Idealized CO2 Increases Drive Enhanced Fire Activity due to Vegetation and the CO2 Fertilization Effect

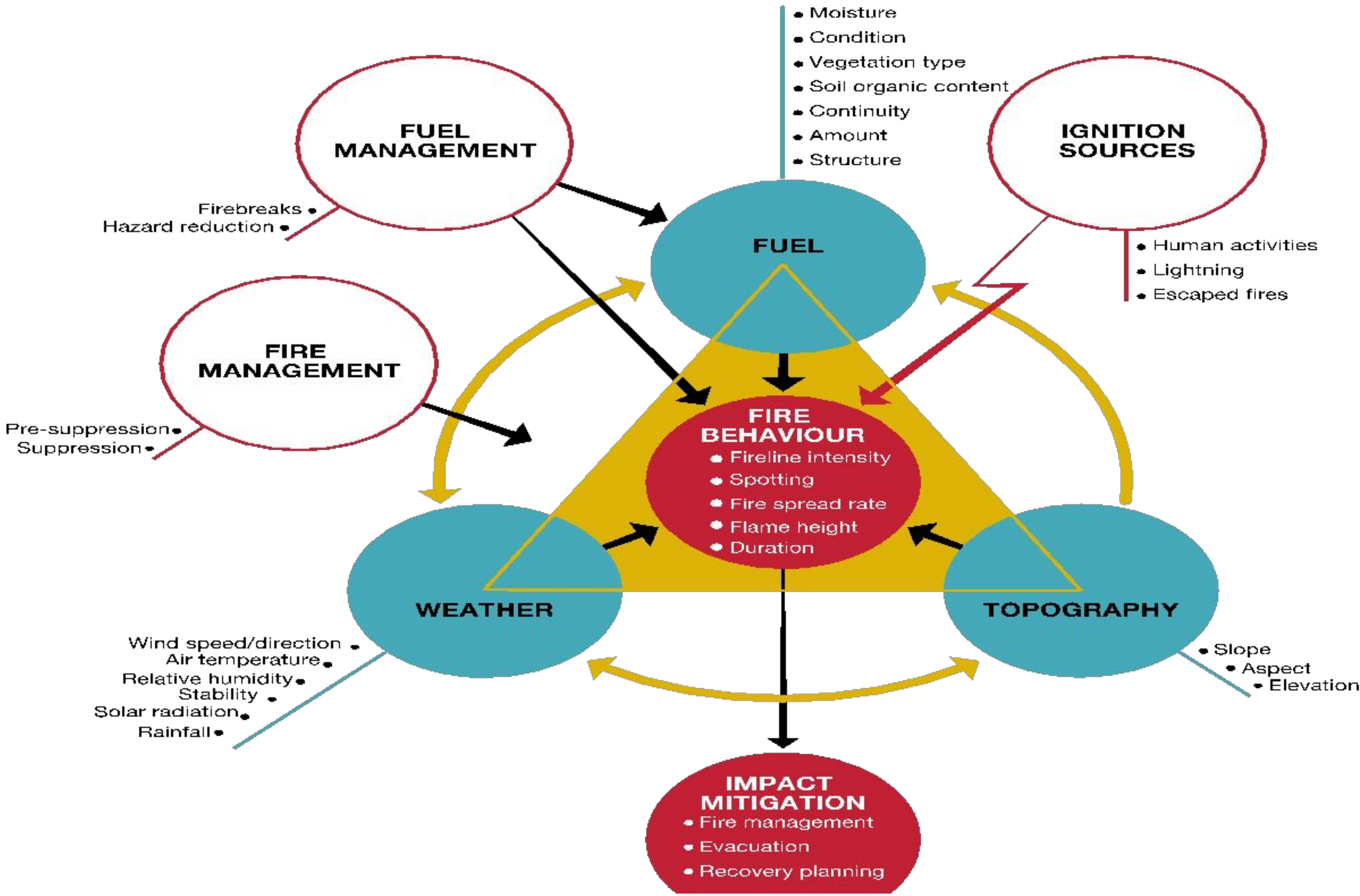
Robert J. Allen
UC Riverside

And: James Gomez, Larry Horowitz and Elena Shevliakova

United Nations Environment Programme. Spreading like Wildfire – The Rising Threat of Extraordinary Landscape Fires (2022).

- A ***wildfire*** is the result of a complex interaction of many factors:
  - **Biological**
  - **Meteorological**
  - **Physical**
  - **Social**
- These factors influence wildfire characteristics:
  - **Likelihood**
  - **Behavior**
  - **Duration**
  - **Extent**
  - **Impact**

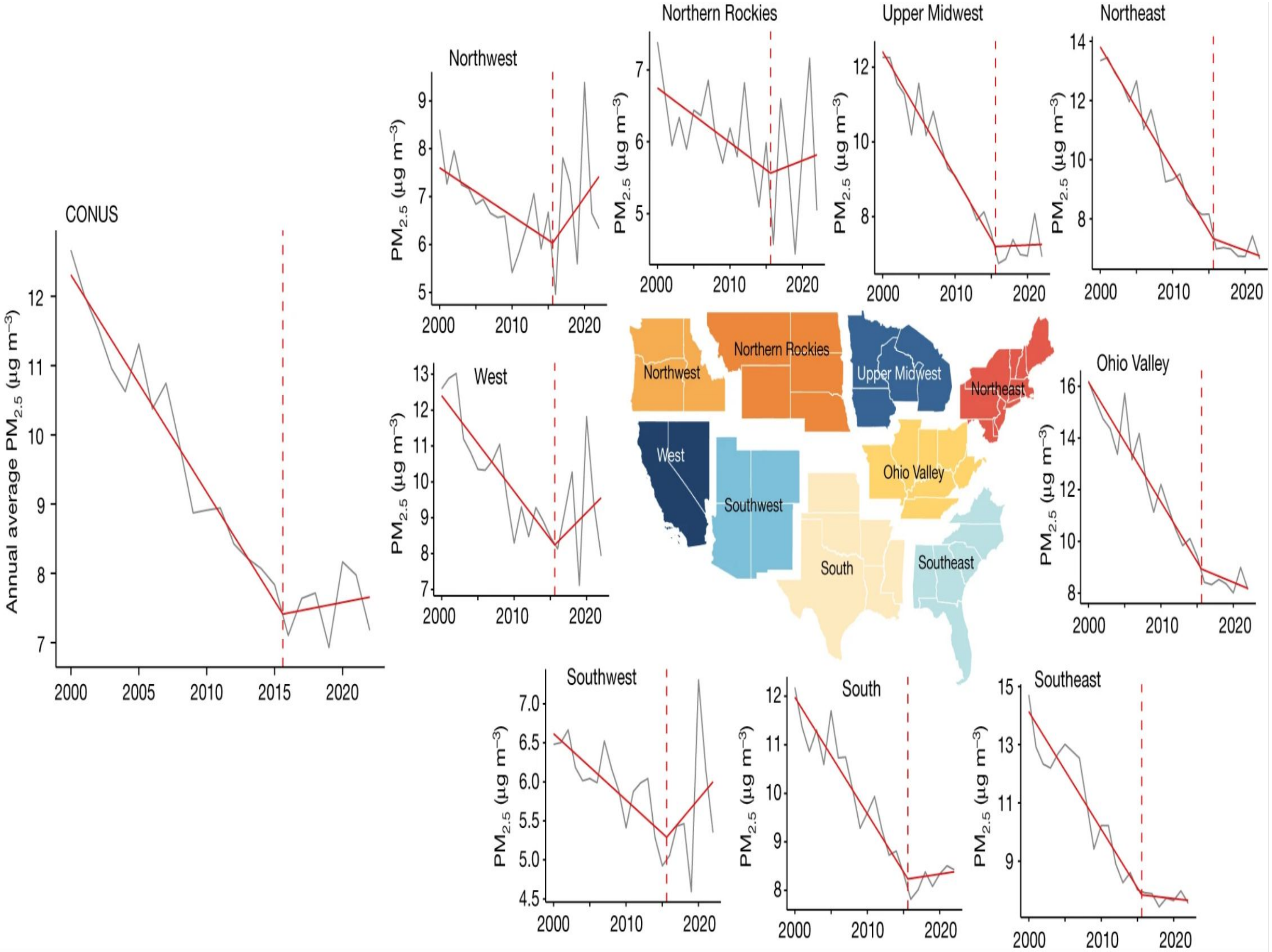
Factors and conditions influencing wildfire occurrence



Changes in many of these factors are ***increasing*** the **risk of wildfire** globally

Wildfire smoke Up to half of PM2.5 in Western U.S.

- Nationwide, **wildfires** are now responsible for up to **25%** of **fine-particle pollution**.
- Has ***reduced*** **multi-decadal US progress in reducing PM2.5**.
- Is **climate change** (e.g., ***warming*** and ***drying***) the ***dominant driver*** of this ***increase***?
- **What about changes in *vegetation (fuel)?***
- Observations show ***intensification*** of **terrestrial biosphere activity** including **"greening" of the planet**:
  - Much of which was attributed to the **CO2 fertilization effect** ***enhanced*** **carbon uptake and storage**.

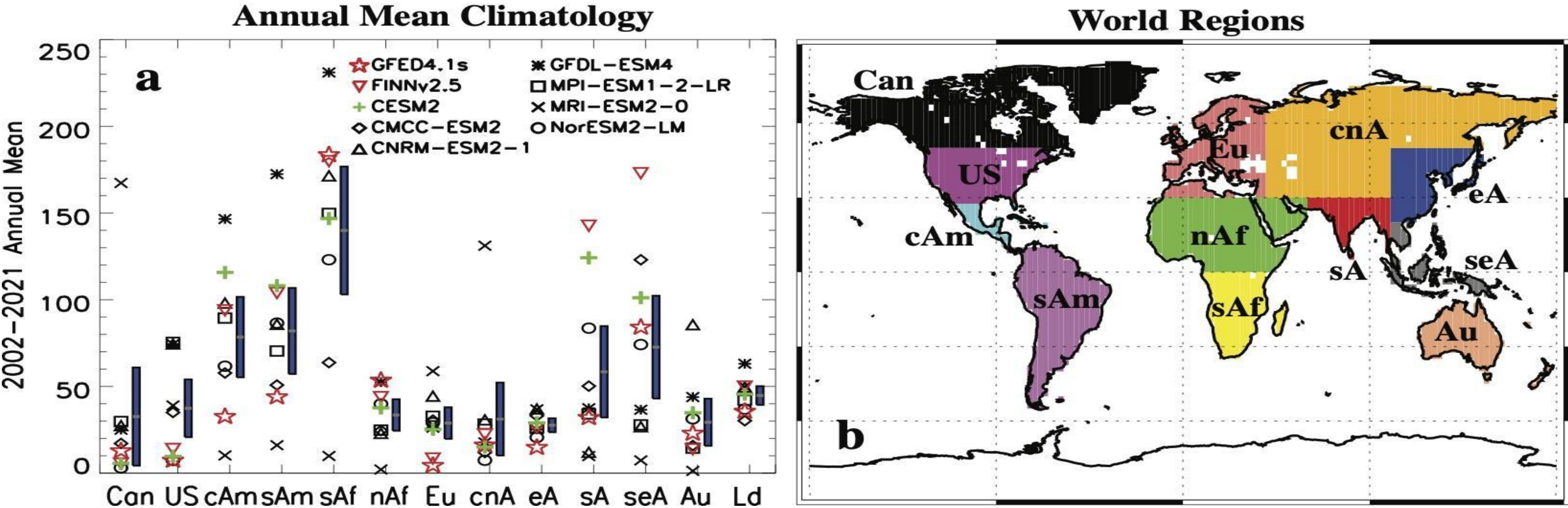


https://www.pnas.org/doi/10.1073/pnas.2011048118
https://www.latimes.com/california/story/2021-01-13/wildfire-smoke-fine-particle-pollution-western-us-study
Burke, M. et al. The contribution of wildfire to $PM_{2.5}$ trends in the USA. *Nature* (2023).

Models and Experiments

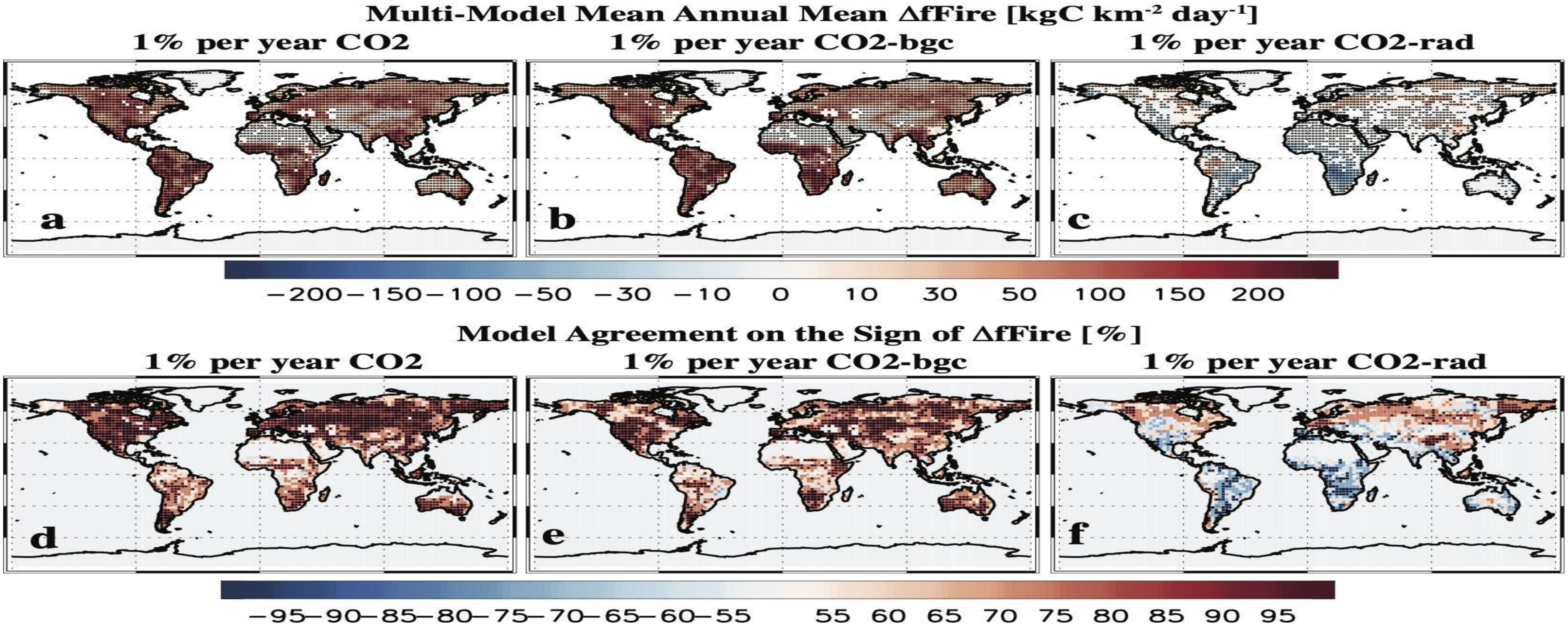
- **7 CMIP6 ESMs** performed and archived **1% per year CO_2** experiments.
  - **Atmospheric CO_2 concentrations** ***increase*** from 1850 levels (~284 ppm).
  - Both **biogeochemical** and **radiative** processes respond to ***increasing*** CO_2.
  - Fixed 1850 land-use land change, population, and non-CO_2 forcing agents.
  - All 7 ESMs have a fire module (of varying complexity) that simulates wildfire activity.
    - Emissions from wildfires ***do not feedback*** onto climate.
- Additional, analogous simulations include:
  - **1% per year CO_2-bgc** □ ***biogeochemical processes*** over land and ocean respond to ***increasing*** **atmospheric CO_2 concentrations** □ atmospheric radiative transfer calculations use a CO_2 concentration that is fixed at the preindustrial value.
  - **1% per year CO_2-rad** □ ***increasing*** **atmospheric CO_2 concentration** impacts ***atmospheric radiative transfer and thus climate***, but not the biogeochemical processes directly over land and ocean (which see the preindustrial atmospheric CO_2 concentration).
- Climate responses are based on the difference in years 100-140 relative to the corresponding 40 years from the **preindustrial control** simulation:
  - CO_2 had quadrupled by year 140.
  - Similar results at the time of CO_2 doubling (year 70), with ~1/2 the magnitude.

2002-2021 FIREC Annual Climatologies [kgC km^{-2} day^{-1}]



- CMIP6 MMM global **fFire** response and 90% confidence interval **45.3±6.6 kgC km^{-2} day^{-1}.**
  - **GFED4.1s 35.6 kgC km^{-2} day^{-1} (models tend to *overestimate*)**
  - **FINNv2.5 49.9 kgC km^{-2} day^{-1} (within CMIP6 90% CI)**
- Regionally, considerable ***model diversity exists*** (and in some cases observational diversity), including notable biases e.g., overestimation for US and Europe.

Although *uncertainties* remain, CMIP6 models can reasonably reproduce the observed amount of fire carbon emissions in most regions (and interannual variability & seasonality).



- 1% per year CO2 & 1% per year CO2-bgc □ Most land areas feature a significant MMM **fFire** ***increase***.
- In contrast, 1% per year CO2-rad shows a **fFire** ***decrease*** in most locations (except higher NH latitudes).
- **Robust responses** in most regions (based on model agreement on the sign of the response).

Nearly all of the MMM **fFire** ***increase*** under 1% per year CO2 occurs under 1% per year CO2-bgc

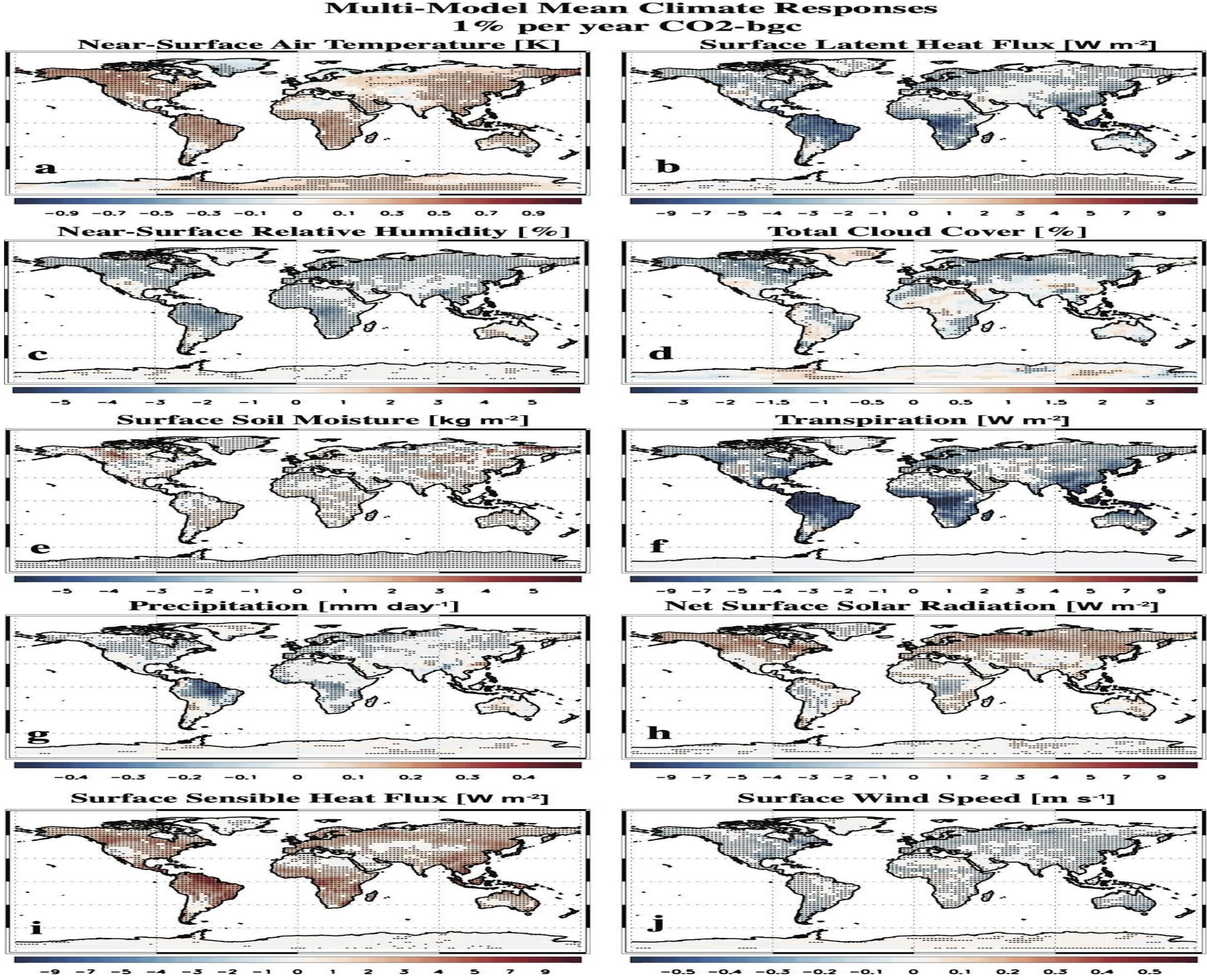
Model Breakdown of Global ΔfFire

- **Model diversity on the ΔfFire magnitude** (e.g., GFDL-ESM4).
- ***Nonlinearity***:
  - 4 models show **larger fFire** ***increase*** in **1% per year CO2** relative to (**rad** + **bgc**).
  - Could be because some ***climate change*** occurs in **1% per year CO2-bgc** (but probably not).
  - May be related to the superposition of **enhanced vegetation** (**fuel load**) plus **strong climate change** (***drying*** □ ***increase* fuel flammability**) that occurs only in **1% per year CO2**.

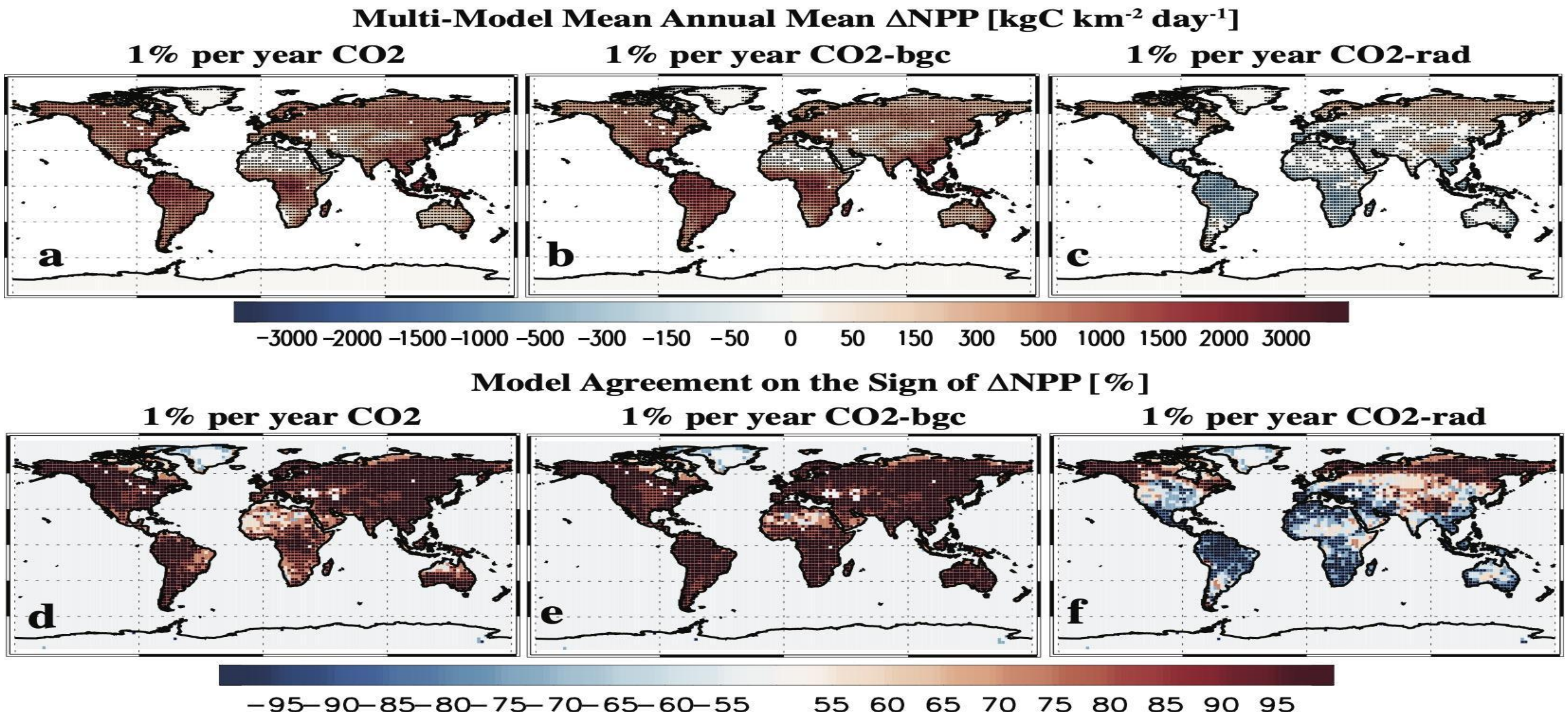
Model Name	1% per year CO_2	1% per year CO_2-bgc	1% per year CO_2-rad
CESM2	**26.7** (91.0%)	**7.8** (26.6%)	0.5 (1.8%)
CMCC-ESM2	**24.1** (91.4%)	−1.0 (−3.8%)	**11.2** (42.6%)
CNRM-ESM2-1	**18.3** (36.8%)	**23.4** (47.1%)	**−14.9** (−30.1%)
GFDL-ESM4	**293.8** (408.6%)	**335.4** (466.4%)	**−15.7** (−21.9%)
MPI-ESM1-2-LR	**38.3** (125.9%)	**40.1** (131.7%)	**1.2** (3.8%)
MRI-ESM2-0	**26.9** (60.4%)	**48.3** (108.6%)	**−10.3** (−23.1%)
NorESM2-LM	**18.1** (79.7%)	**5.9** (26.0%)	**4.1** (17.8%)
MMM	63.7 (127.7%)	65.7 (114.7%)	−3.4 (−1.3%)
MMM (no GFDL-ESM4)	25.4 (80.9%)	20.8 (56.0%)	−1.4 (2.1%)

Importance of **interactions among both the** ***physical drivers*** (e.g., heat waves, droughts) and ***biotic factors***

- ΔClimate in **1% per year CO_2-bgc**:
  - ***Warming*** and a change in **atmosphere-land water partitioning** □ **atmospheric drying** and a (less robust**) soil moisture *increase***.
- Likely driven by a ***decrease*** in **transpiration (−15.4±7.9%):**
  - Consistent with ***reduced* stomatal conductance** under ***higher* CO_2** □ **more efficient stomata** that ***lose less water*** to the atmosphere.
- Most Δvegetation lead to Δclimate that:
  - Amplify **fFire *increase*** due to Δbiomass alone □ **warming**, ***decrease* RH/PRECIP, *increase* SW**.



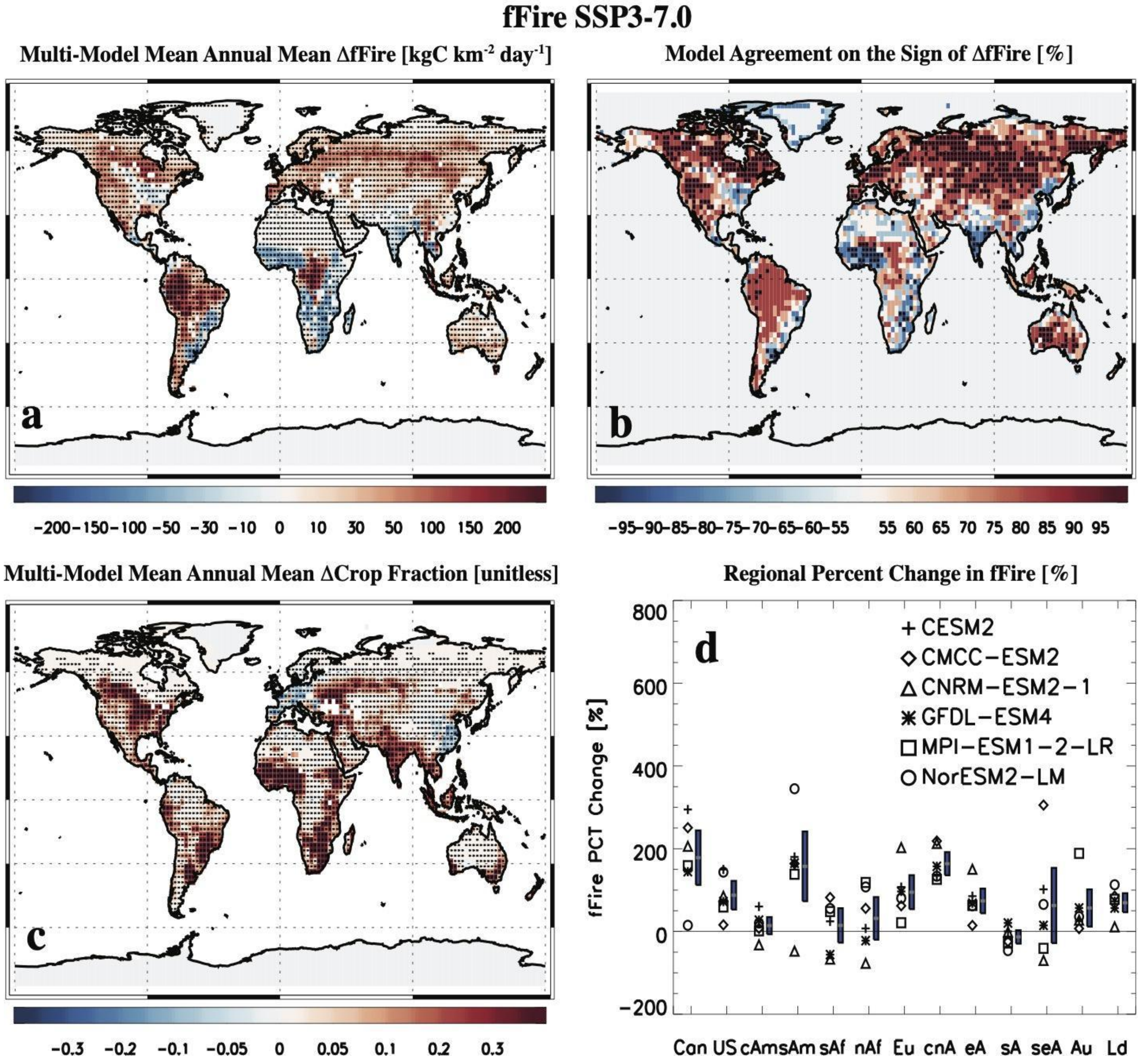
CO_2 fertilization impacts **energy/water/momentum fluxes** & **climate** □ ***warming*** (& ***increased* wildfire activity)** will **mute** the ***enhanced* carbon sequestration** □ important for **land-based climate policies** & "**natural climate solutions**"



- A robust ***increase*** in NPP for **1% per year CO2** & **1% per year CO2-bgc** □ **CO2 fertilization effect.**
  - **1% per year CO2 □ 74.8±13.8% (all models yield an *increase*)**
  - **1% per year CO2-bgc □ 77.1±21.3% (all models yield an *increase*)**
- **1% per year CO2-rad □ *decrease*** at **−7.3±4.5% (6 of the 7 models yield a *decrease*).**
- The spatial pattern of the NPP response is quite similar to the corresponding spatial pattern of the **fFire** response:
  - Consistent with the large **fFire *increase*** in GFDL-ESM4, there is also a large **NPP *increase*** (both **1% per year CO2** and **bgc**).

The **fFire *increase*** is largely due to the ***increase*** in **biomass production (more fuel to burn)**

- **SSP3-7.0** □ **ΔfFire** (& **ΔNPP**) ***weaker than*** **1% per year CO2**:
  - **23.5±7.7** vs. **63.7±63.4** **kgC km^{-2} day^{-1}.**
  - Some of this difference is due to GFDL-ESM4 (***less of an outlier*** in **SSP3-7.0**).
  - ***Also ΔCO2*** □ **422 ppm** vs. **641 ppm**.
- 90% **confidence intervals** without GFDL-ESM4 (and MRI-ESM2-0):
  - **19.9±6.2** vs. **25.1±6.1** **kgC km^{-2} day^{-1}**.
- Normalizing by ΔCO2:
  - **0.05±0.01** vs. **0.04±0.01** **kgC km^{-2} day^{-1} ppm^{-1}.**
- Additional **SSP** considerations:
  - ***fire suppression*** & ***ignition*** □ function(population, GDP).
  - **LULCC** □ ***increase*** in **SSP3-7.0 crop fraction** (**265%**) □ associated ***reduced*** **fire activity** (esp. w/ GFDL-ESM4).
    - Further verified in **SSP3-7.0** vs. **SSP3-7.0-SSP1-2.6Lu**.



Conclusions

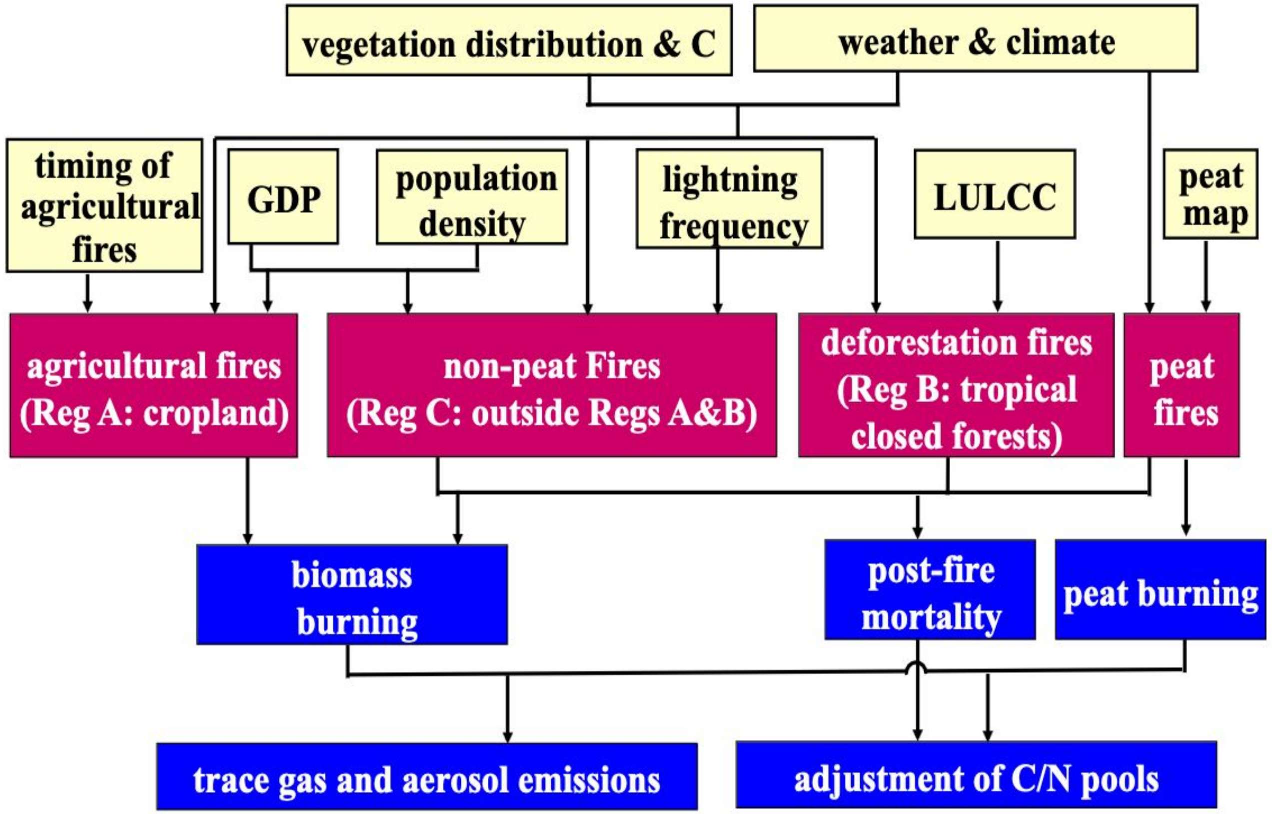
- CMIP6 ESMs yield a robust ***increase*** in **fire carbon emissions** under idealized ***increases*** in atmospheric CO2 concentrations.
  - Largely due to the **CO2 biogeochemical effects on vegetation** □ **CO2 fertilization effect**.
  - **Radiative effects** alone yield a ***non-significant fFire decrease*** (except for NH high-lats).
- Importance of interactions among both the **physical drivers** (e.g., heat waves, droughts) and **biotic factors** □ tends to ***amplify*** fFire signal.
- Only 2 models have **Dynamic Global Vegetation** (MPI and GFDL) □ likely important for future wildfire activity under increasing CO2.
- Policy efforts to **mitigate fire risk** should ***not*** **overlook the importance of ecological drivers**.
- Furthermore, there are implications for **Natural Climate Solutions**:
  - e.g., **reforestation/afforestation initiatives** (like Trillion Trees), which seek to enhance carbon sequestration by repopulating the world's trees.

https://www.nature.com/articles/s43247-024-01228-7

Extra Slides

CLM Fire Parameterization

- CESM fire model has 4 components:
  - **"Wildfires" □ Region C.**
- Burned area/fire emissions depend on:
  - **Climate and weather conditions**:
    - **Fuel combustibility** □ function of soil wetness (i.e., RZSW = volumetric soil moisture relative to that at saturation), RH and TAS.
    - **Fire spread** □ depends on WS, RH and soil moisture (here, RZSW).
  - **Fuel load** □ Vegetation composition and structure.
  - **Human ignition & suppression** □ depends on population & GDP
  - **Natural ignition** □ Lighting flash rate is prescribed from observations
- Fire trace gases and aerosol emissions do NOT feedback on climate.



Li et al., 2013. Quantifying the role of fire in the Earth system – Part 1: Improved global fire modeling in the Community Earth System Model (CESM1), Biogeosciences, 10, 2293-2314

Li et al., 2012. A process-based fire parameterization of intermediate complexity in a Dynamic Global Vegetation Model. Biogeosciences, 9, 2761-2780