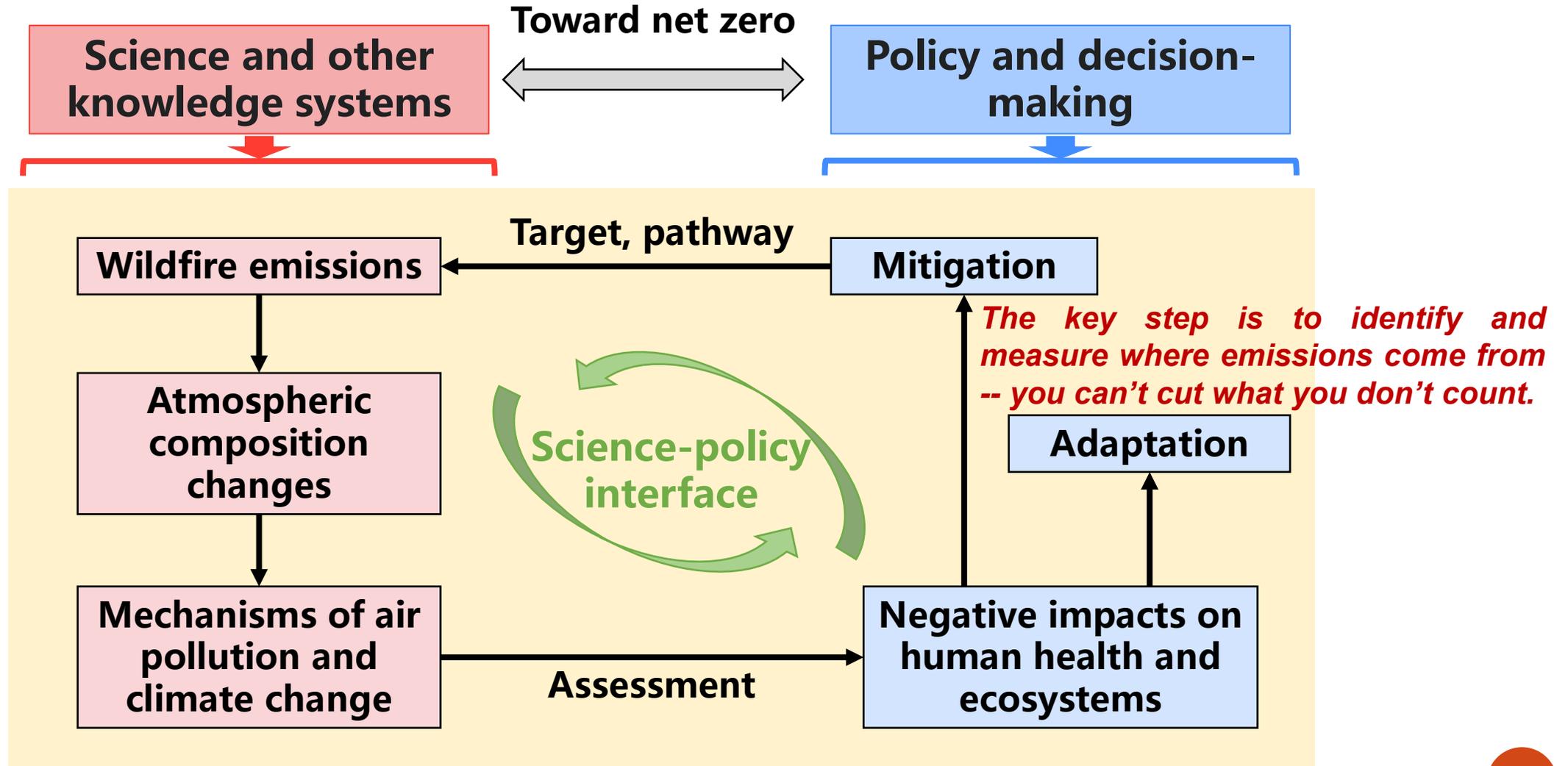# A hybrid approach to monitor wildfire emissions based on satellite observations

Bo Zheng, Philippe Ciais, Frederic Chevallier, Qiang Zhang , Kebin He

SEPTEMBER 14, 2023

Greenhouse Gas Emissions from Wildland Fires: A Workshop

Emission-related studies bridge the science-policy gap
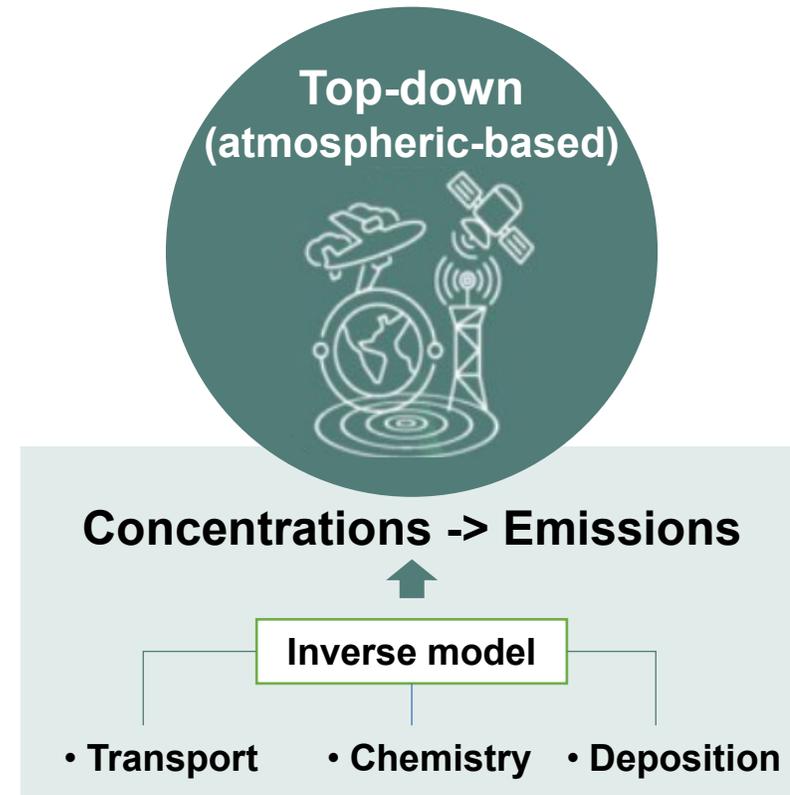
Methodologies to monitor wildfire emissions

- **Bottom-up**: estimates based on fire activities (e.g., burned area and fire radiative power), which are typically detected by satellite remote sensing technique for global spatial coverage.
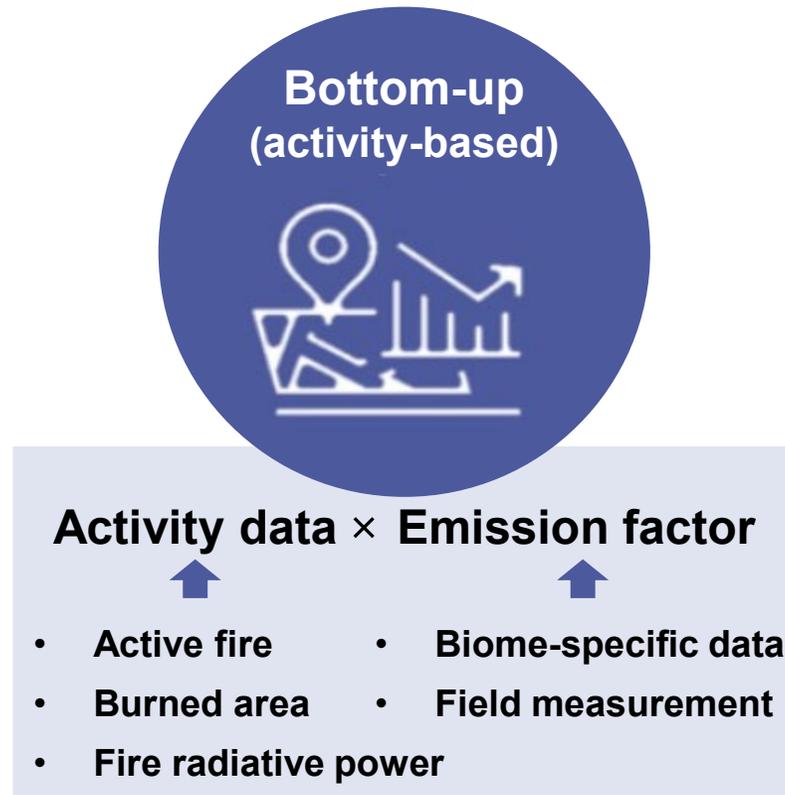
- **Top-down**: estimates inferred from atmospheric concentrations of fire released pollutants, based on inverse modeling constrained by measurement (e.g., aircraft, satellite).

Bottom-up (activity-based)

Activity data × Emission factor

- Active fire
- Burned area
- Fire radiative power
- Biome-specific data
- Field measurement

Top-down (atmospheric-based)

Concentrations -> Emissions

Inverse model

- Transport
- Chemistry
- Deposition

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Strengths and weaknesses of these two approaches

Strengths

Weaknesses

Bottom-up (activity-based)

- Multiple species
- Near-real-time update
- Familiar to decision makers

- Undetected small fires
- Average emission factors
- Potential large uncertainties
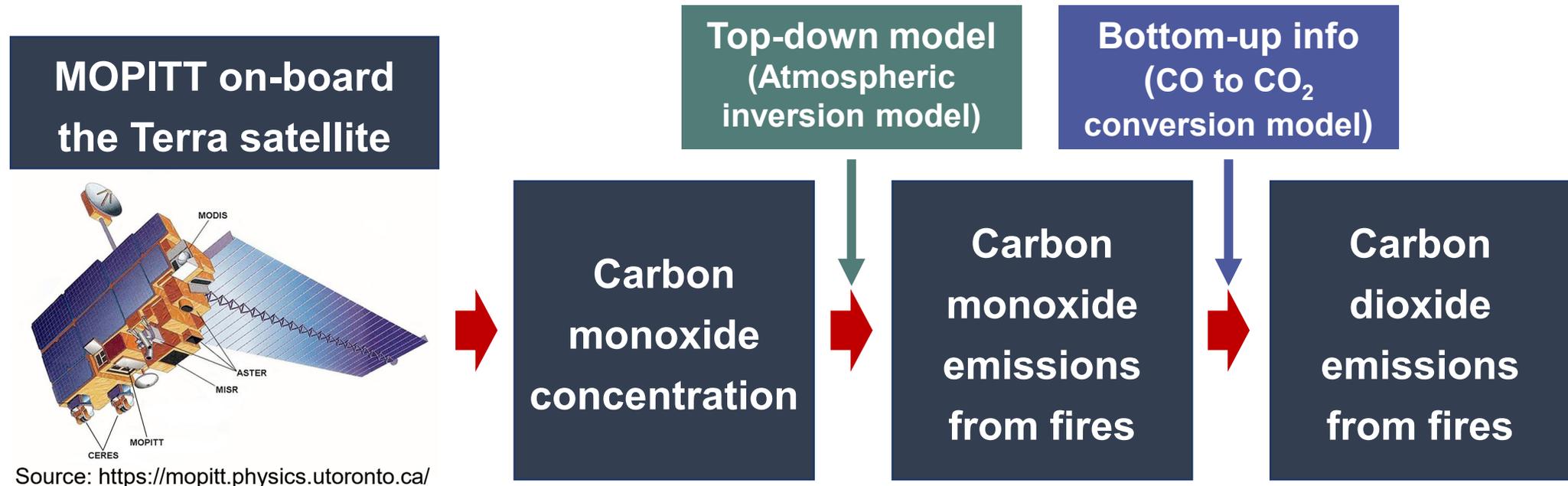
Top-down (atmospheric-based)

- Extensively developed
- Consistency with measured smoke pollutant burden
- Spatial-temporal dynamics

- Several limited species
- Difficult to constrain CO_2 emissions directly due to high background values

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A hybrid approach combining the two approaches

- **Atmospheric inversion model:**

  Satellites observe the amounts of air pollutants in the atmosphere and our atmospheric inversion model tells us the reason that causes it (i.e., surface emissions from wildfires).
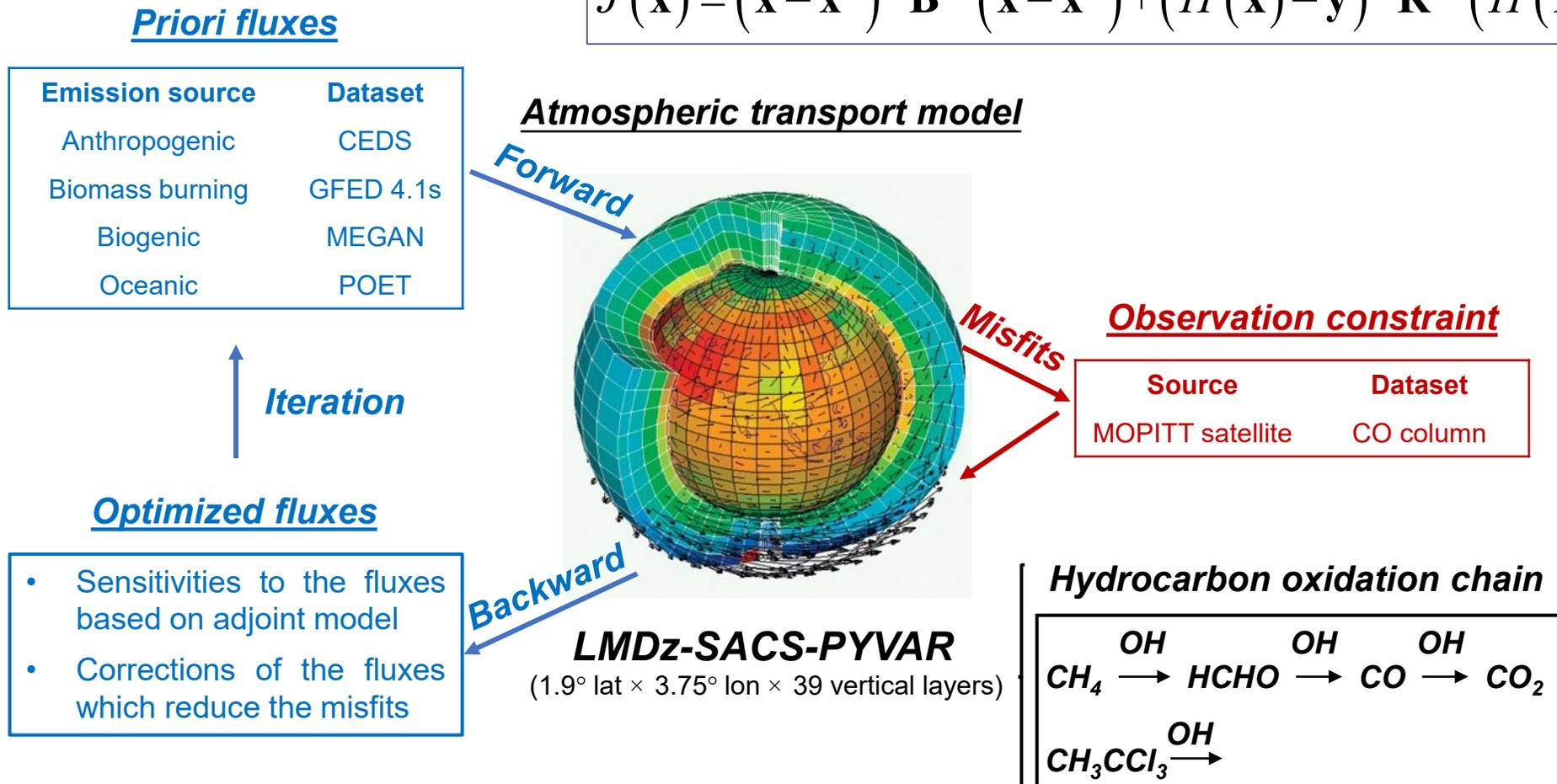
| MOPITT on-board the Terra satellite | | Top-down model (Atmospheric inversion model) | | Bottom-up info (CO to CO_2 conversion model) | |

Source: https://mopitt.physics.utoronto.ca/

Carbon monoxide concentration → Carbon monoxide emissions from fires → Carbon dioxide emissions from fires

Why isn't it possible to just take CO_2 measurements from a satellite for fire CO_2 emission estimate?
- CO_2 has a long lifetime to stay in the atmosphere for centuries, which makes its background concentrations quite high. We cannot easily separate and quantify CO_2 plumes from wildfires.

Atmospheric inversion model for global CO budget estimate

Cost function for Bayesian inversion

$$J(\mathbf{x}) = (\mathbf{x} - \mathbf{x^b})^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x^b}) + (H(\mathbf{x}) - \mathbf{y})^T \mathbf{R}^{-1} (H(\mathbf{x}) - \mathbf{y})$$

Priori fluxes

Emission source	Dataset
Anthropogenic	CEDS
Biomass burning	GFED 4.1s
Biogenic	MEGAN
Oceanic	POET

Forward

Atmospheric transport model

Iteration

Misfits

Observation constraint

Source	Dataset
MOPITT satellite	CO column

Optimized fluxes

- Sensitivities to the fluxes based on adjoint model
- Corrections of the fluxes which reduce the misfits

Backward

LMDz-SACS-PYVAR
(1.9° lat × 3.75° lon × 39 vertical layers)

Hydrocarbon oxidation chain

$$CH_4 \xrightarrow{OH} HCHO \xrightarrow{OH} CO \xrightarrow{OH} CO_2$$

$$CH_3CCl_3 \xrightarrow{OH}$$

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Zheng et al., ERL, 2018; Zheng et al., GRL, 2018

Reconstruction of global atmospheric CO budget since 2000

MOPITT CO total column $=$ **Source** $-$ **Sink**

2587 Tg CO   2609 Tg CO

$-0.34 \pm 0.05\% \text{ yr}^{-1}$ *** $-0.39 \pm 0.27 \% \text{ yr}^{-1}$ *** $-0.36 \pm 0.23 \% \text{ yr}^{-1}$ ***

Direct emissions   **Chemical production**

1372 Tg CO   1215 Tg CO

$-9.4 \pm 7.0 \text{ Tg CO yr}^{-2}$ ** $-0.6 \pm 1.4 \text{ Tg CO yr}^{-2}$

Anthropogenic emissions   **Biomass burning emissions**

723 Tg CO   445 Tg CO

$-5.6 \pm 2.2 \text{ Tg CO yr}^{-2}$ *** $-3.8 \pm 4.9 \text{ Tg CO yr}^{-2}$

(*$P < 0.1$, **$P < 0.05$, and ***$P < 0.01$)

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Zheng et al., ESSD, 2019

Comparison with GFED v4.1s fire emissions

- The burned area-based GFED v4.1s data tend to underestimate the fire CO emissions from the tropical regions (e.g., Brazil, Africa) and also underestimate the declining trends.

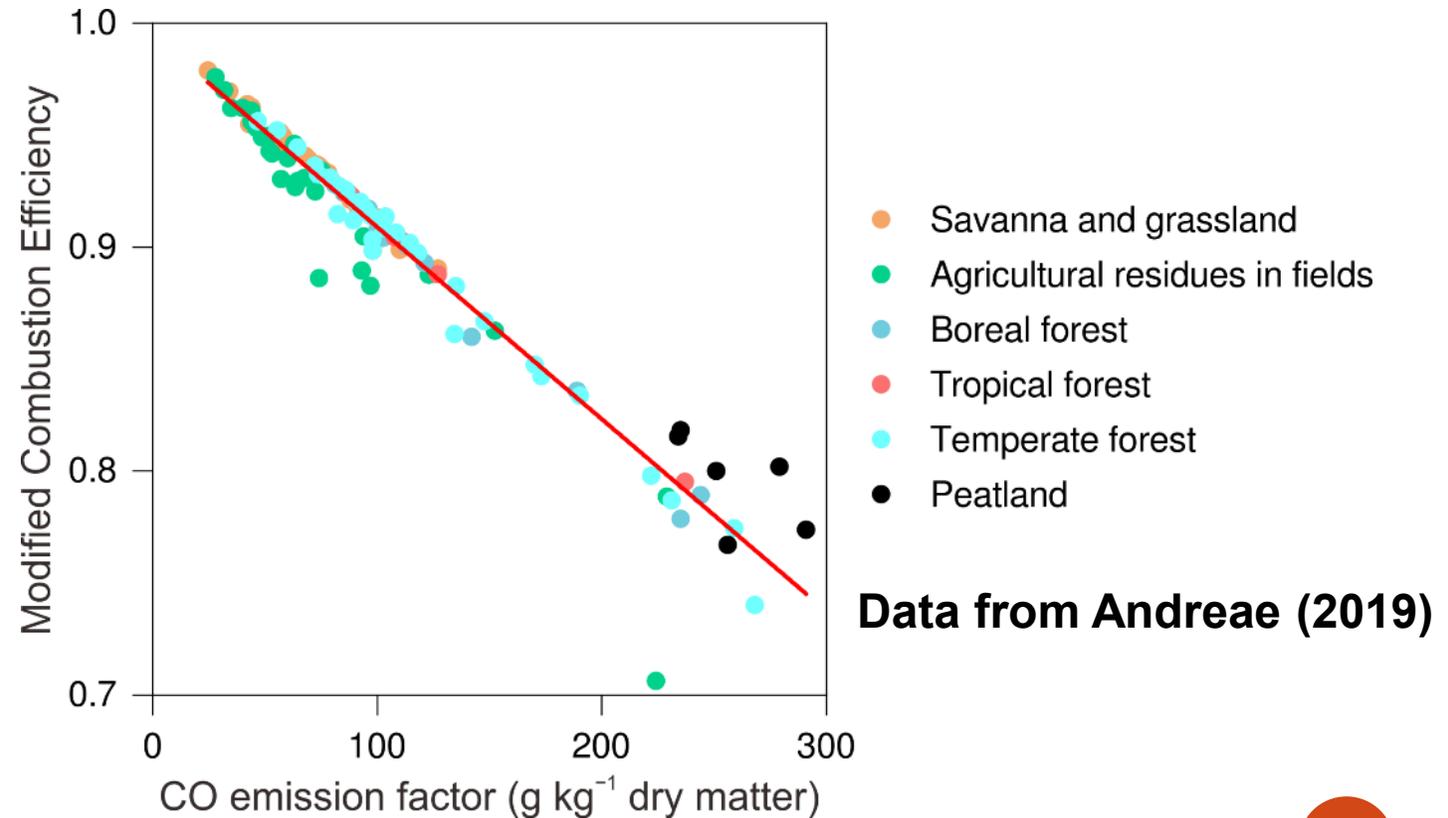- We notice that GFED v5 has largely increased burned area compared to GFED v4.1s.
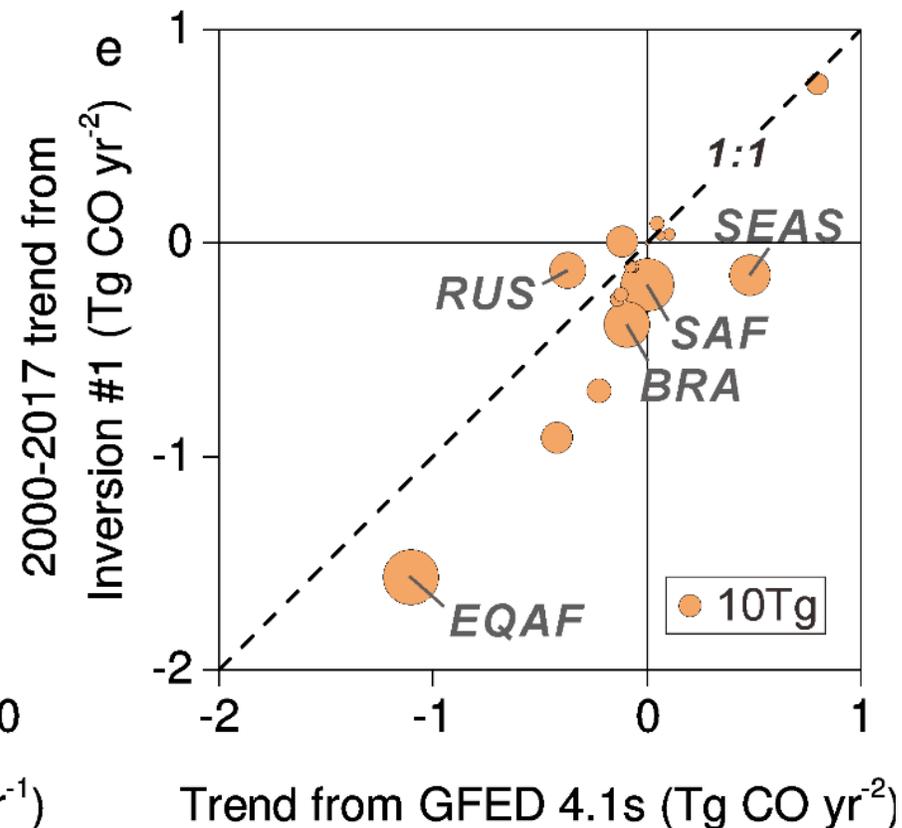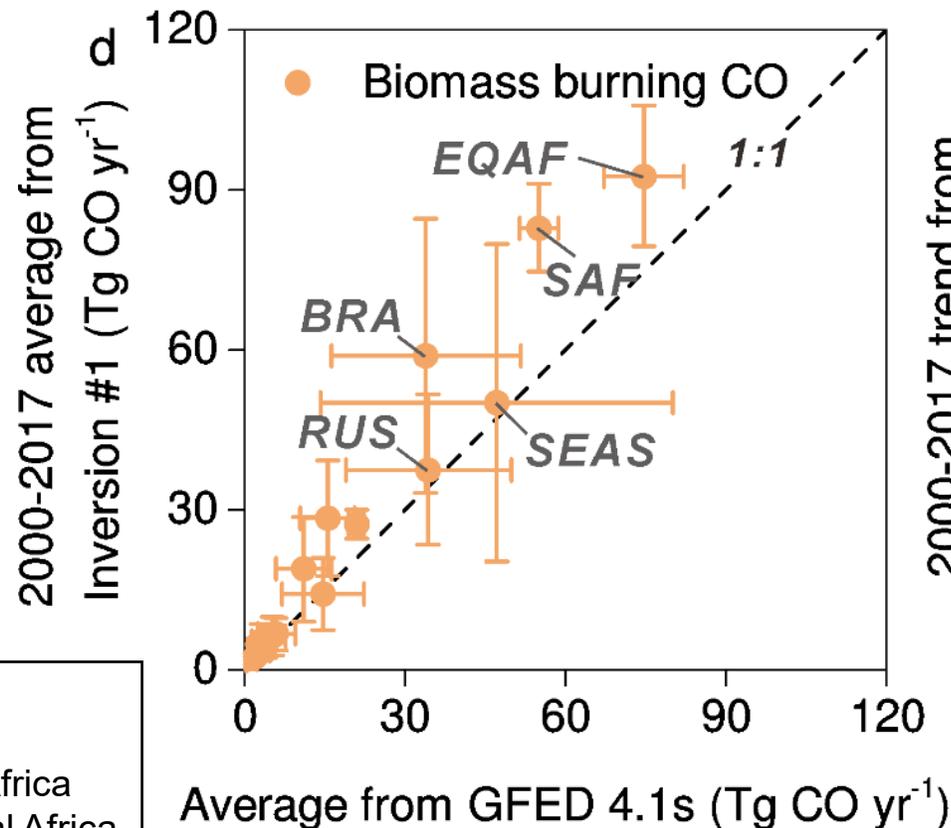
BRA: Brazil
RUS: Russia
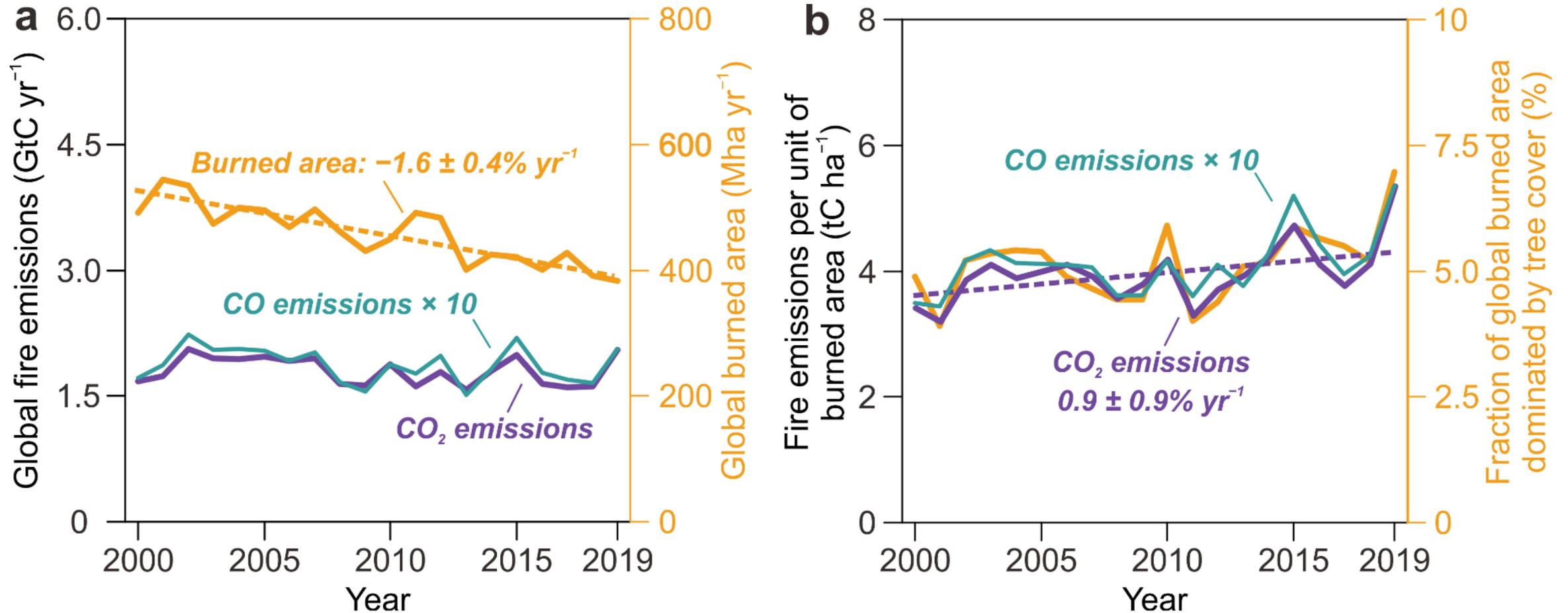SAF: Southern Africa
EQAF: Equatorial Africa
SEAS: Southeast Asia

Zheng et al., ESSD, 2019

Constraint on fire CO_2 emissions based on fire CO emissions

| Fire CO emissions | → | CO emission factor | → | Combustion efficiency | → | Fire CO_2 emissions |
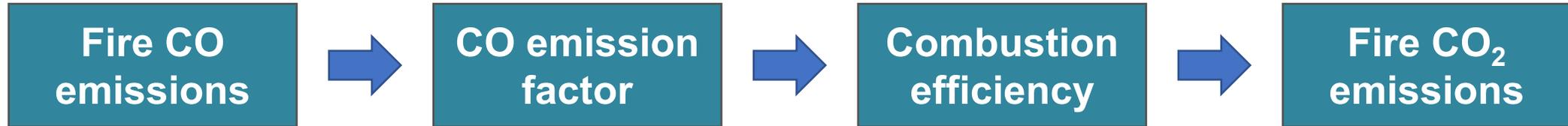
$$E_{CO2,i,j} = \frac{MCE_{i,j}}{1 - MCE_{i,j}} \times E_{CO,i,j} \times \frac{44}{28}$$

$$MCE_{i,j} = a + b \times EF_{CO,i,j}$$

$$EF_{CO,i,j} = \frac{E_{CO,i,j}}{BA_{i,j} \times Fuel_{i,j}}$$

- Savanna and grassland
- Agricultural residues in fields
- Boreal forest
- Tropical forest
- Temperate forest
- Peatland

Data from Andreae (2019)

Zheng et al., Science Advances, 2021

Global fire CO and CO$_2$ emissions since 2000

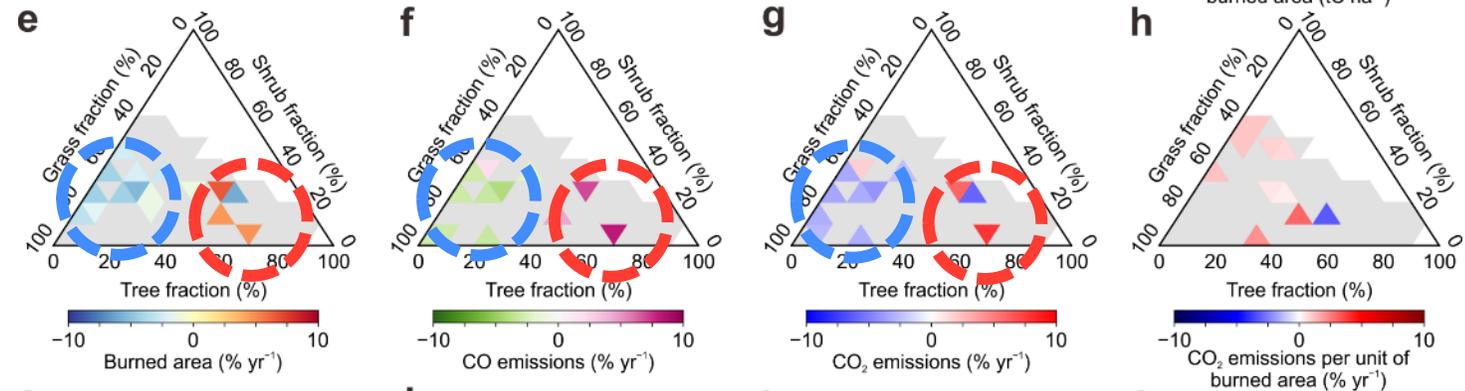Zheng et al., Science Advances, 2021

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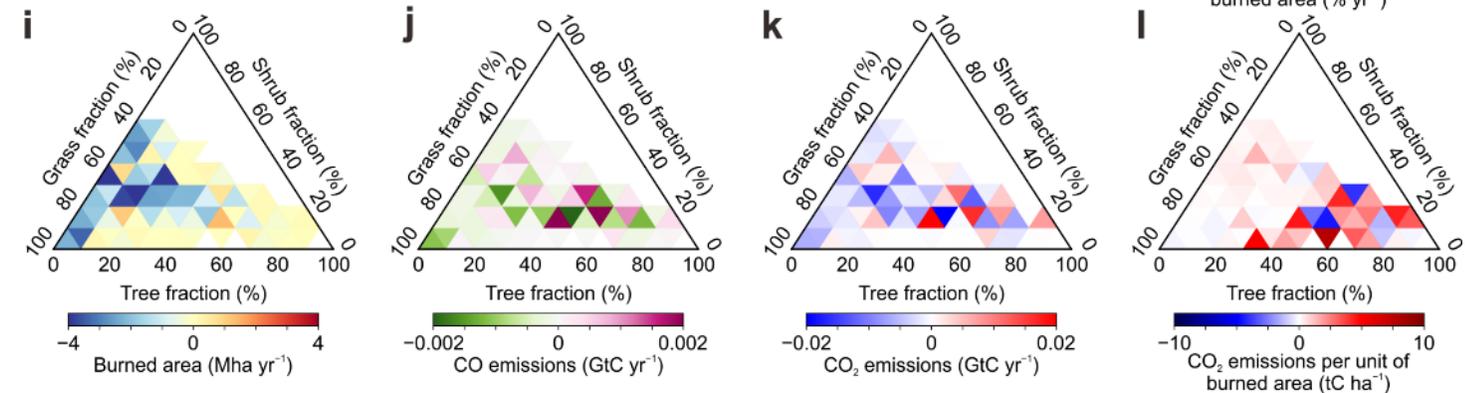# Less burning over grasslands but more burning over forests

**Average between 2000 and 2019**
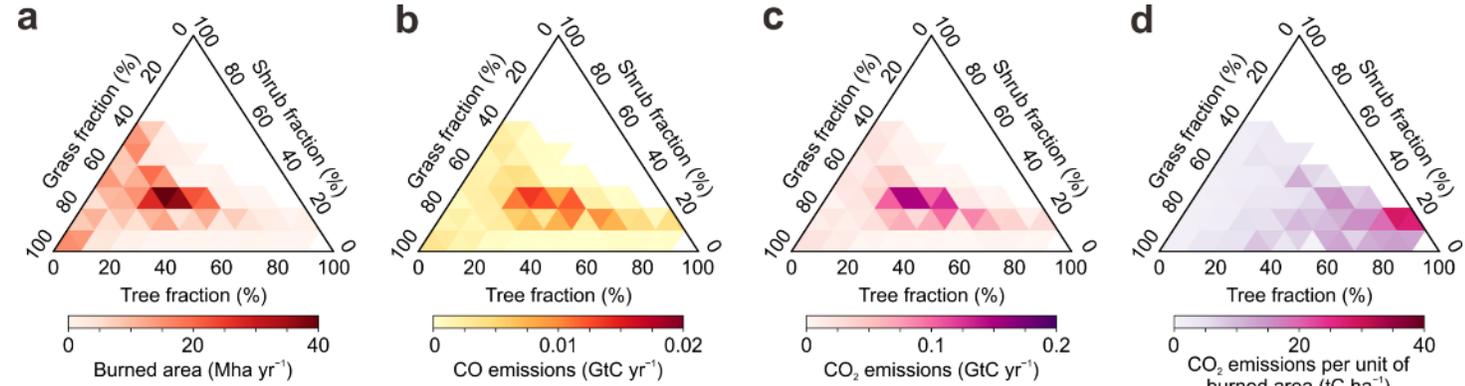
Annual trend from 2000 to 2019

**Differences between 2010-2019 and 2000-2009**


Zheng et al., Science Advances, 2021

Record-high CO$_2$ emissions from boreal fires in 2021

- **Boreal fires released 1.76 billion metric tons of CO$_2$ in 2021, by far the highest since 2000.**

- **Boreal fires in 2021 contributed 23% of global fire CO$_2$, while account for only 10% in 2000s.**

- **This is the biggest singular fire emissions event globally ever recorded since 2000.**

- **The vast carbon release is comparable to the annual fossil fuel CO$_2$ emissions from Japan.**

Boreal fire CO$_2$ emissions 2000-2021
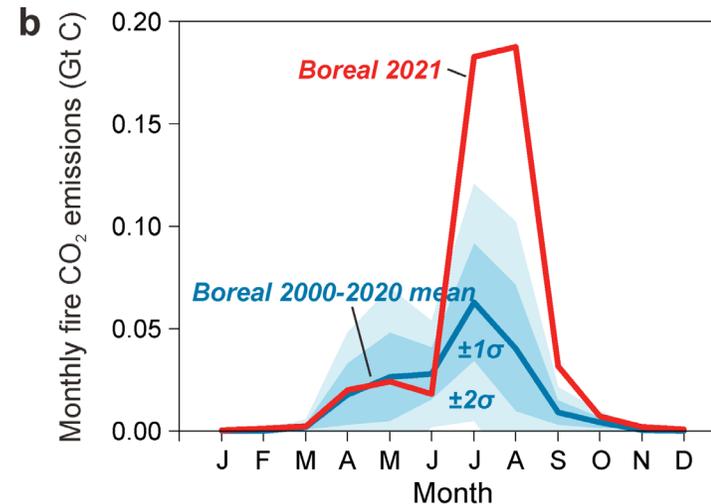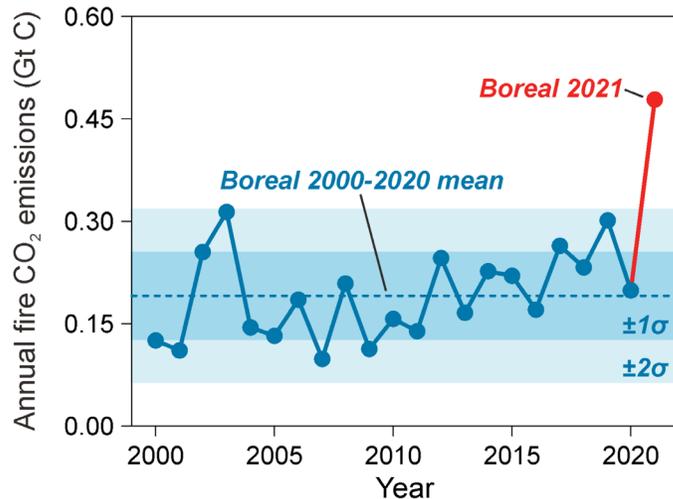
Where did the boreal fires occur in 2021?


Zheng et al., Science, 2023

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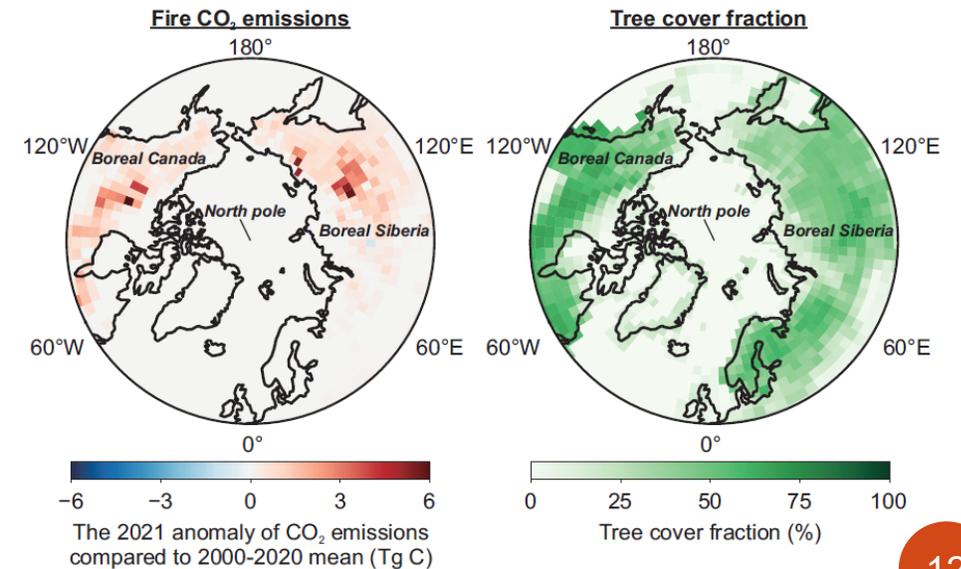
Why was 2021 an "abnormal year"?

- **Fire emissions rise sharply with climatic water deficit lower than a threshold value (~ zero).**

- **The abnormal fires in 2021 coincide with high water deficit, severe heatwave, and drought.**

- **In 2021, both North American and Siberian boreal forests experienced severe droughts (climatic water deficit < −20 mm) in both regions, the first occurrence since 2000.**

Zheng et al., Science, 2023
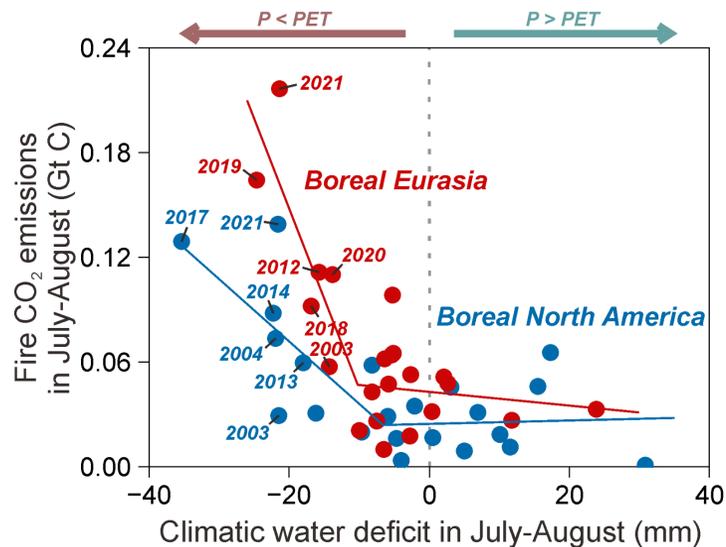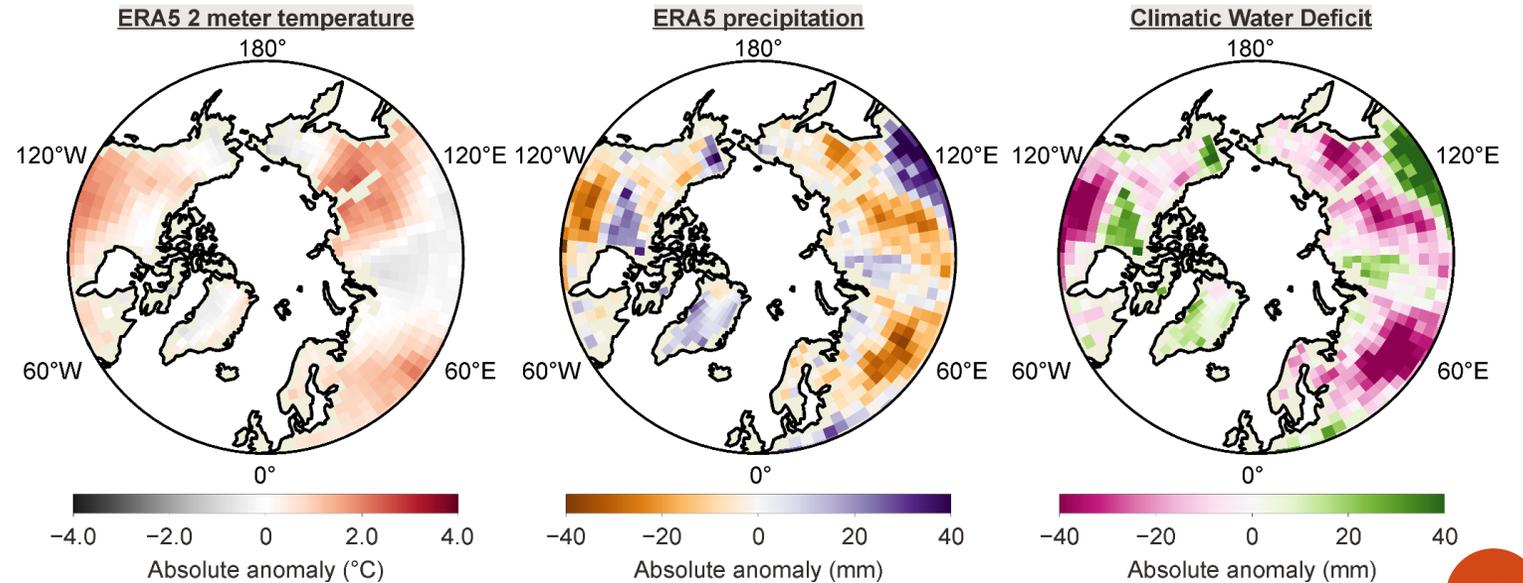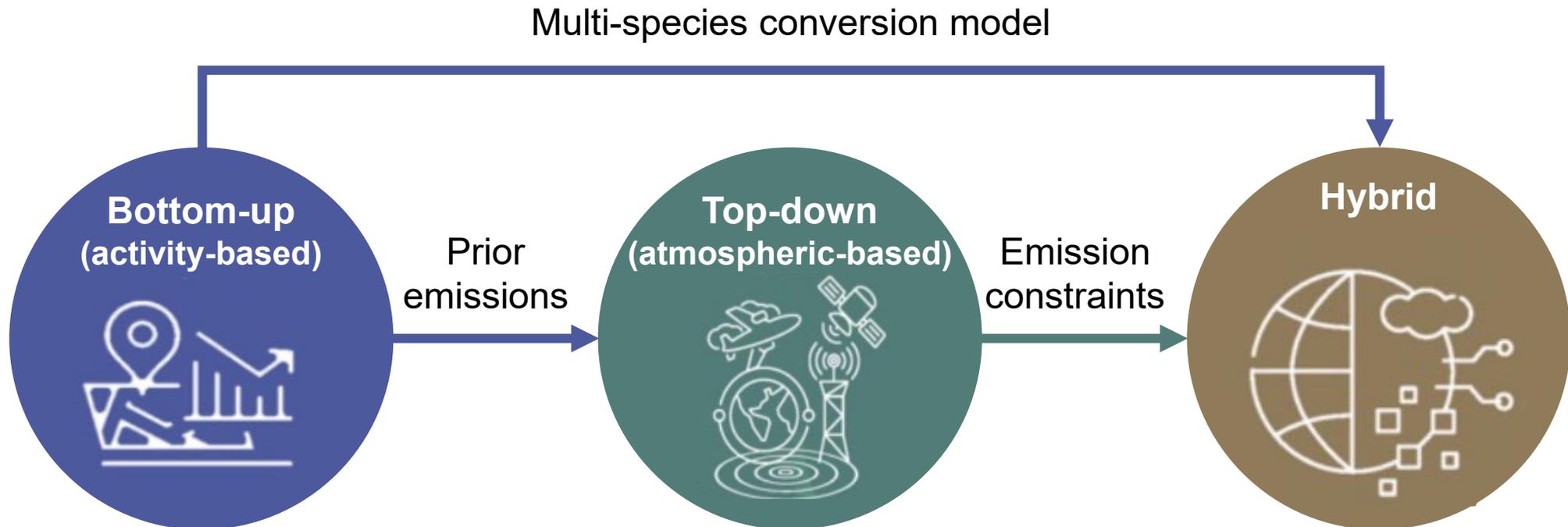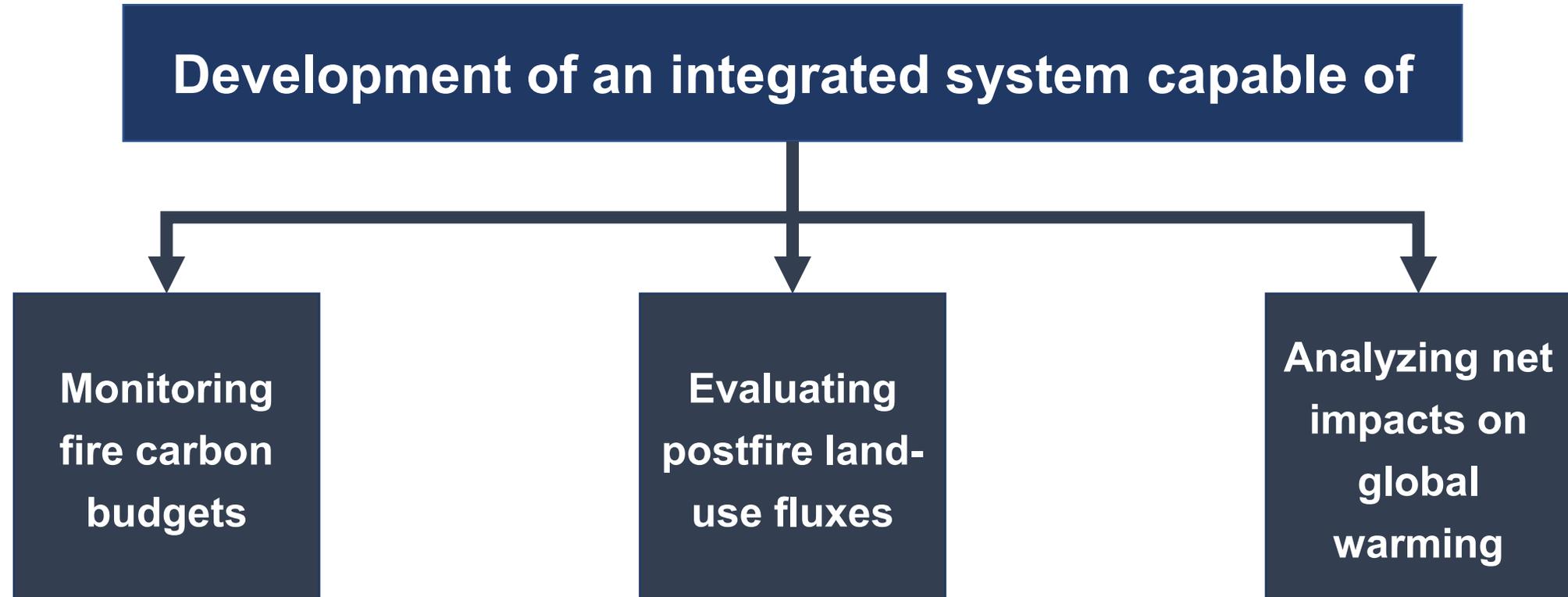
Advantages of our hybrid approach

- **Integration of concepts, techniques, and data from different fields of established researches to provide a more comprehensive picture of global and regional fire emissions.**

- **Better constraints, multiple species, and spatial-temporal dynamics.**

- **Possible to develop a near-real-time operational model system (what happened in 2023?).**

Multi-species conversion model

Bottom-up (activity-based) → Prior emissions → Top-down (atmospheric-based) → Emission constraints → Hybrid

What comes next for our research?

Development of an integrated system capable of

Monitoring fire carbon budgets

Evaluating postfire land-use fluxes

Analyzing net impacts on global warming

Thanks for your attention!
Look forward to your comments and questions.

Bo Zheng

bozheng@sz.tsinghua.edu.cn

https://www.zheng-bo.com/