Greening and Browning in Response to the Effects of Rising CO_2

Driver Attribution Using Causal Theory

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What is driving the observed changes in natural vegetation?

- Human dominated land surface is greening due to **land management** (Chen et al., 2019).
- **Rising CO_2** as driver of changes in natural vegetation is **debated**:
  - **CO_2 fertilization** explain 70% of the global greening trend (Zhu et al., 2016).
  - However, **no significant increase** in leaf area under elevated CO_2 in field studies (e.g. Norby et al. 2003).
- A **rigorous regional attribution at biome-level** of what is behind the observed changes is currently lacking.

Our approach:

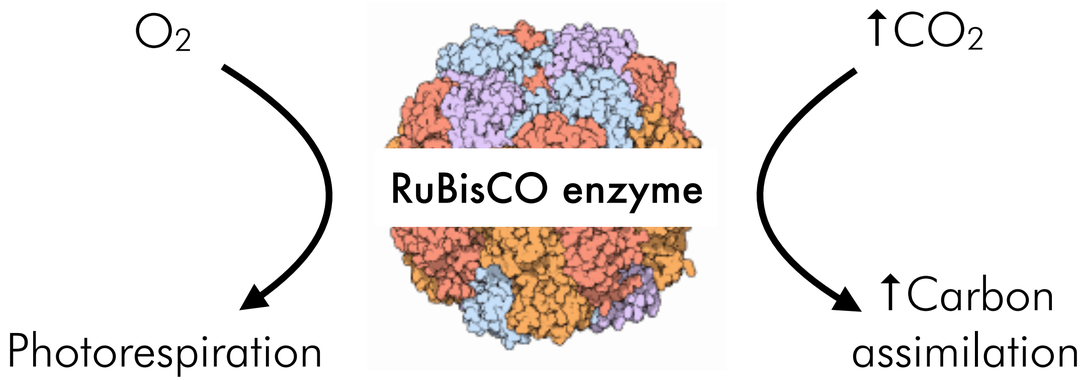
- Analyze multi-decadal satellite observations of natural vegetation
- Disentangle the effects of CO_2 in idealized model simulations
- Apply Causal Theory for driver attribution on biome scale*

* here only tropical forests and northern ecosystems are shown

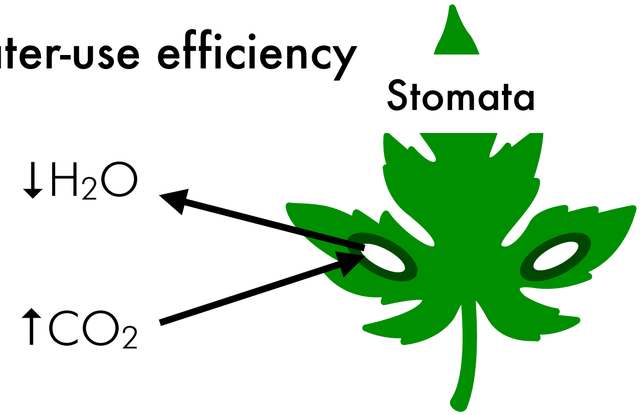
How Rising CO_2 Affects Plant Productivity

Physiological effect (**PE**): CO_2 fertilization

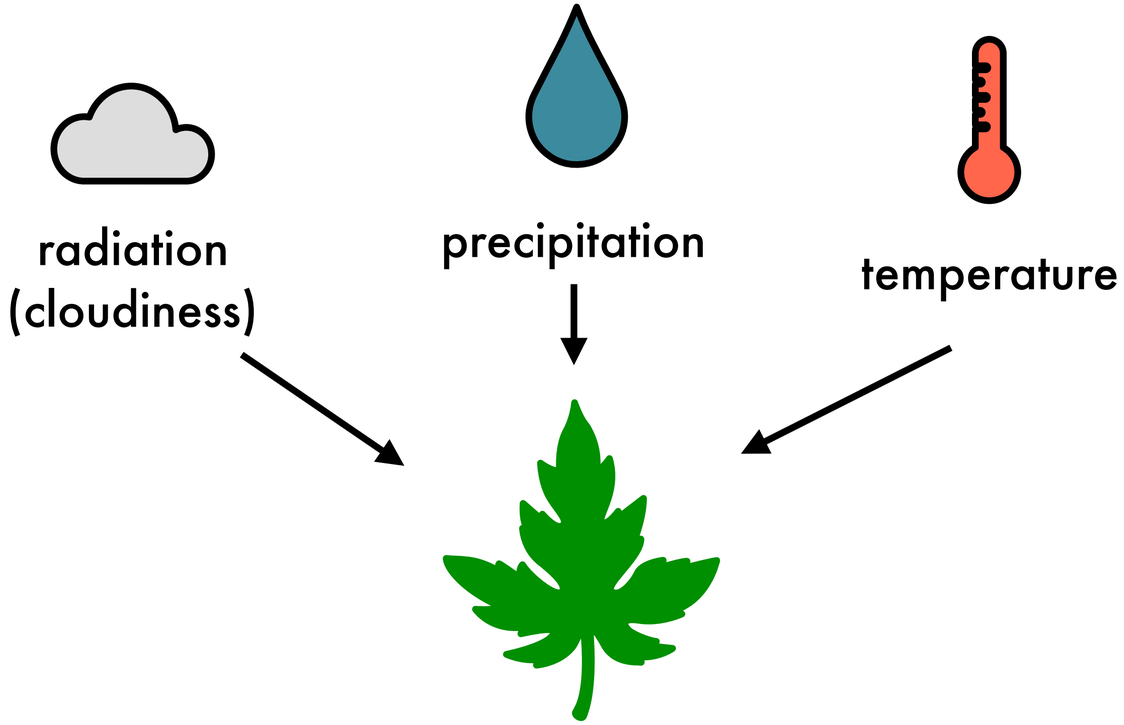
1. Stimulation of carbon fixation



2. Enhancement of water-use efficiency



Radiative effect (**RE**): Climatic changes



Plant productivity can be affected either way:

↑ Increase due to e.g. warming or increased rainfall

↓ Decline due to e.g. drying or disturbances

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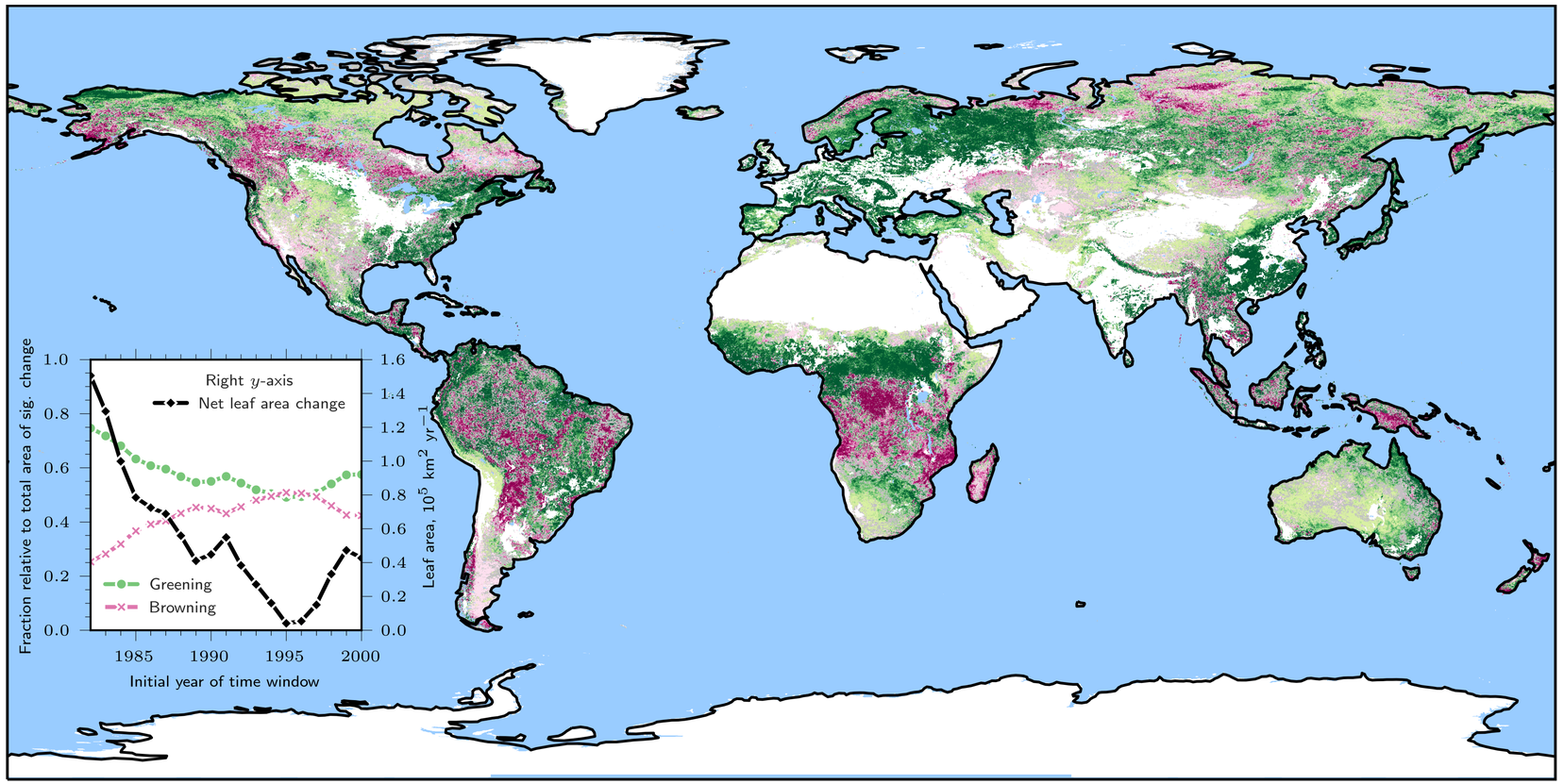
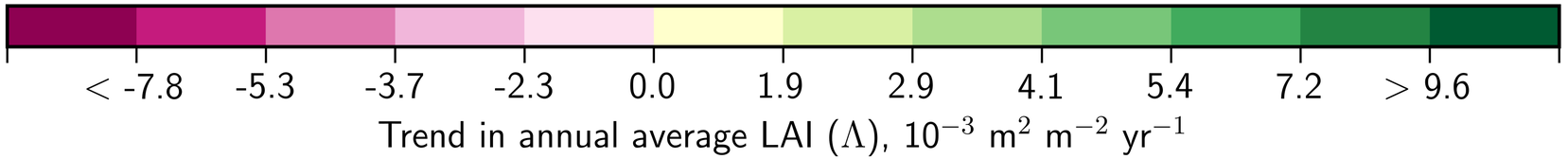
Observed Patterns of Greening and Browning

AVHRR LAI3g

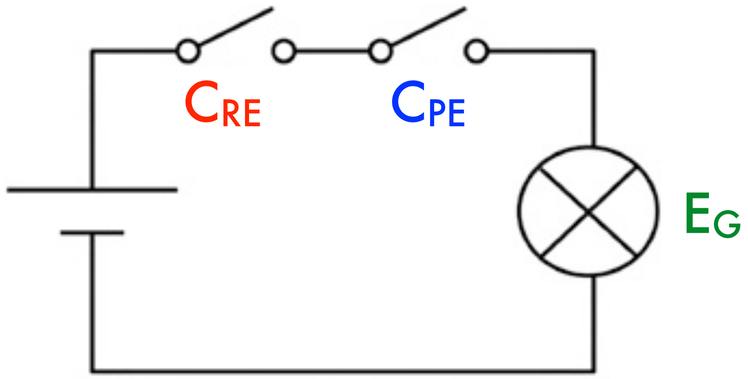
- CO_2 increased by **65 ppm** throughout the satellite era (1982 to 2017).
- Satellite observations of **leaf area index** (LAI, leaf area per unit ground area).
- **54%** of Earth's natural vegetation exhibit significant* trends:
  - Greening: **40%**
  - Browning: **14%**

* Mann-Kendall test ($p < 0.1$)

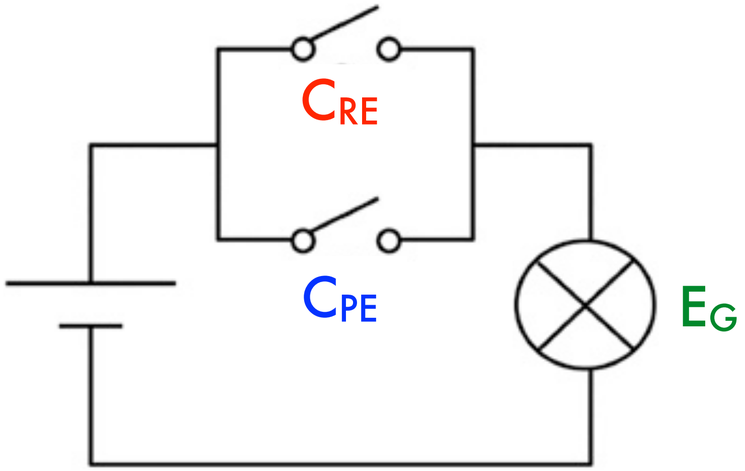




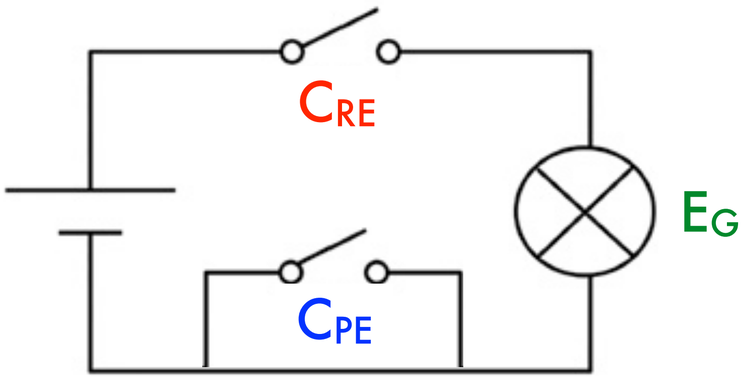
Driver Attribution Using Causal Theory



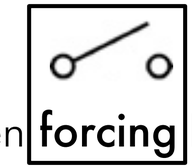
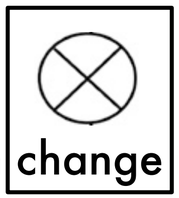
Probability of
Necessary Causation



Probability of
Sufficient Causation



Probability of **Necessary and Sufficient** Causation — PNS

What is the **probability** that a given  (**forcing**: flip switch) has caused a long-term  (**change**: light bulb) in the system?

Event **E**: occurrence of long-term change in the system, e.g. greening (E_G)

Cause **C**: presence of given forcing, e.g. radiative (C_{RE}) or physiological (C_{PE}) effect of CO_2

High PNS reflects evidence for the existence of a causal relationship.

Model Simulations

Overview of experiments:

1. Control run at **preindustrial** conditions
2. Historical simulation with **all forcings**

All historical forcings except the

3. **physiological effect of CO_2** (No PE)
4. **radiative effect of CO_2** (No RE)
5. combined **effect of CO_2** (No CO_2)

Single Model Ensemble: MPI-ESM1.2

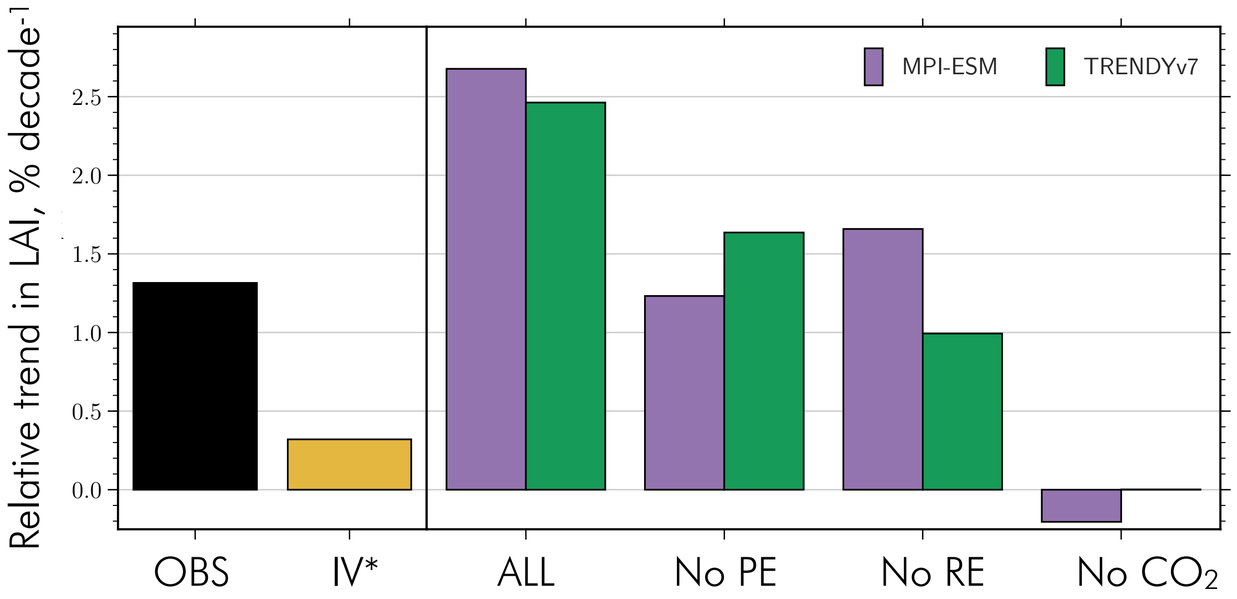
- Fully-coupled Earth system model
- Historical simulations 1850-2013
- Ensemble of 6 realizations

Multi-Model Ensemble: TRENDYv7

- Stand-alone land surface models
- Driven with observed climate 1900-2017
- Ensemble of 13 different models

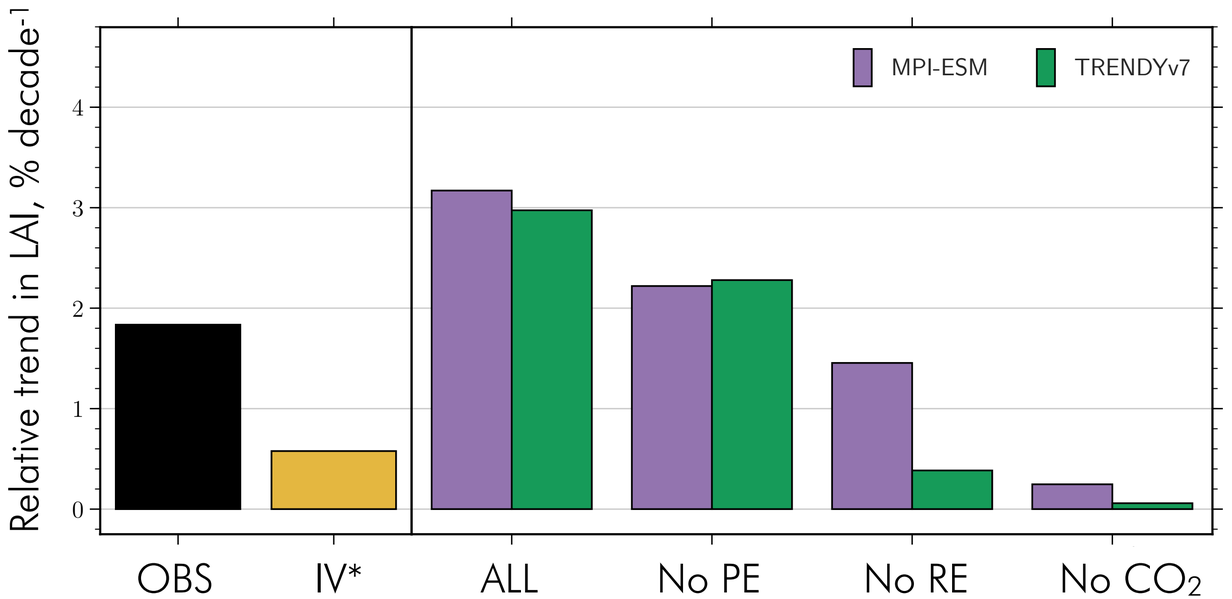
Radiative Effect is Dominant Driver in the North

Boreal Forests



PNS	MPI-ESM	TRENDYv7
Combined	99 %	99 %
Physiological	98 %	61 %
Radiative	86 %	87 %

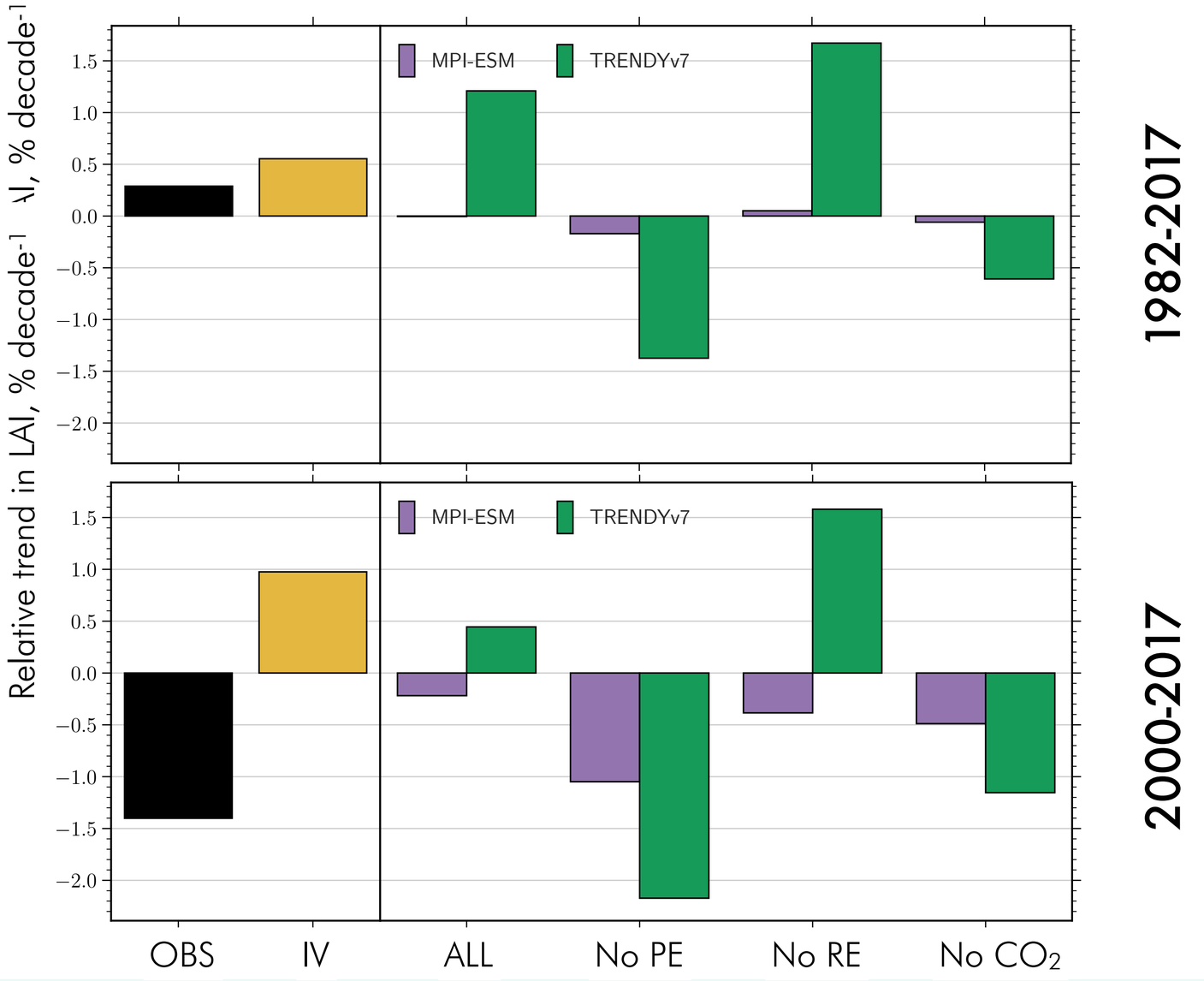
Tundra



PNS	MPI-ESM	TRENDYv7
Combined	98 %	99 %
Physiological	59 %	47 %
Radiative	84 %	99 %

Tropical Forests are Browning with Rising CO_2

- **No attribution possible** due to high uncertainty.
- Models show **compensatory effects** of rising CO_2.
- **Observed trend switches sign** in recent decades.



Conclusions

- **Northern ecosystems** are mainly greening due to the radiative effect of CO_2.
- **Tropical forests** enter browning phase which is not captured by models.
- ☞ Rising CO_2 drives **divergent responses** of the natural vegetation:

  Persistent **leaf area loss in tropical forests** and **gain in northern ecosystems.**
- This development indicates the respective contributions of these ecosystems to the recent **terrestrial carbon sink**.