

CLM-FATES

Global implementation, opportunities and plans

Rosie Fisher
CICERO Center for International Climate Research, Oslo, Norway.

CLM tutorial: 19.11.2026



Crystal Mirallegro/unsplash.com

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On behalf of:
the NorESM land team

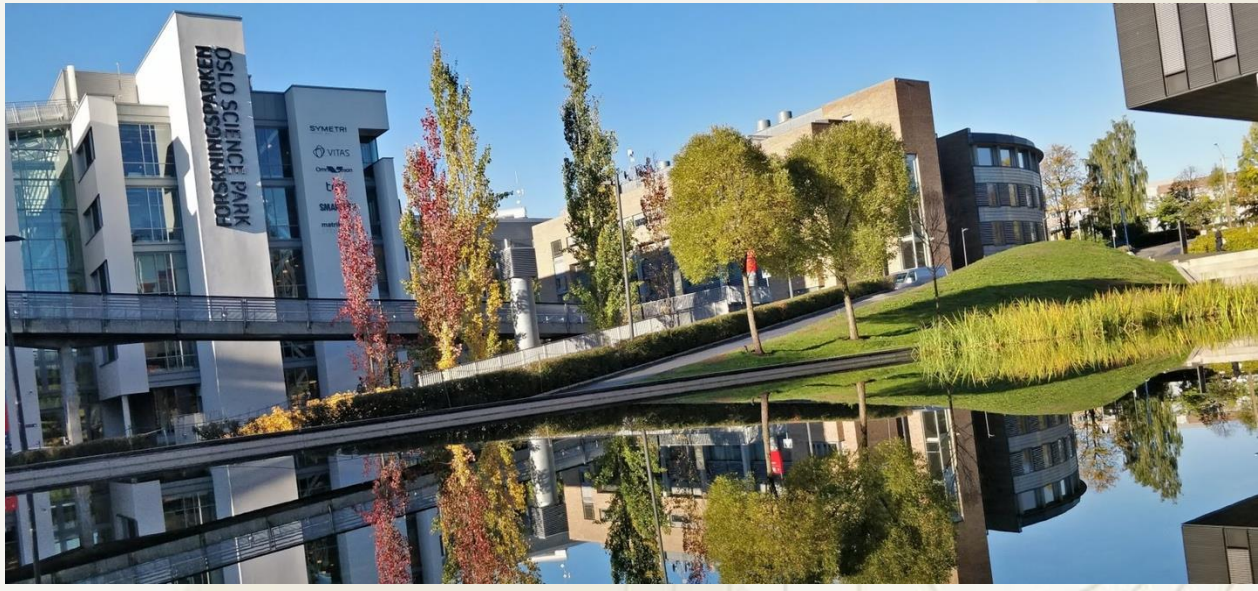
Kjetil Aas

Jessica Needham

Matvey Debolskiy

Marit Sandstad

Mariana Vertenstein











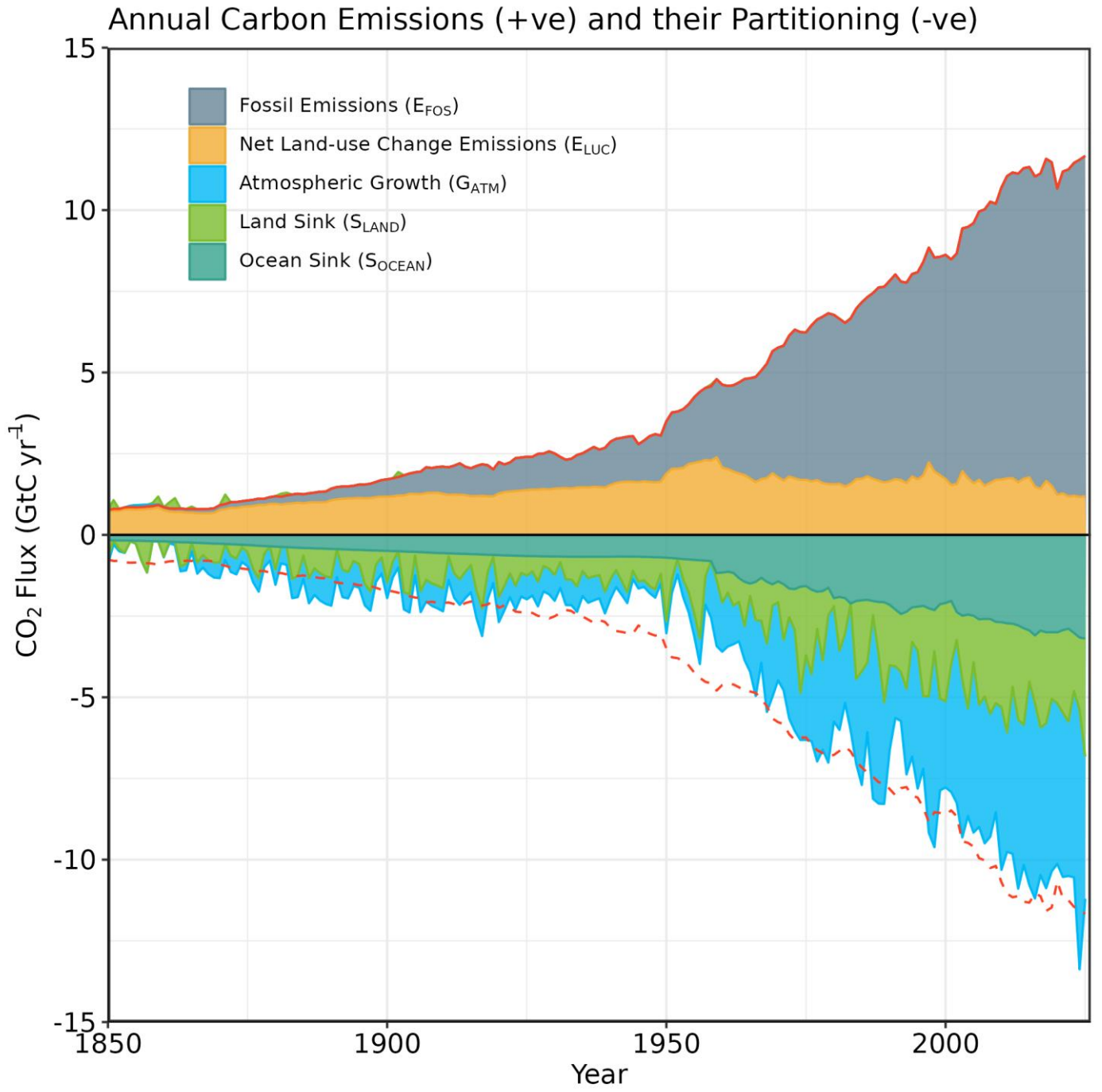
& the FATES development team

Charlie Koven
Adrianna Foster
Ryan Knox
Greg Lemiuex
Sam Rabin
Marcos Longo
Jennifer Holm

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FATES

***How much carbon* does the terrestrial biosphere *absorb*?**



GLOBAL CARBON project

emissions

land use change

ocean

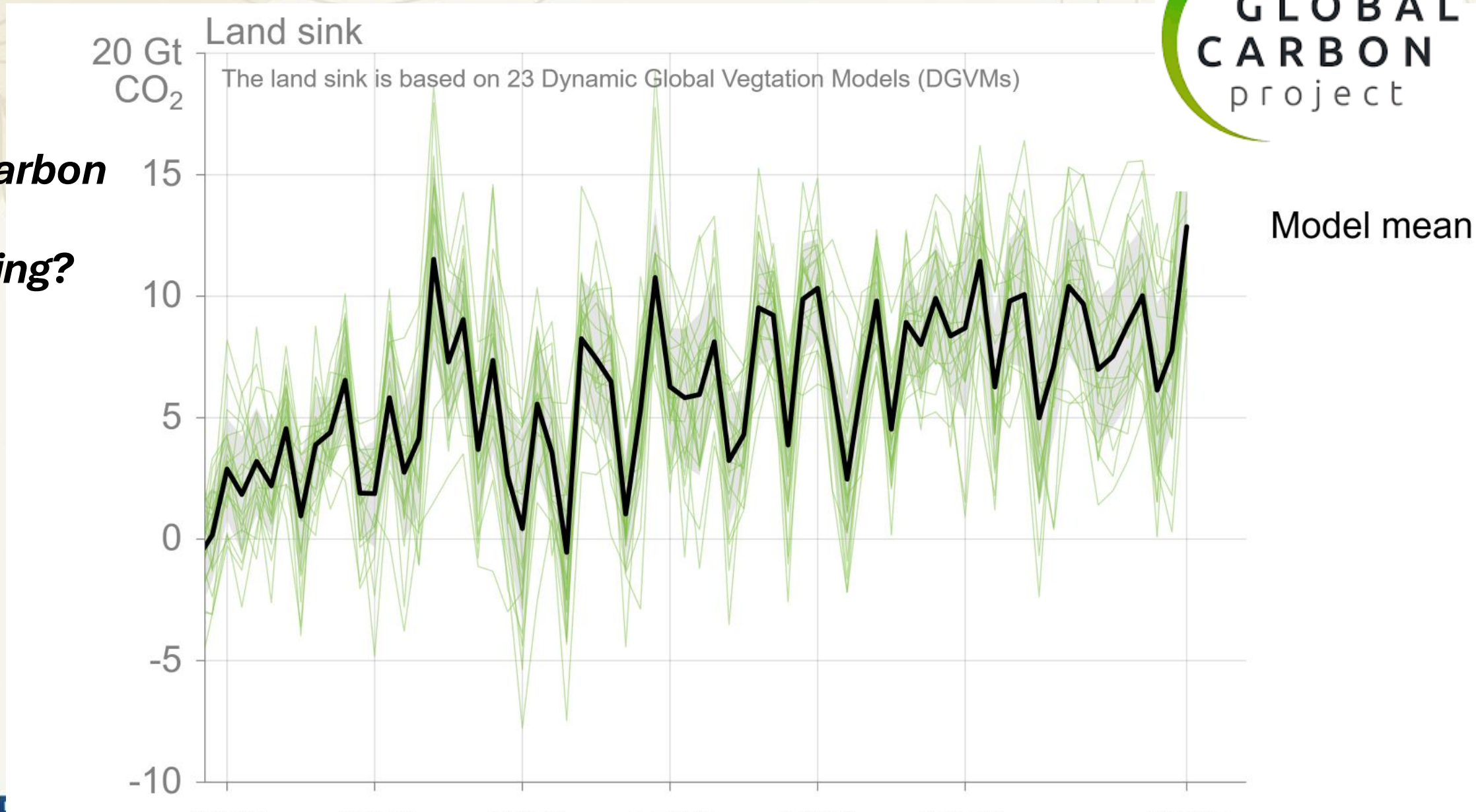
land sink

atmospher
e

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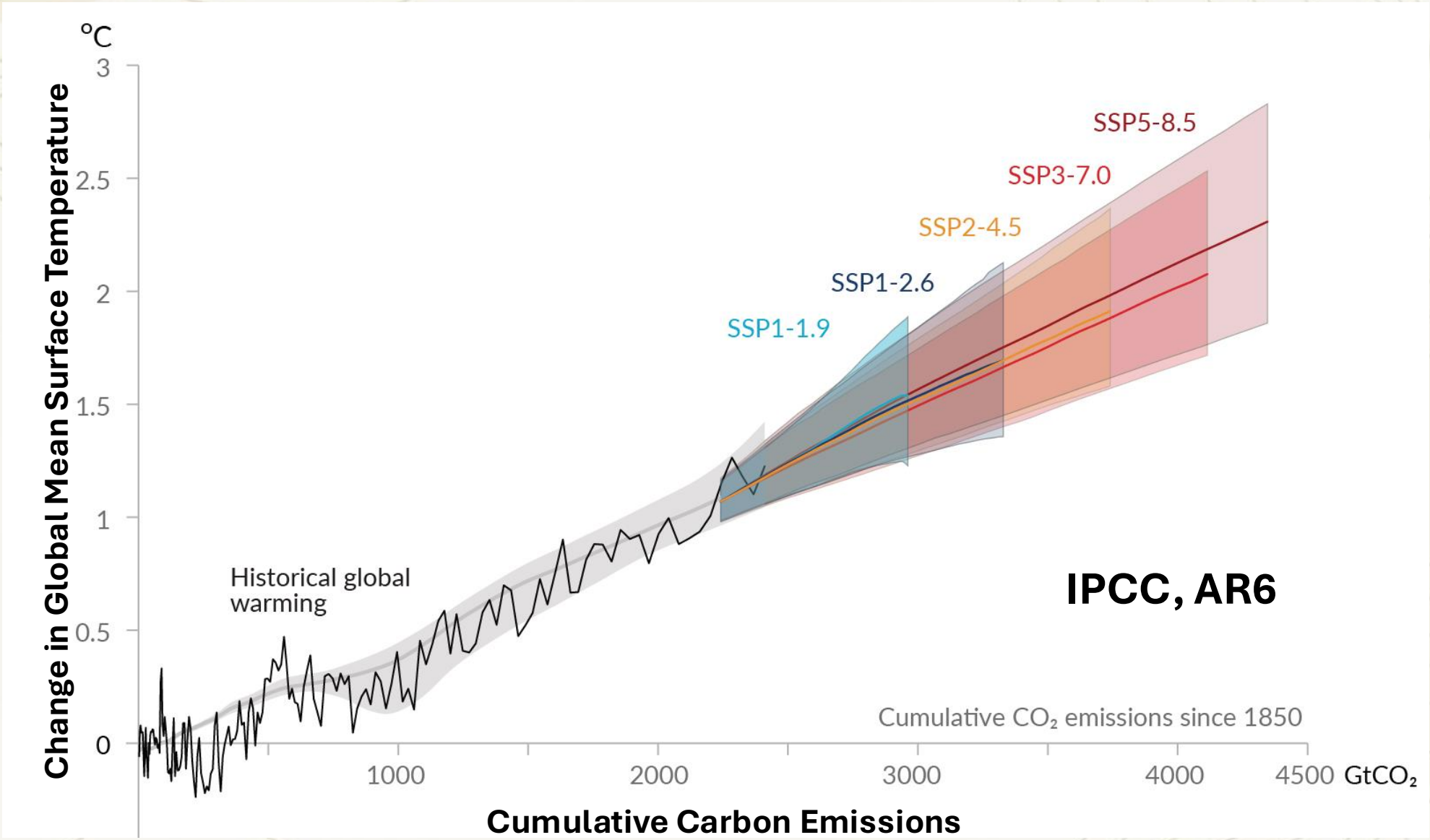
globalcarbonbudget.org

Is the carbon sink saturating?



Transient Response to Cumulative Emissions (TCRE)

How much *more* carbon can we emit (to achieve a given temp. target)



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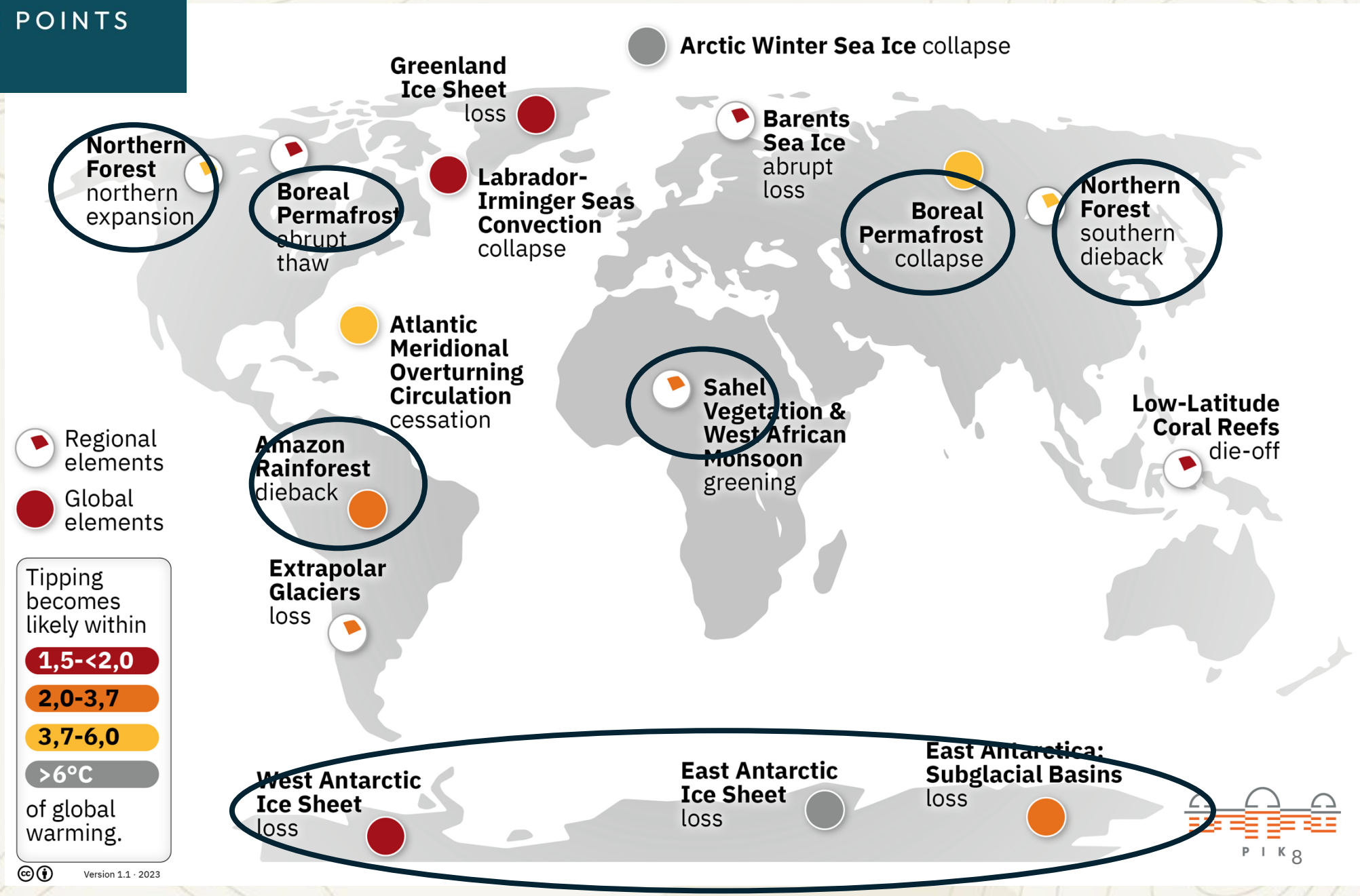
GLOBAL TIPPING

THE GLOBAL TIPPING POINTS REPORT 2025

Are there land-mediated climate '*tipping points*' in the Earth System?

Lenton et al. 2008

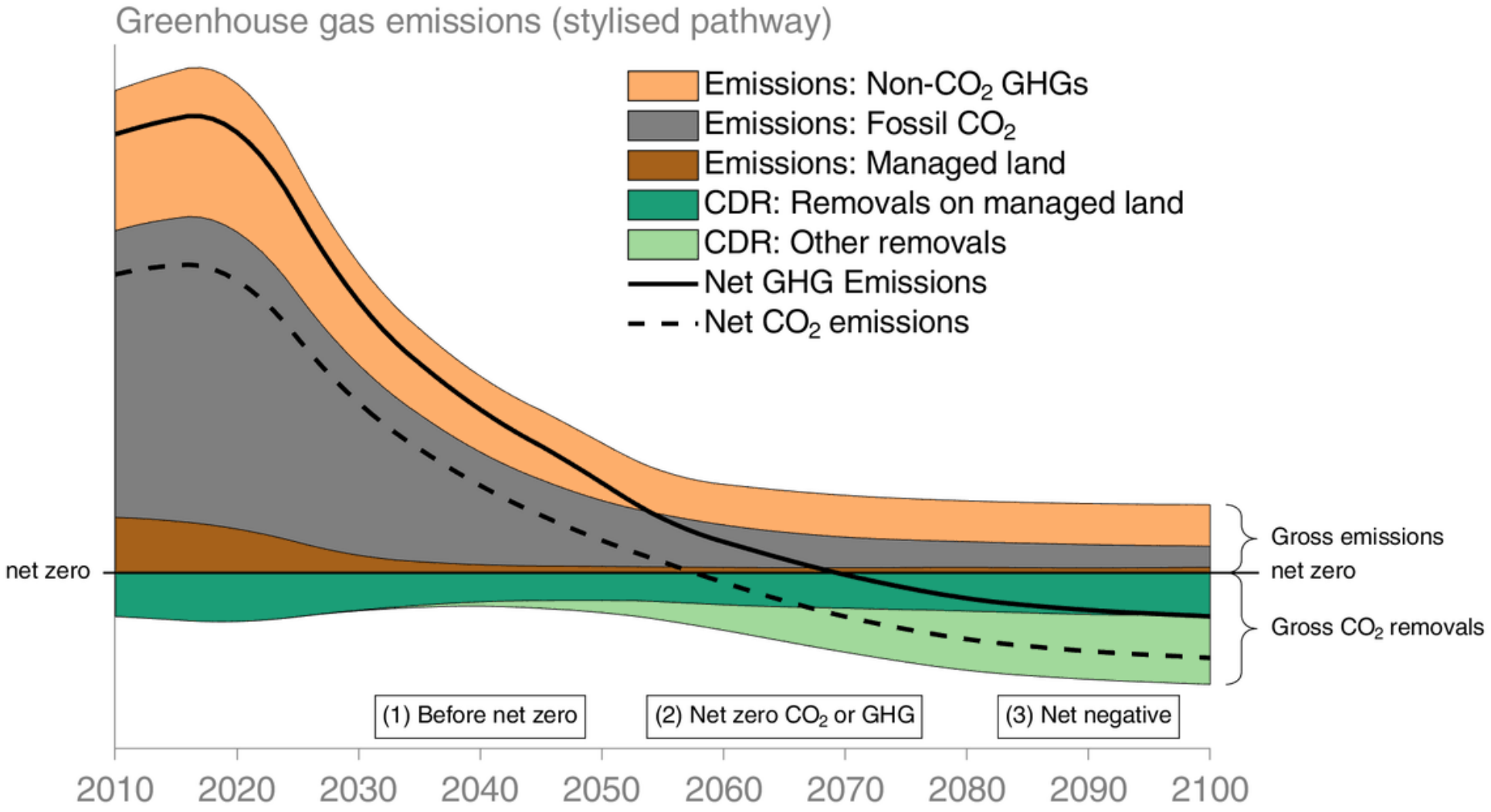
Armstrong-McKay et al. 2022 DOI: 10.1126/science.abn7950



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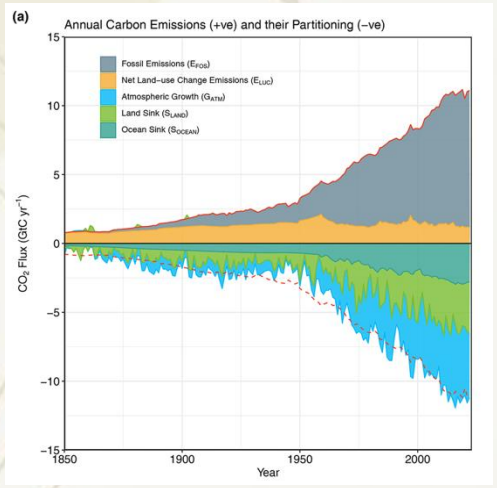
Carbon sources & sinks in Paris- compatible future scenarios

Can & should human interventions modify the land surface to *keep absorbing* our CO2 emissions?

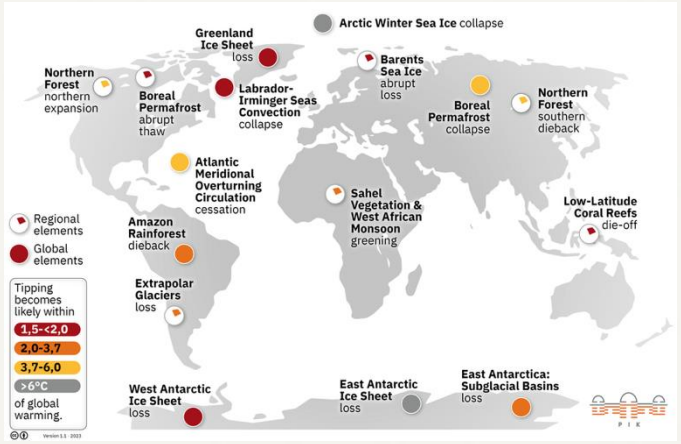


*Glen Peters, based on **IPCC AR6 WG3***

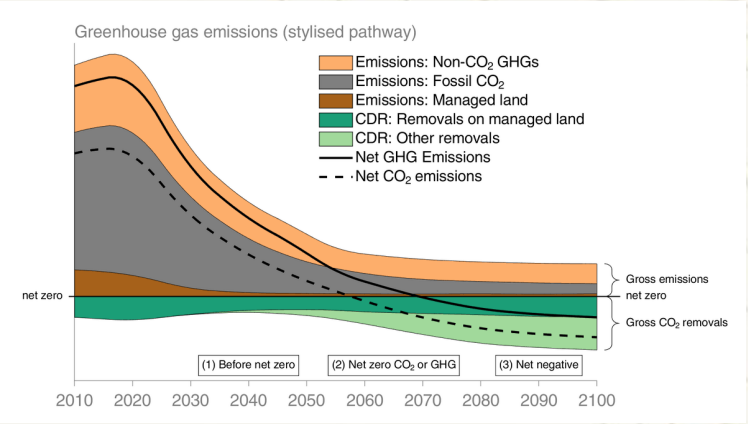
These questions map on to **specific features** of the carbon cycle



Are we capturing **land use change** legacies on **ecosystem structure**?



Are we getting **ecosystem mortality** right?



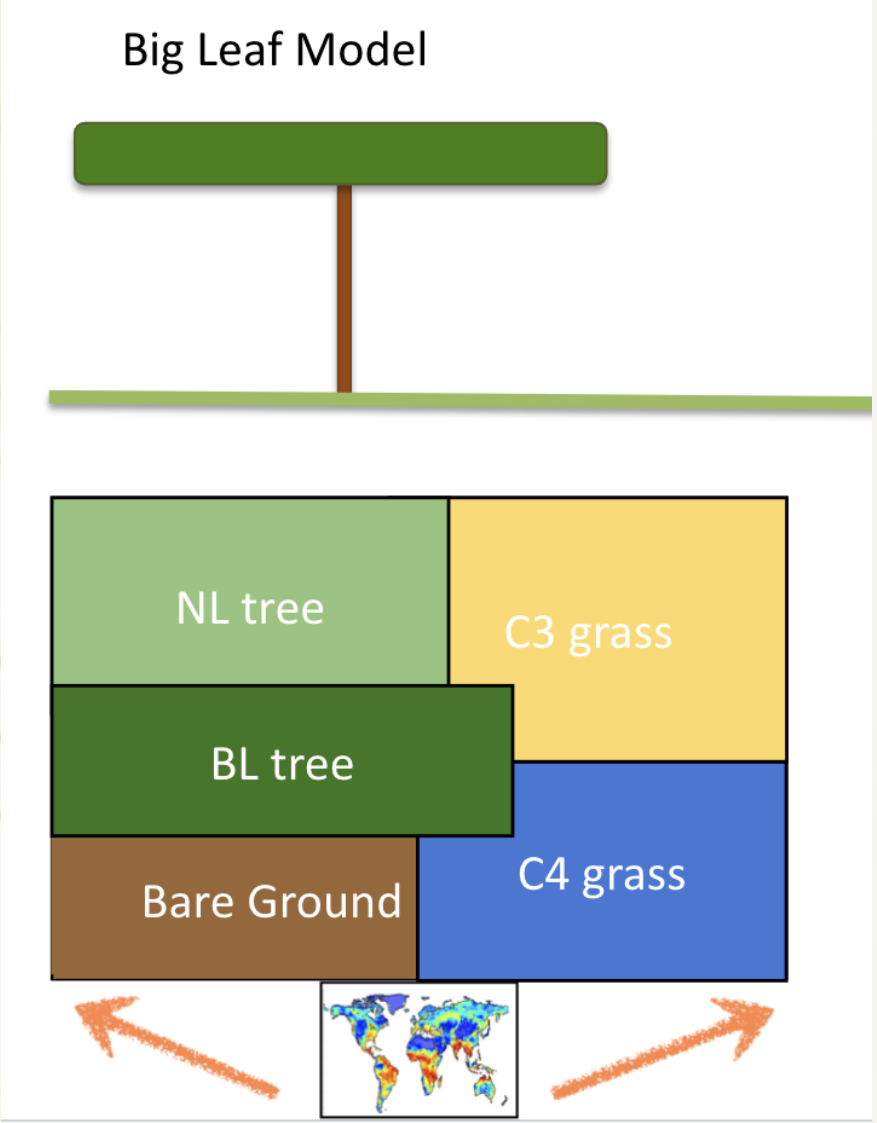
Are we getting **regrowth rates** right?

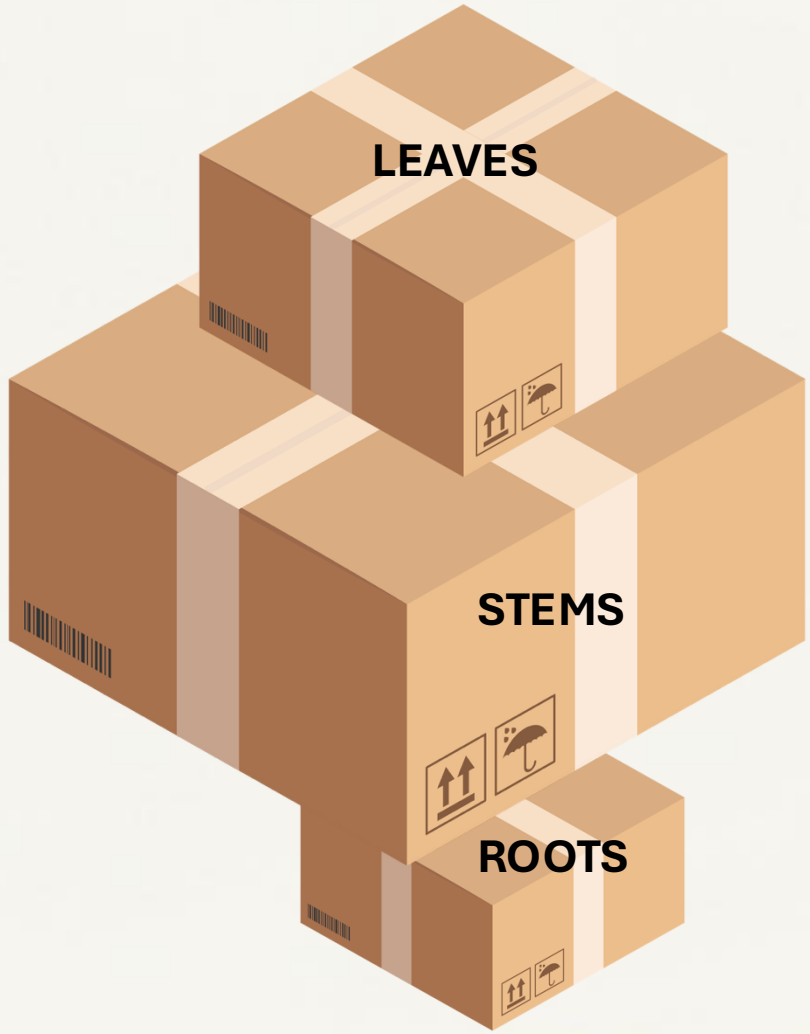


Most land surface models are missing representations of **forest age**, **plant size** and **plant mortality**.

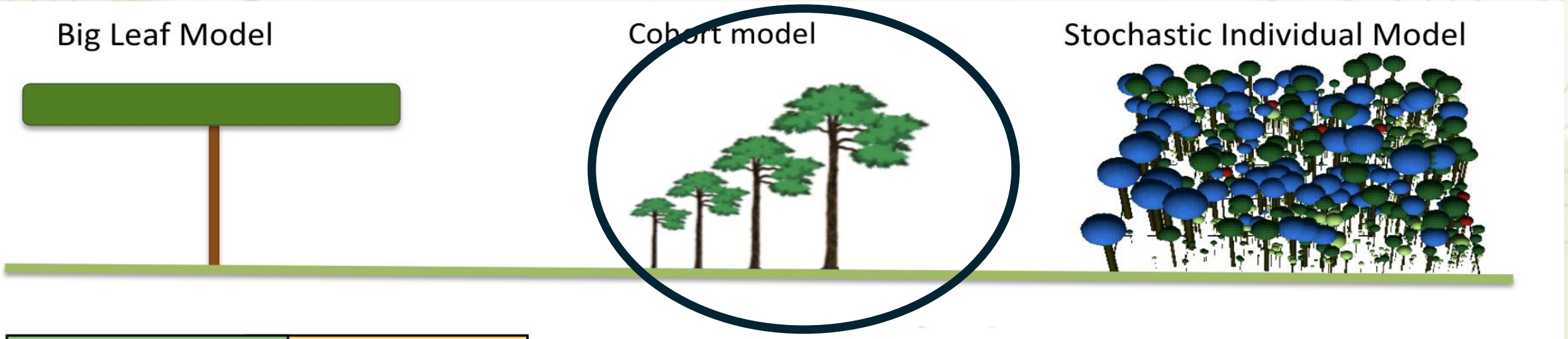
This has potentially large implications for **global-scale questions**

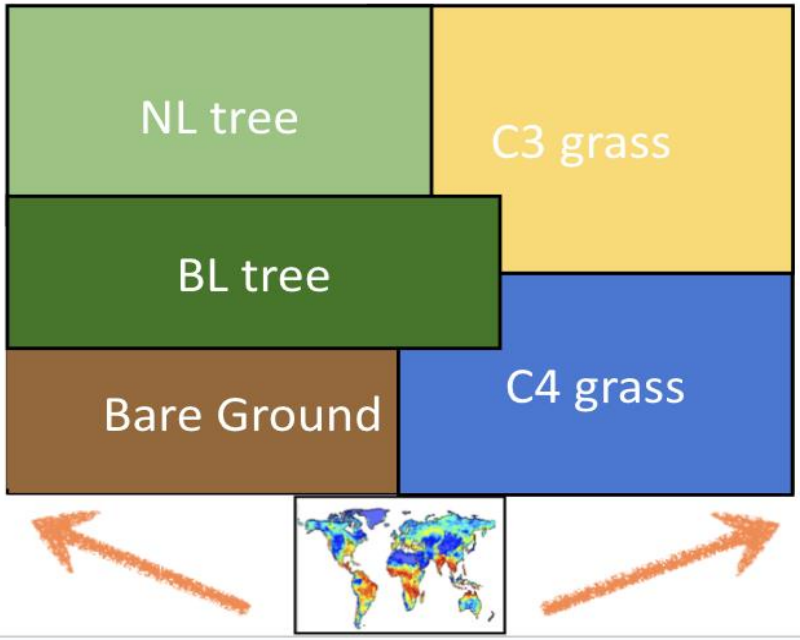
Ecosystem Processes in Land Surface Models

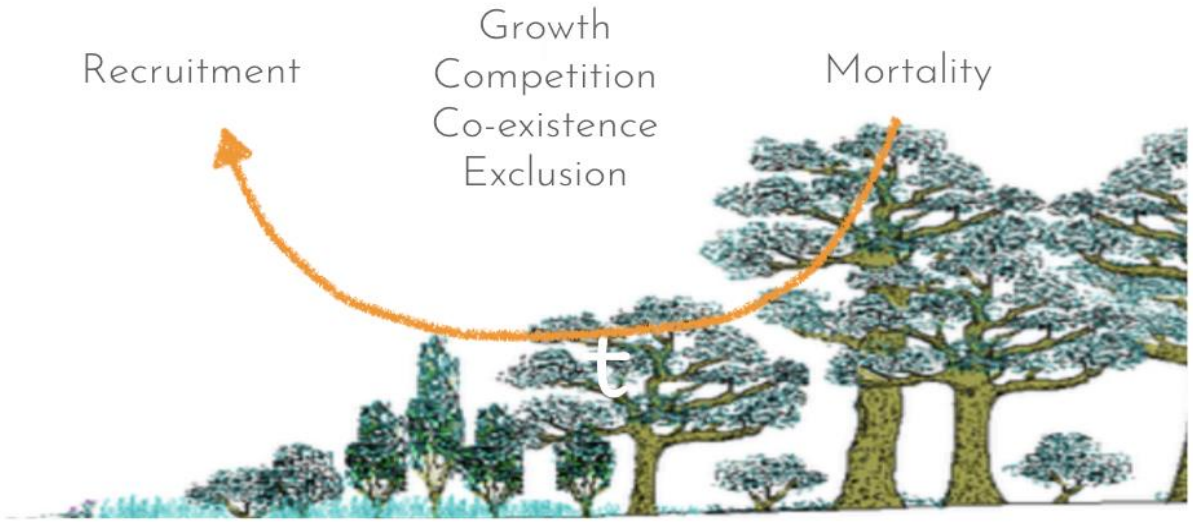




Ecosystem Processes in Land Surface Models







FATES: the Functionally Assembled Terrestrial Ecosystem Simulator

https://github.com/NGEET/fates

FATES is a demographic **vegetation** model, integrated into the Community Land Model (**CLM**)

It ~~will be~~ ***is*** the default vegetation in the Norwegian Earth System Model NorESM3

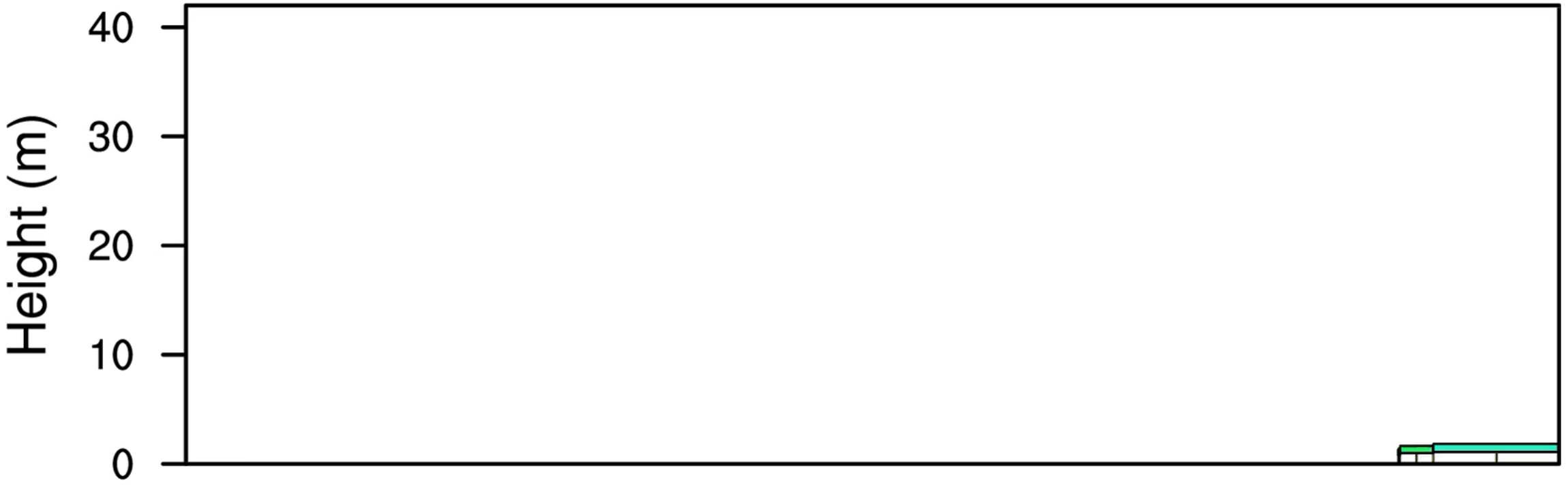


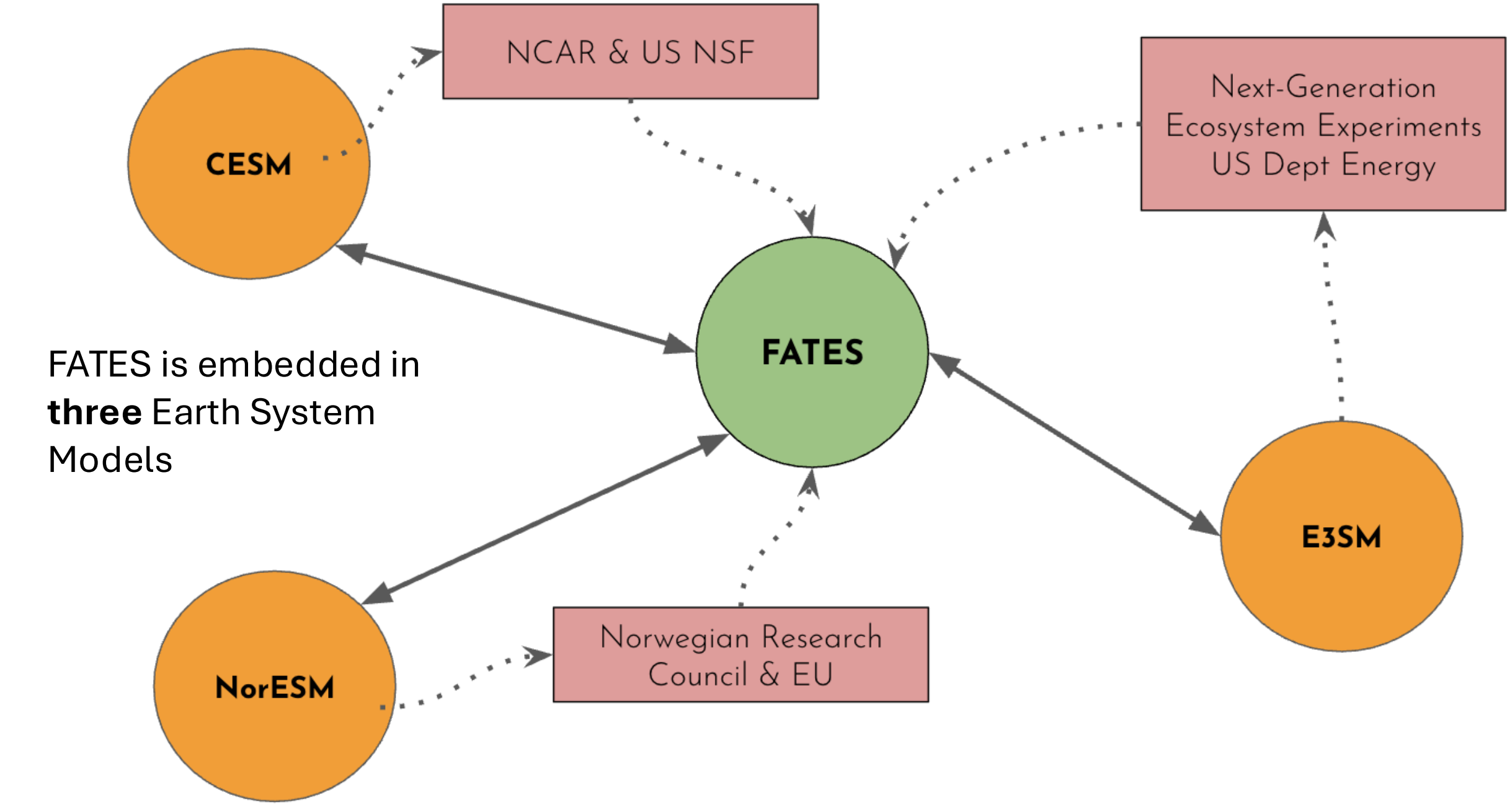
Open source, decentralized **community** development.

Flexible structural assumptions, parameters and complexity

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FATES: the Functionally Assembled Terrestrial Ecosystem SImulator (Koven et al. GMD 2020)





FATES is embedded in **three** Earth System Models



NorESM – the **Nor**wegian **E**arth **S**ystem **M**odel

Based on the infrastructure of, but not identical to, the Community Earth System Model (CESM)

NORCE

Norwegian Meteorological Institute

NERSC
NANSEN ENVIRONMENTAL AND REMOTE SENSING CENTER

UNIVERSITAS BERGENSIS

BJERKNES CENTRE for Climate Research

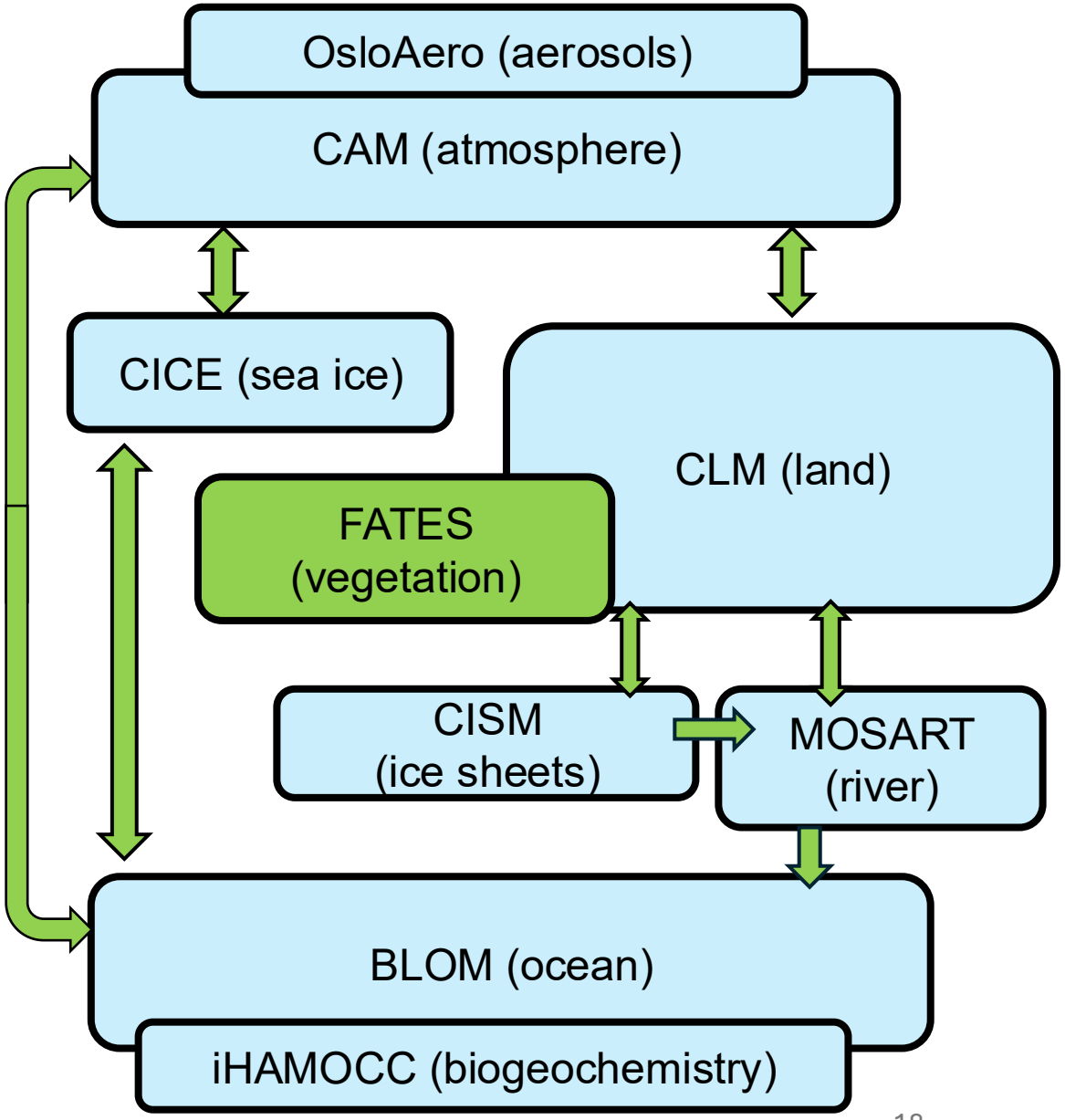
UiO : University of Oslo

NILU

CICERO
Center for International Climate Research

The Norwegian Earth System Model

NorESM =



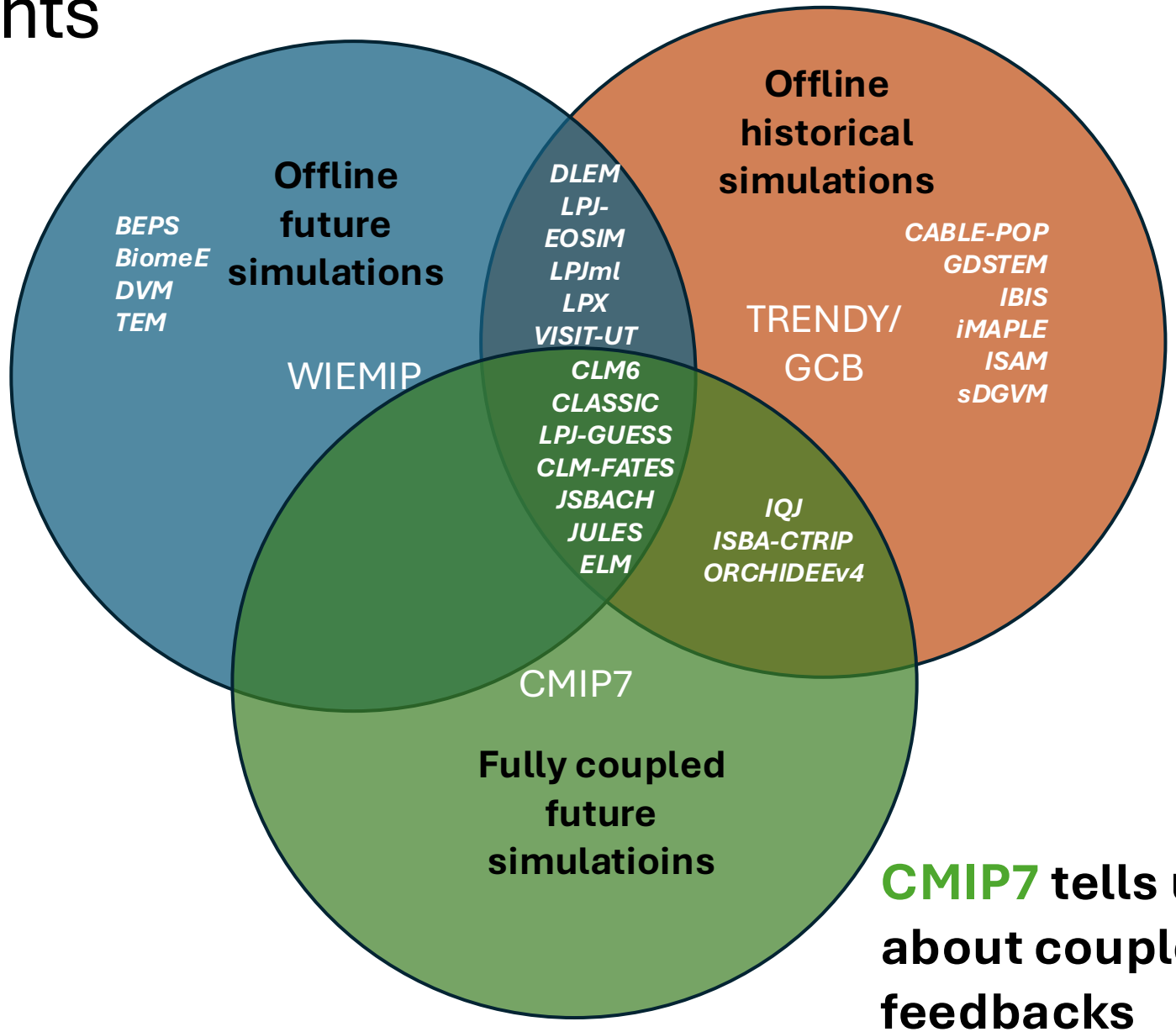
Status of FATES in NorESM3

- After an extremely epic tuning and software engineering process, CLM-FATES is running inside the new version of **NorESM**(3)
- Presently running multiple **historical simulations for CMIP7**
- About to start **future** (scenario) simulations
- Both **emissions-driven** and **concentration-driven** runs going.
- **Jessie** will talk more about this later.

FATES running in 3 model intercomparison experiments

TRENDY tells us how skilled models are

WIEMIP tells us about what land surface processes affect sensitivity to climate & CO2 (*beta/gamma*).



CMIP7 tells us about coupled feedbacks

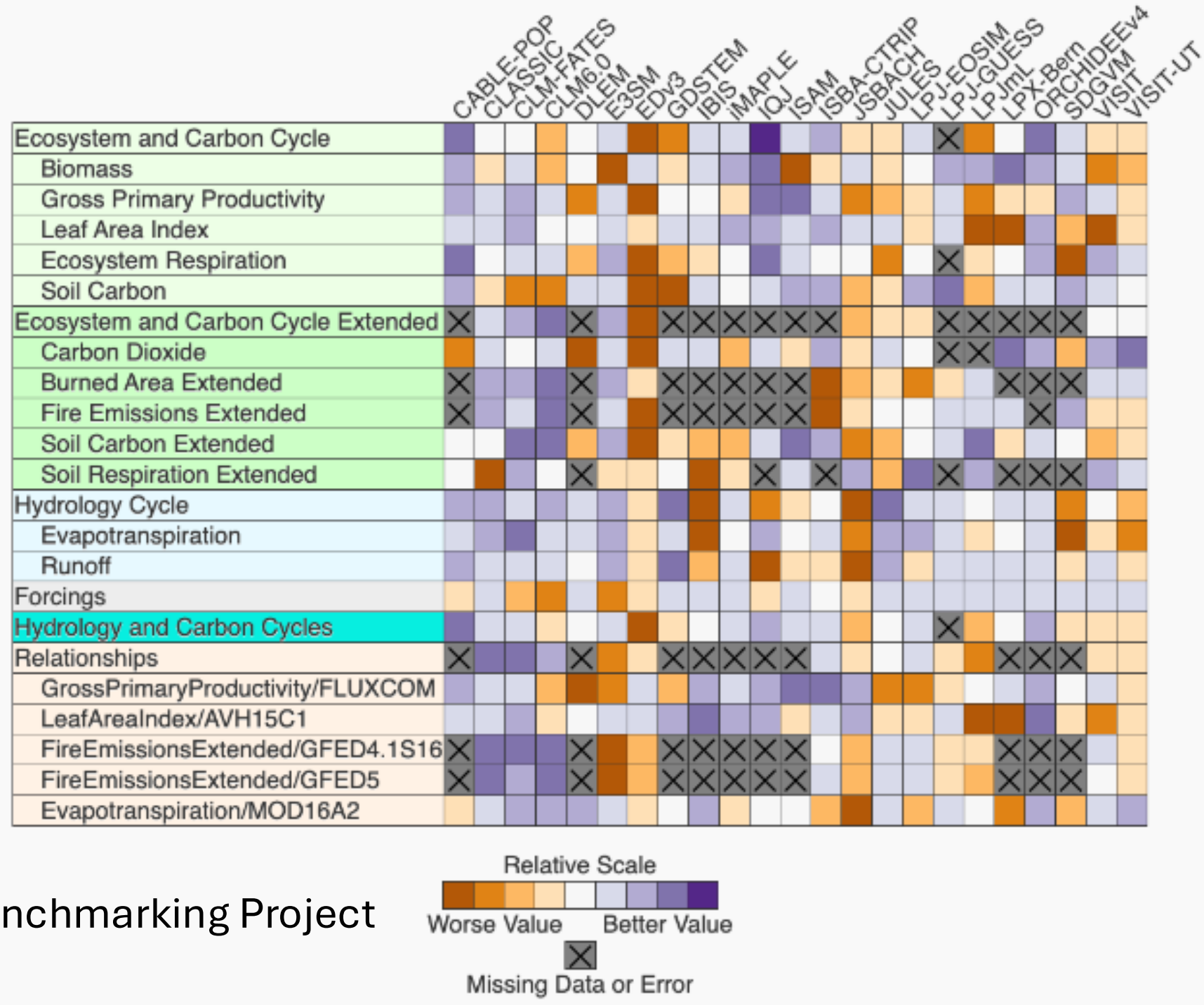
Resouces

- **FATES code:** https://github.com/NGEET/fates
- **Documentation:** https://fates-users-guide.readthedocs.io/projects/tech-doc/en/latest/
- **Users Guide:** https://fates-users-guide.readthedocs.io/en/latest/
- **Mailing List:** https://groups.google.com/g/fates_model
- **Diagnostics Tool:** https://github.com/NorESMhub/xesmf_clm_fates_diagnostic
- rosie.fisher@cicero.oslo.no.
- rosieafisher.com

TRENDY 2026

https://gws-access.jasmin.ac.uk/public/landsurf_rdg/pmcguire/ILAMB_output_TRENDYv15/GCP_27092026a4nC/

FATES global implementation skill scores

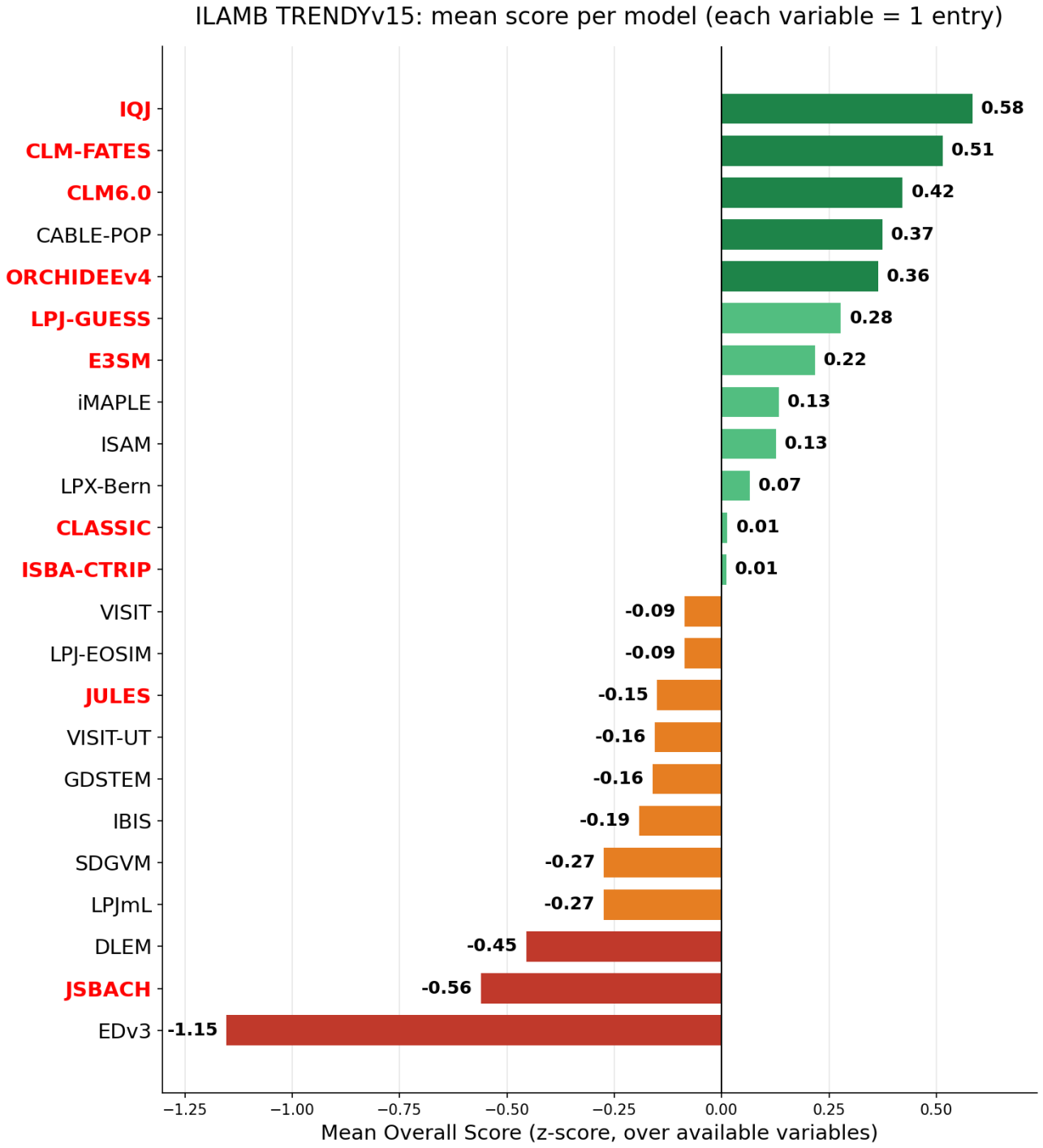


International Land Model Benchmarking Project
www.ilamb.org

TRENDY 2026

https://gws-access.jasmin.ac.uk/public/landsurf_rdg/pmcguire/ILAMB_output_TRENDYv15/GCP_270926a4nC

Mean scores across all variables.

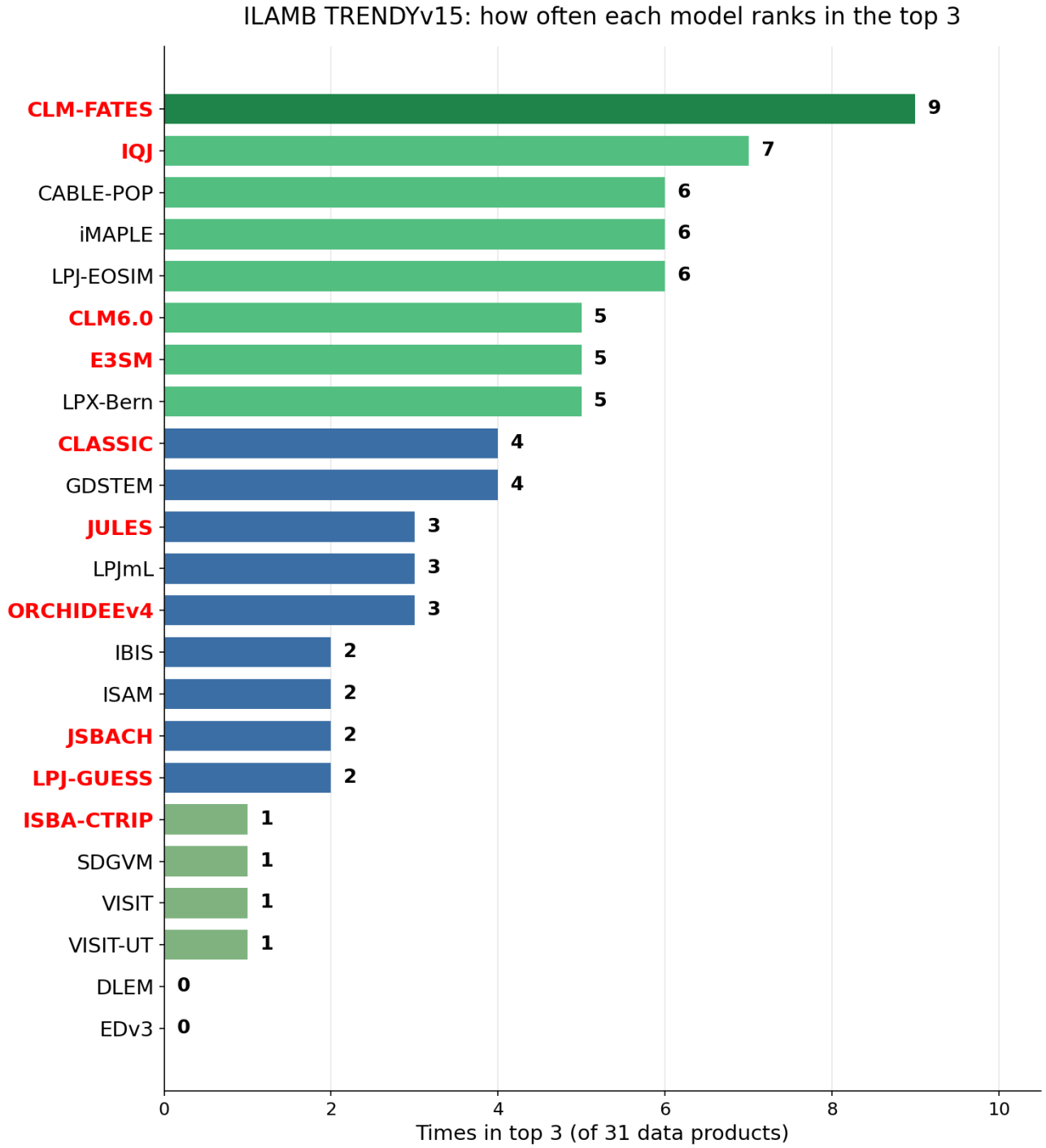


TRENDY 2026

https://gws-access.jasmin.ac.uk/public/landsurf_rdg/pmcguire/ILAMB_output_TRENDYv15/GCP_270926a4nC

FATES is top 3 and **first** for:

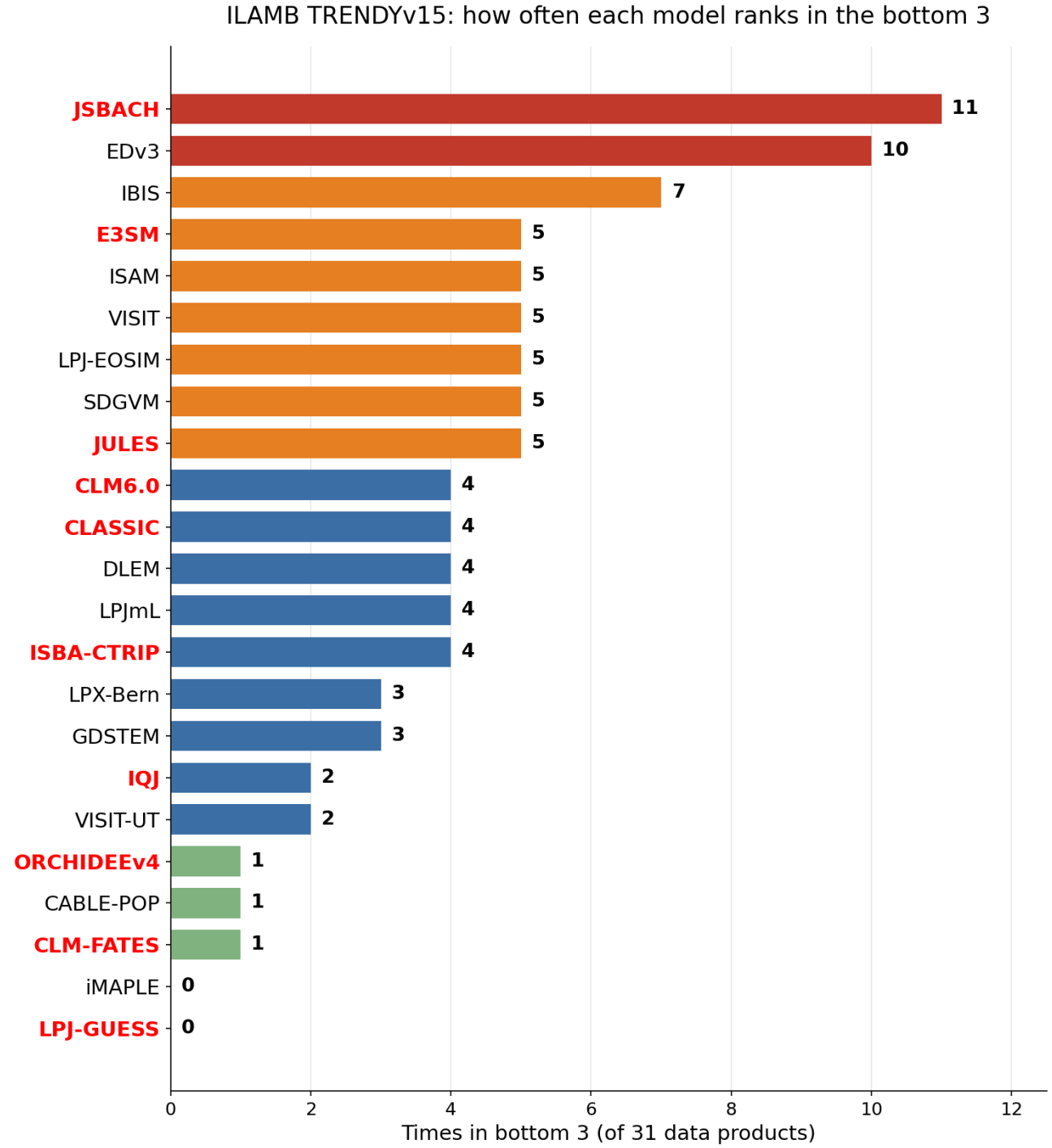
FLUXNET GPP
FLUXCOM GPP
MODIS LAI
GFED 4.1S16 fire emissions
GLEAM evapotranspiration
MODIS evapotranspiration
MOD16A2 evapotranspiration
Burned area vs fire emissions
Koven soil turnover



TRENDY 2026

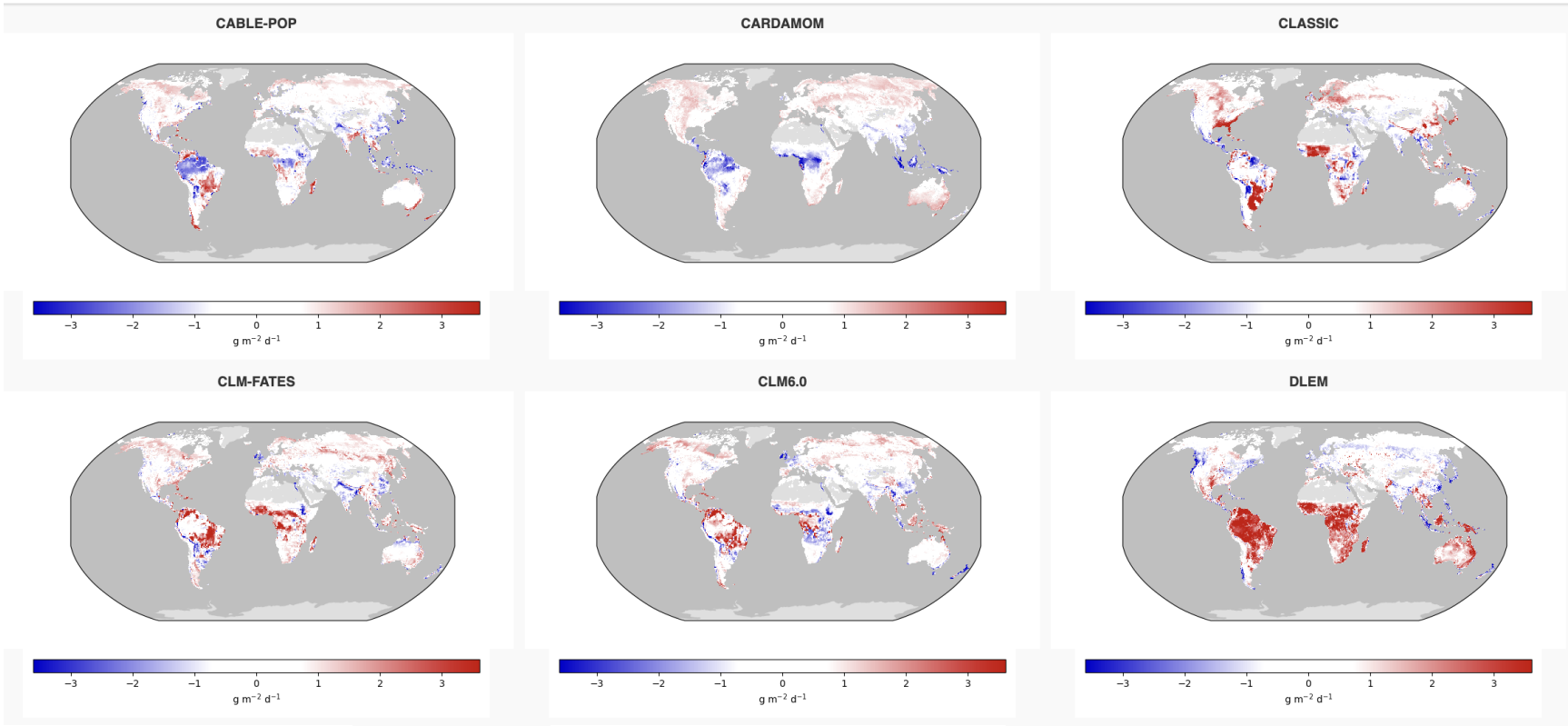
https://gws-access.jasmin.ac.uk/public/landsurf_rdg/pmcguire/ILAMB_output_TRENDYv15/GCP_270926a4nC

FATES is in the **bottom 3 f**or *HSWD Soil Carbon*

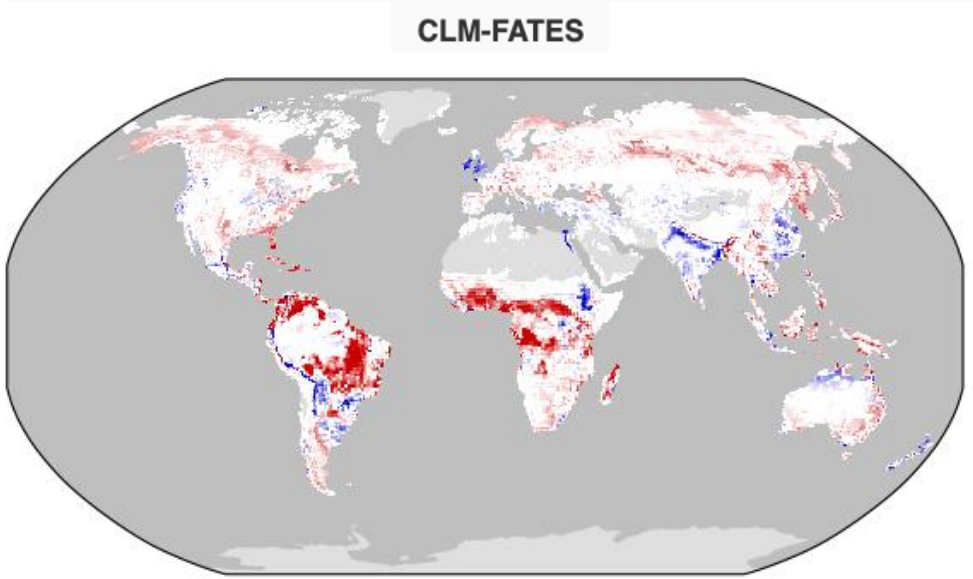


TRENDY 2026

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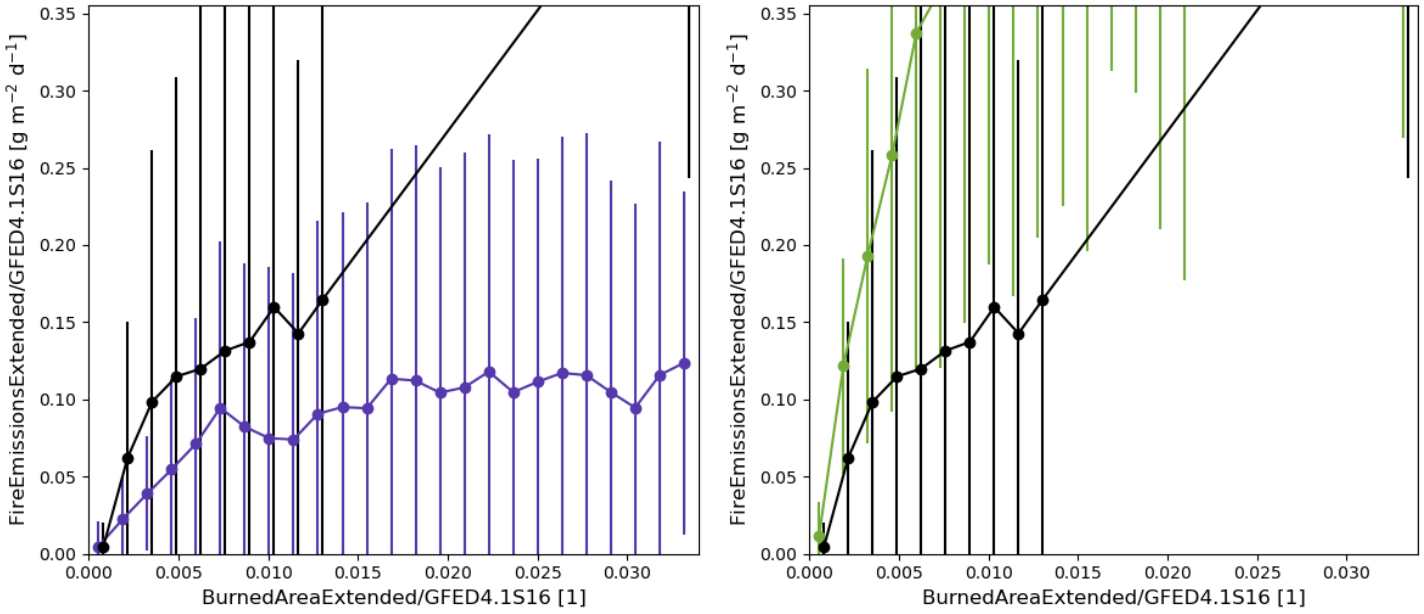
FLUXCOM GPP

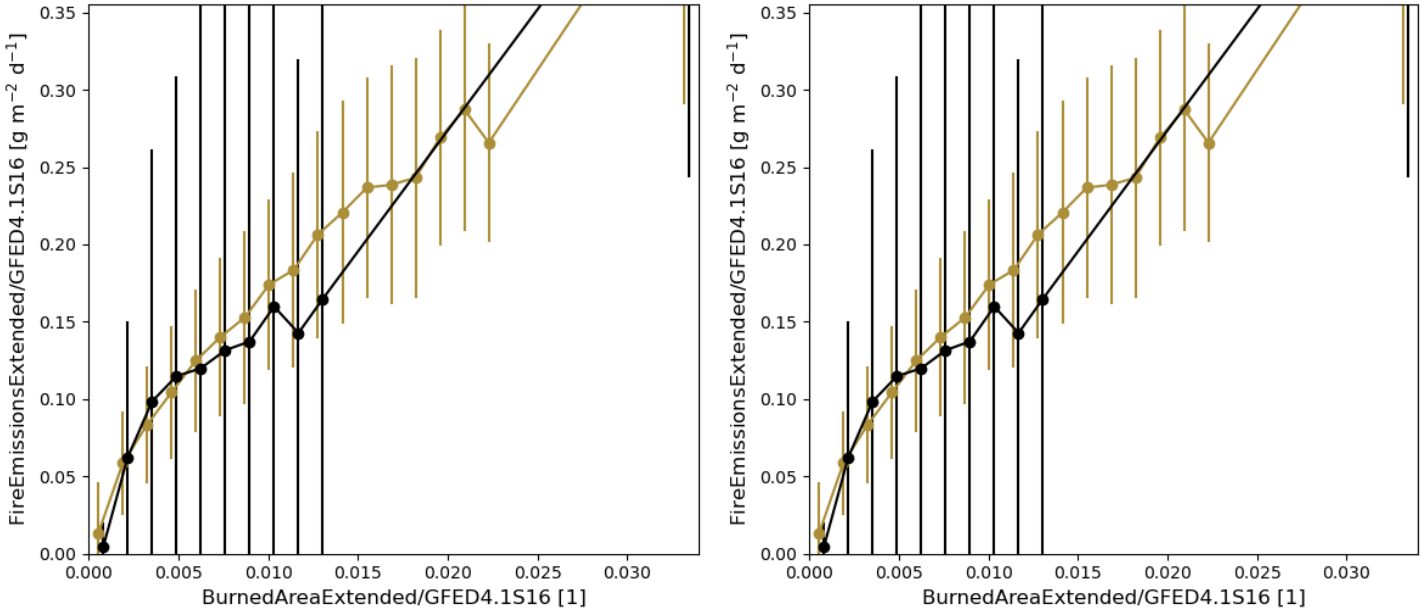


TRENDY 2026

https://gws-access.jasmin.ac.uk/public/landsurf_rdg/pmcguire/ILAMB_output_TRENDYv15/GCP_270926a4nC

Burned area vs fire emissions

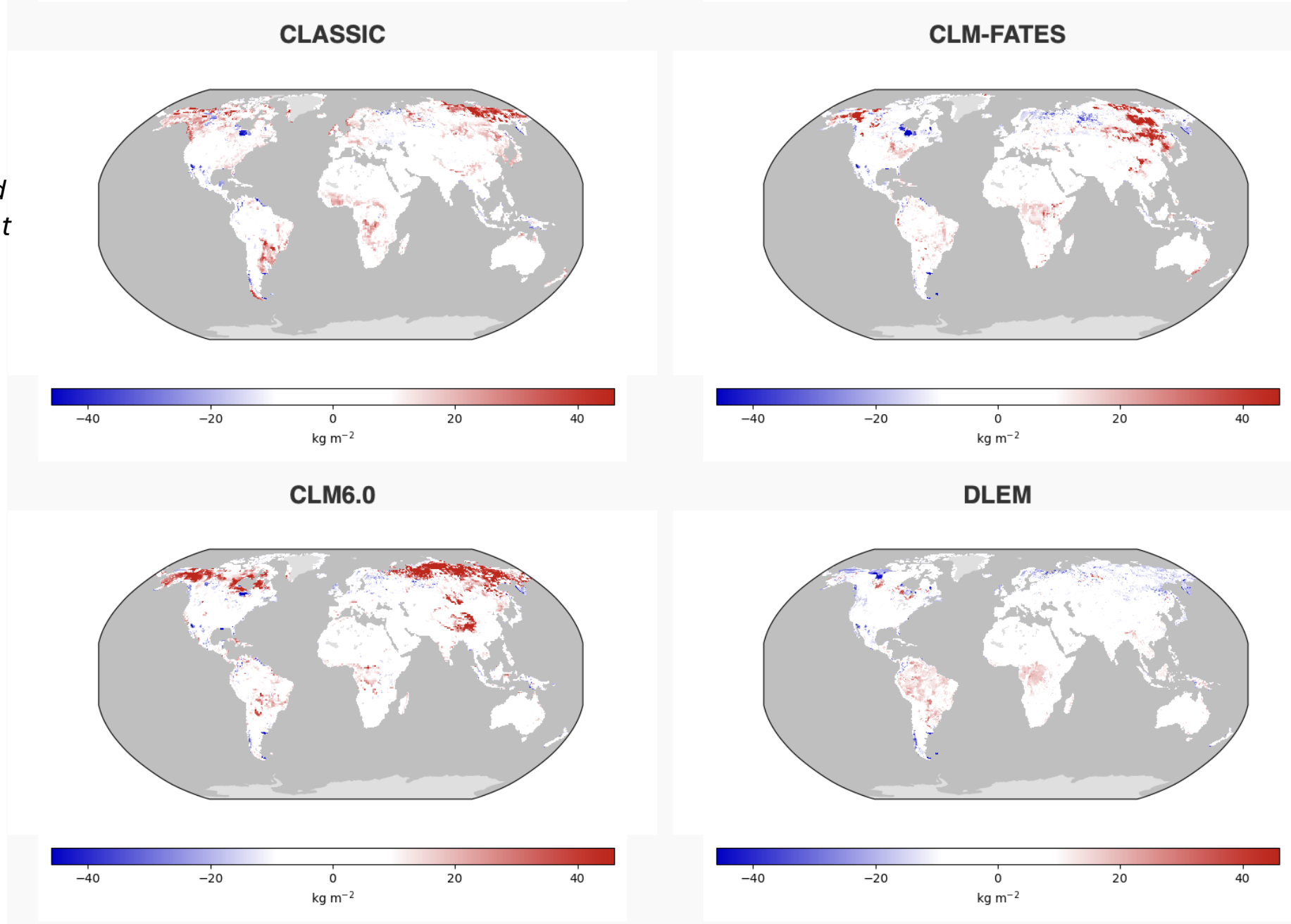




TRENDY 2026

https://gws-access.jasmin.ac.uk/public/landsurf_rdg/pmcguire/ILAMB_output_TRENDYv15/GCP_270926a4nC

HWSD soil carbon ☹





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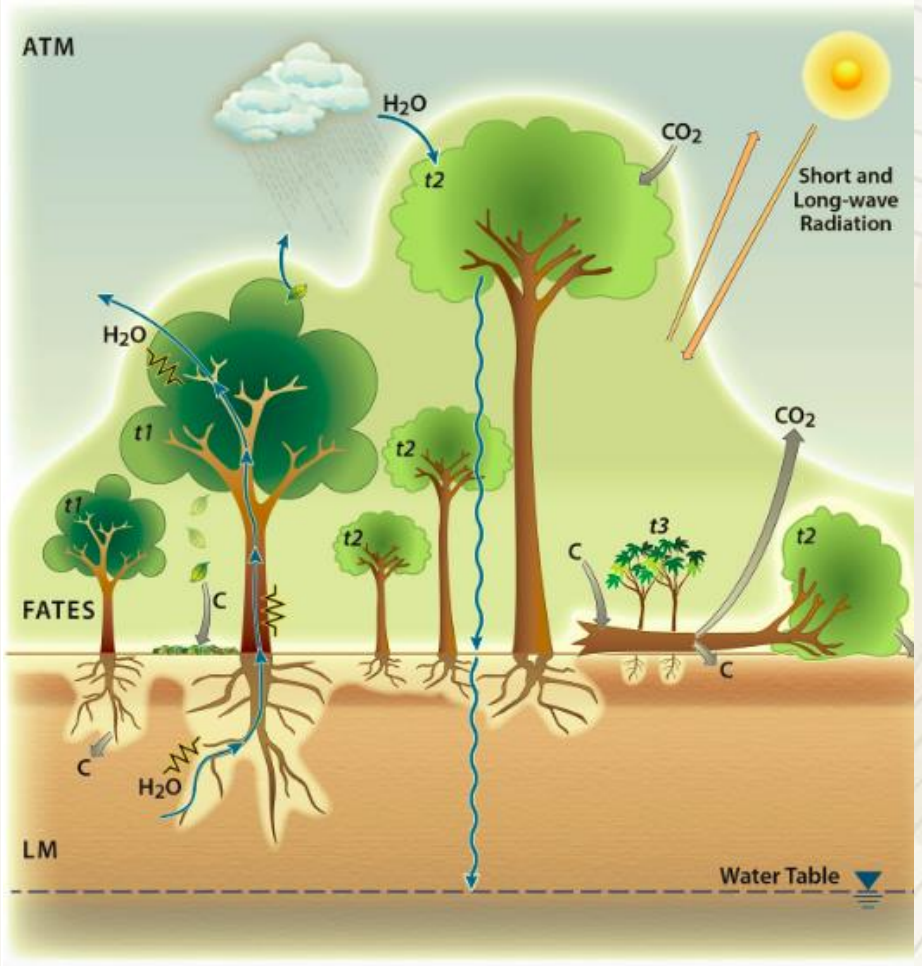
Ringkollen, Nordmarka

So far, so good, but **what scientific advances result** from doing all of this?

What new things does FATES do in NorESM?

(and why do they matter?)

- Resolves plant size
- Resolves ecosystem age since disturbance
- Resolves gross land use transitions
- Resolves vegetation mortality
- Has optimizing LAI

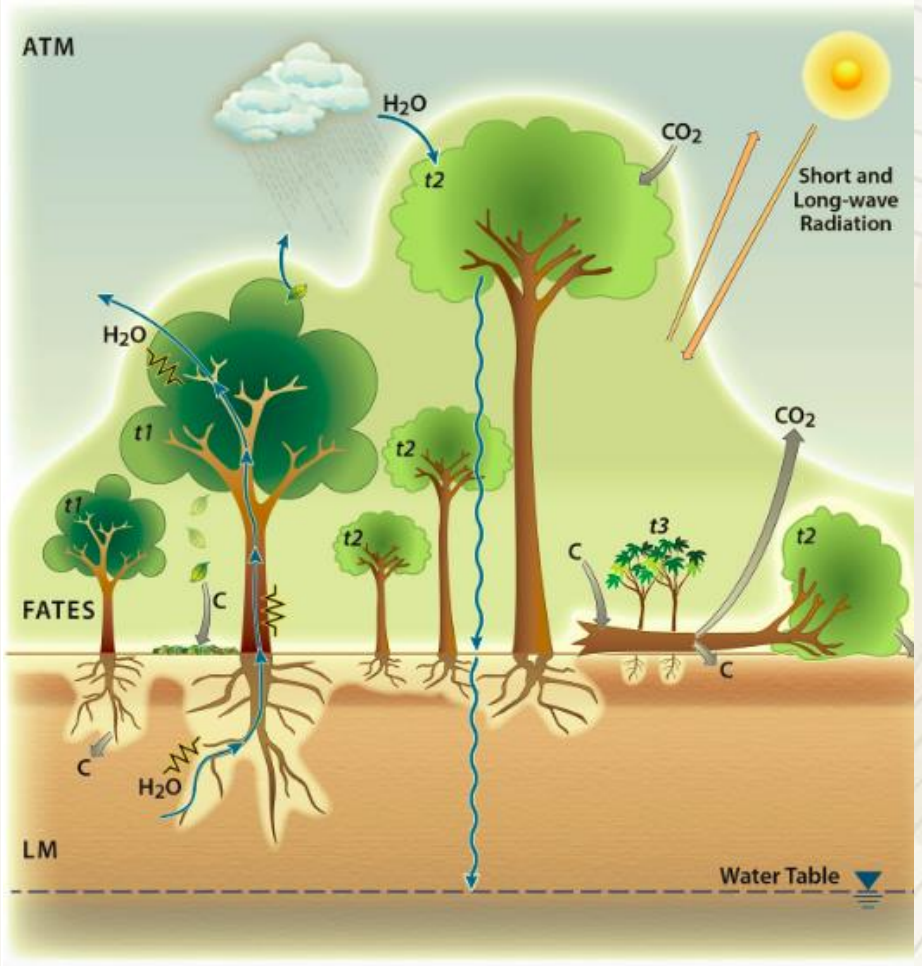


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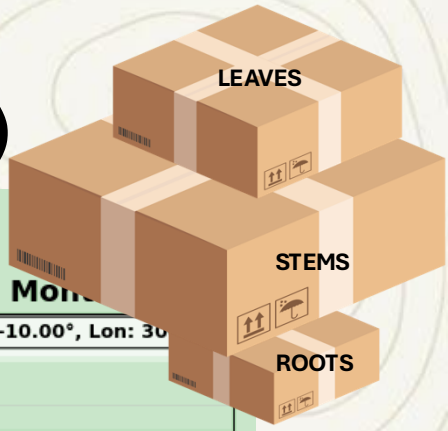
What new things does FATES do in NorESM?

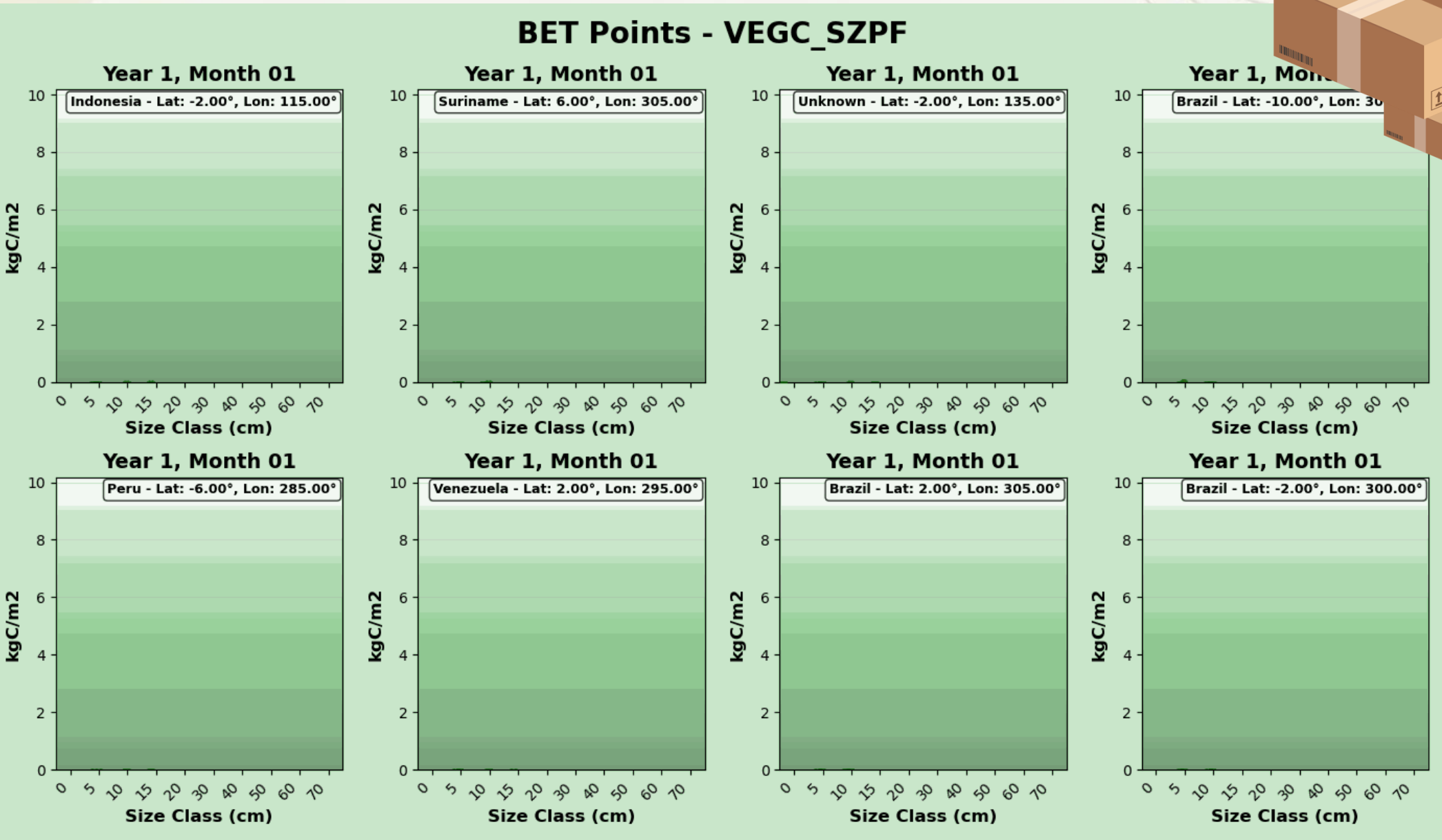
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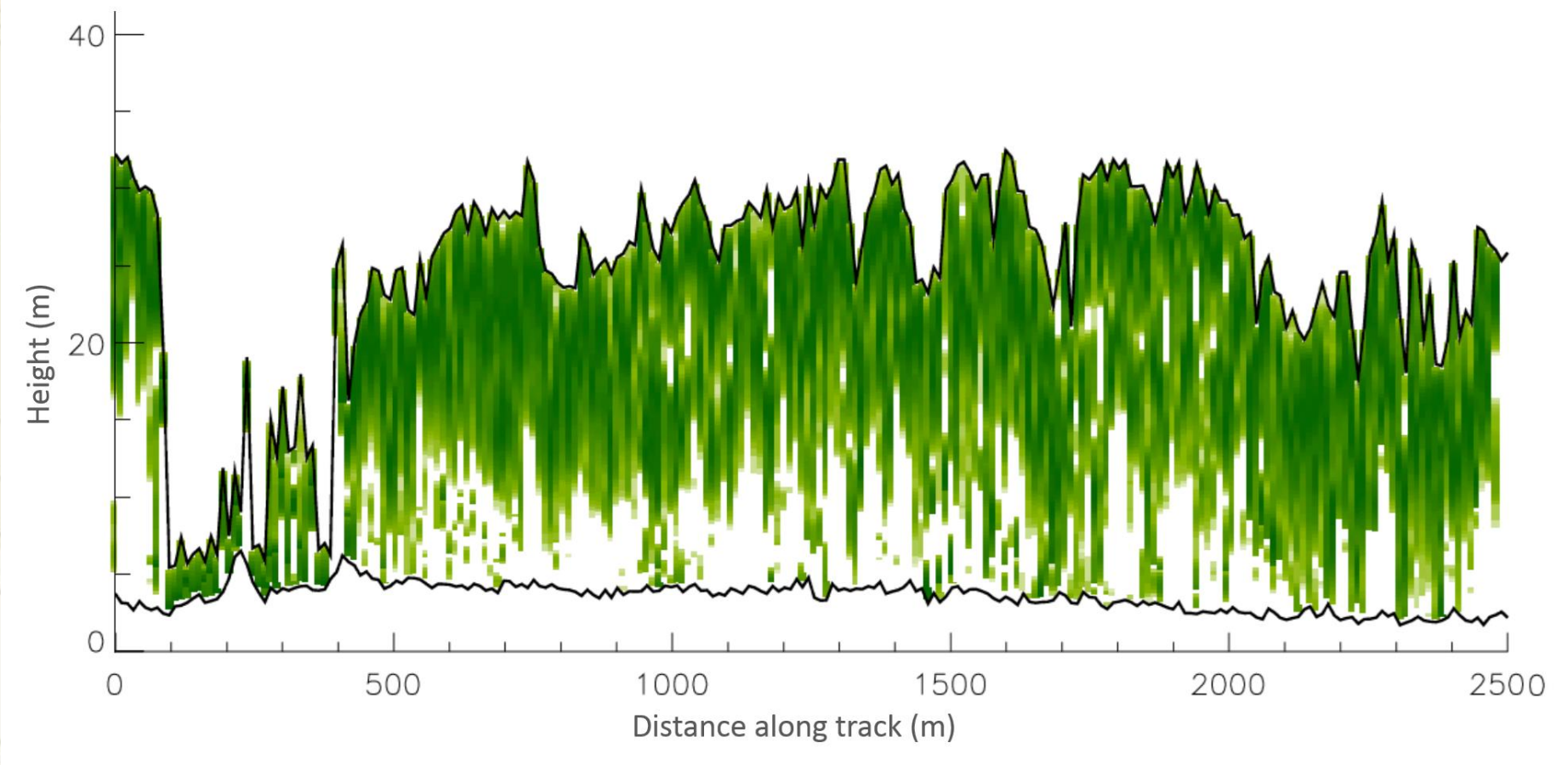
FATES resolves plant size (tropical evergreen)





What can we do when we resolve plant size?

- **Allocation** and allometry: dynamic tissue ratios
- Size structured impact of **fire**
- **Competition** for light between plants and self-thinning
- Dynamically varying **C:N ratio**s via (optional CN model)
- **Water** relations via (optional) FATES(HYDRO) scheme
- Comparison with **observations**…

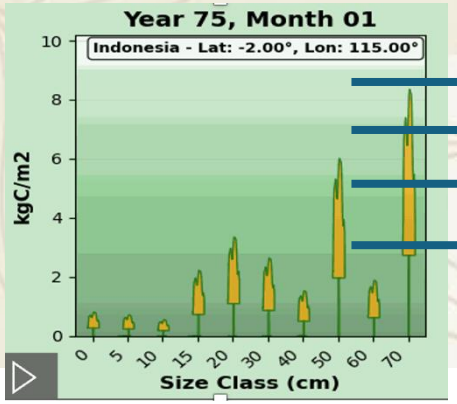


GEDI ECOSYSTEM LIDAR

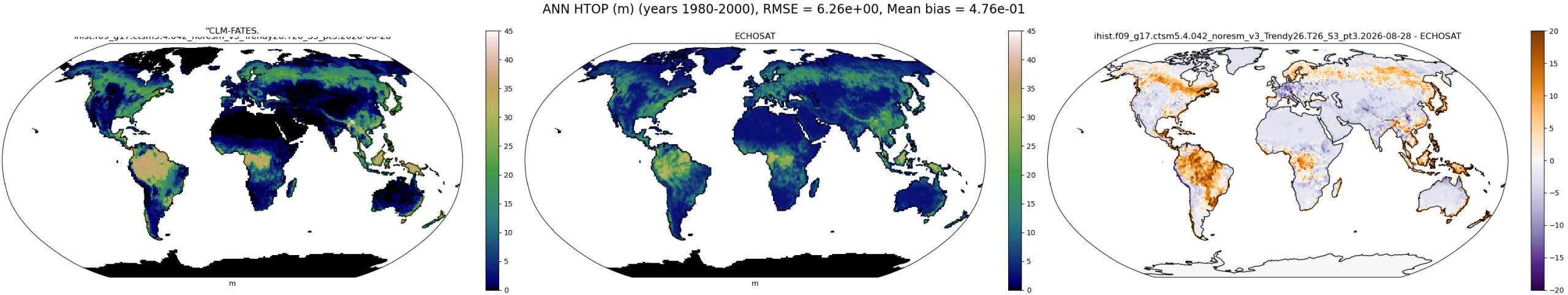
We can see vegetation structure from space.

But what exactly does the satellite data report?

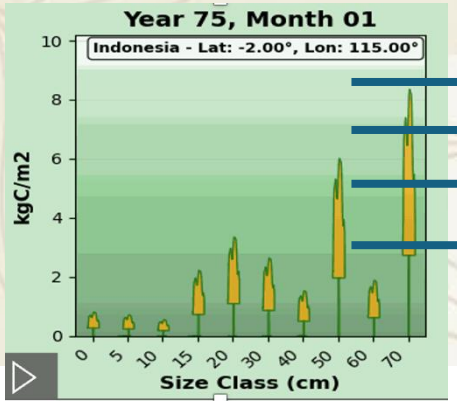
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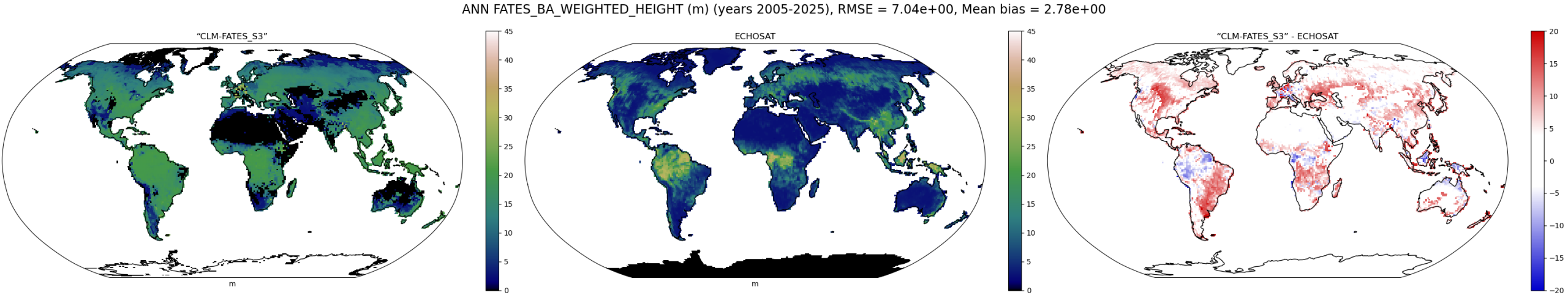
ECHOSAT canopy height vs. **Tallest tree (HTOP).**



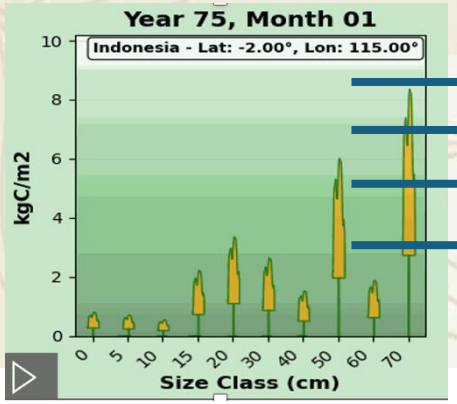
°CICERO



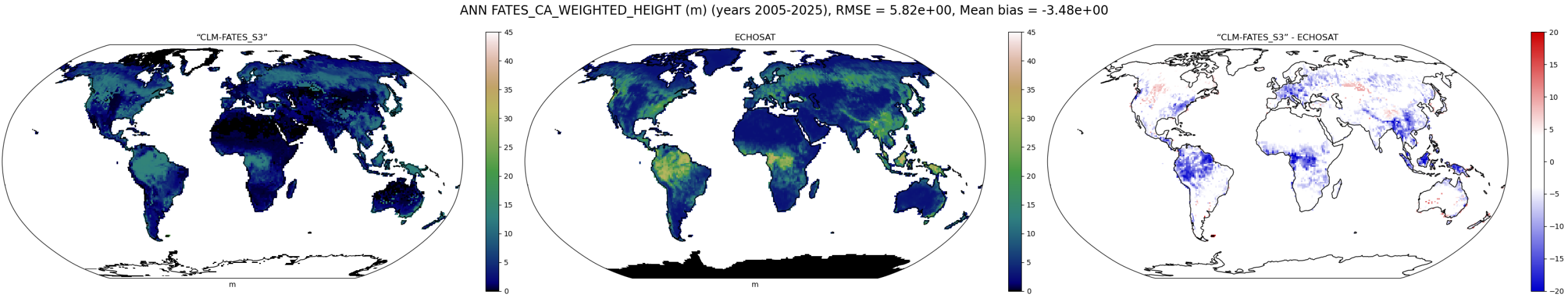
ECHOSAT canopy height vs. **Basal-area weighted height.**



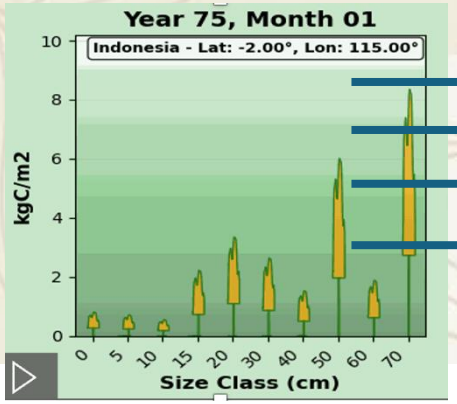
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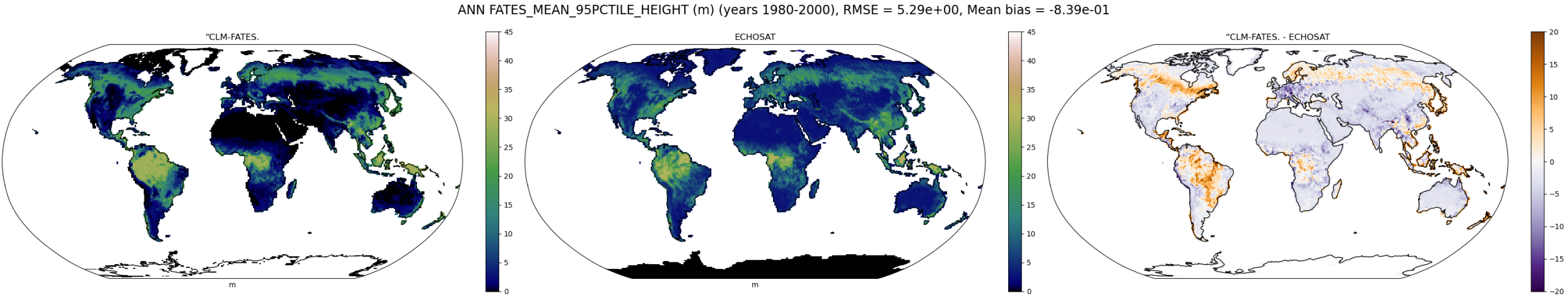
ECHOSAT canopy height vs. **Canopy-area weighted height.**



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ECHOSAT canopy height vs. **95th percentile tree height.**



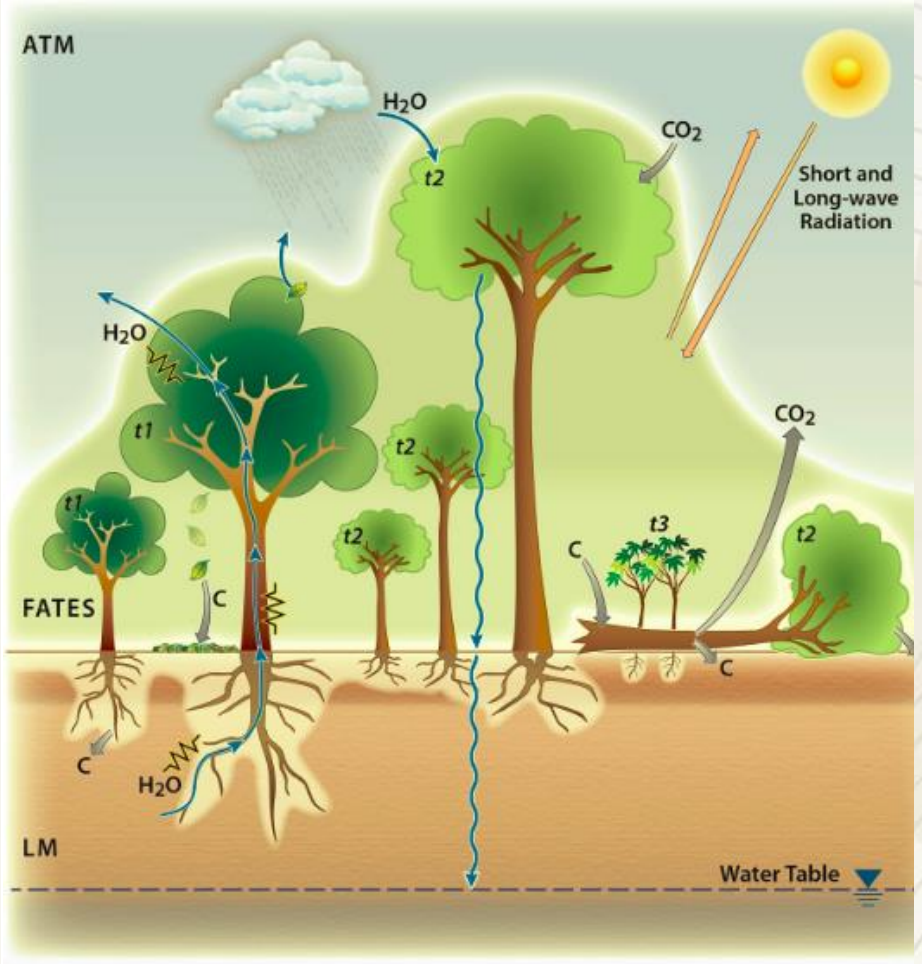
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By resolving plant size, we can come directly to satellite observation of canopy height…

What new things does FATES do in NorESM?

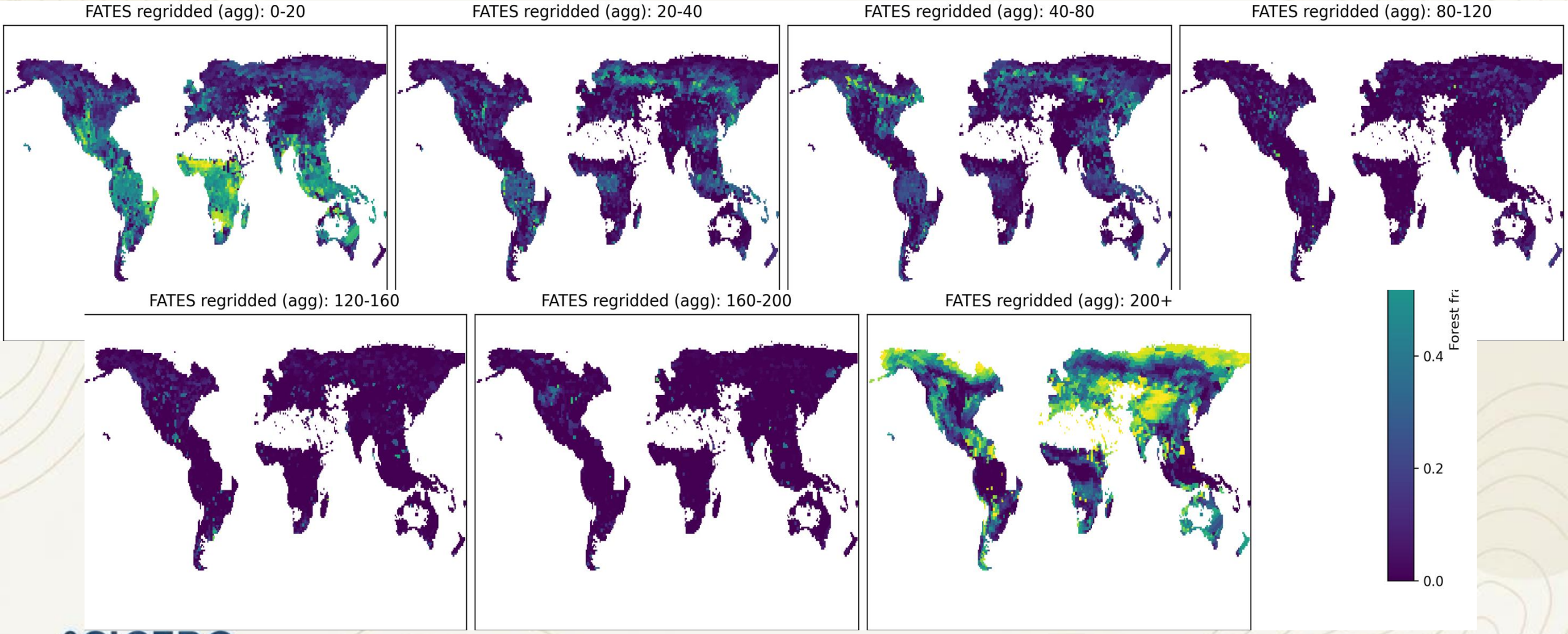
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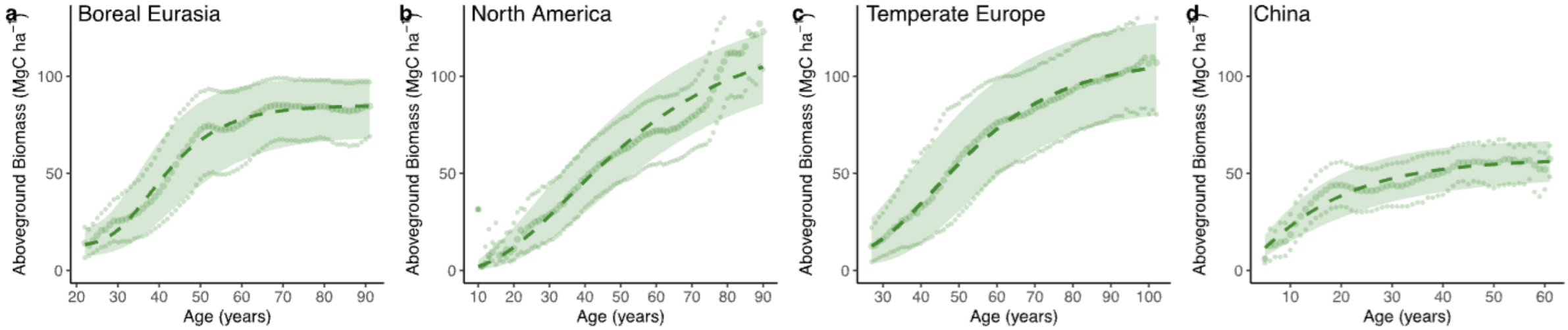
FATES resolves ecosystem ‘age-since-disturbance’



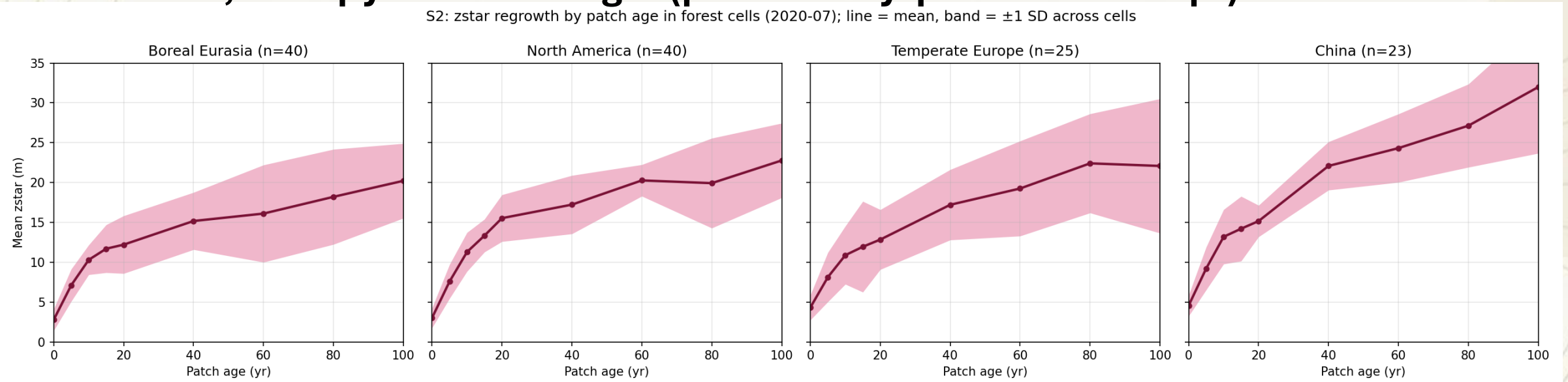
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Comparison with satellite retrieved growth curves

O'Sullivan t al. 2024, aboveground biomass



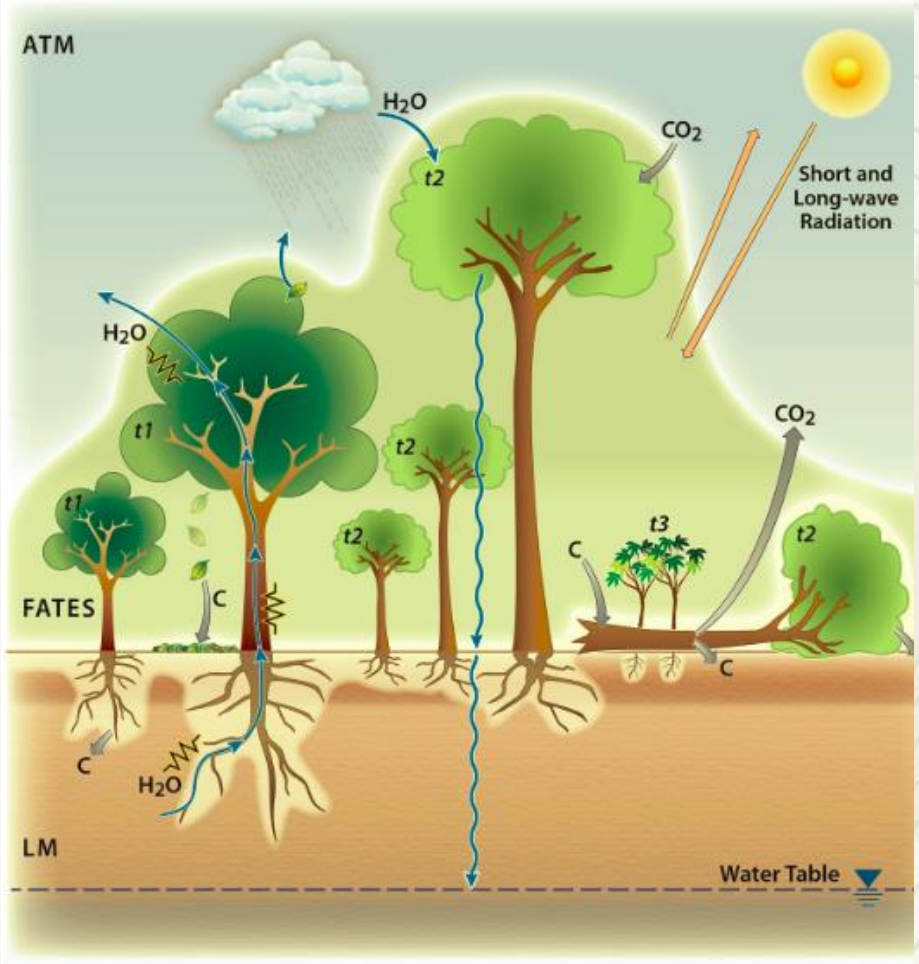
CLM-FATES, canopy closure height (preliminary/proof of concept)



What new things does FATES do in NorESM?

(and why do they matter?)

- Resolves plant size
- Resolves ecosystem age since disturbance
- **Resolves gross land use transitions**
- Resolves vegetation mortality
- Has optimizing LAI

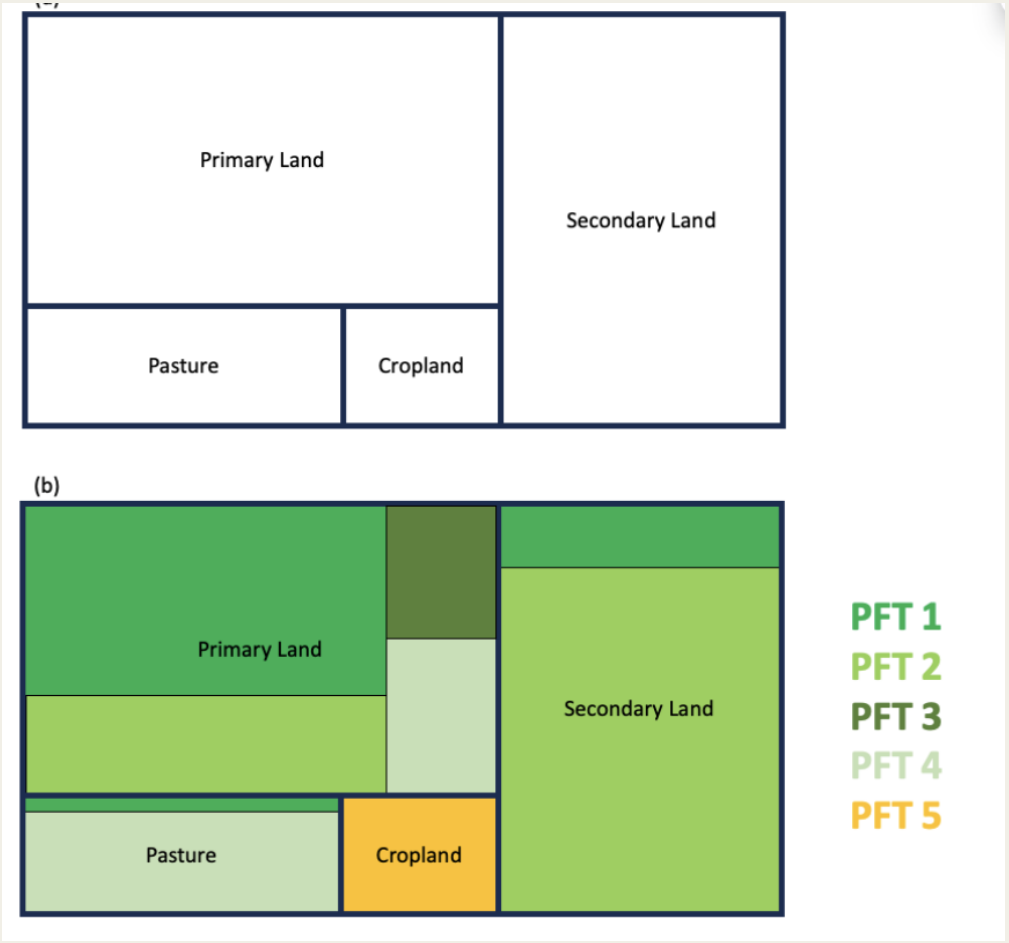


Land use in FATES



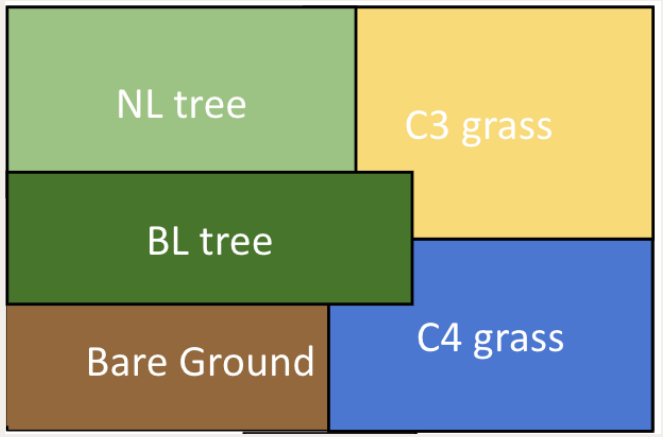
Koven et al. in prep

CLM-FATES land use tiling



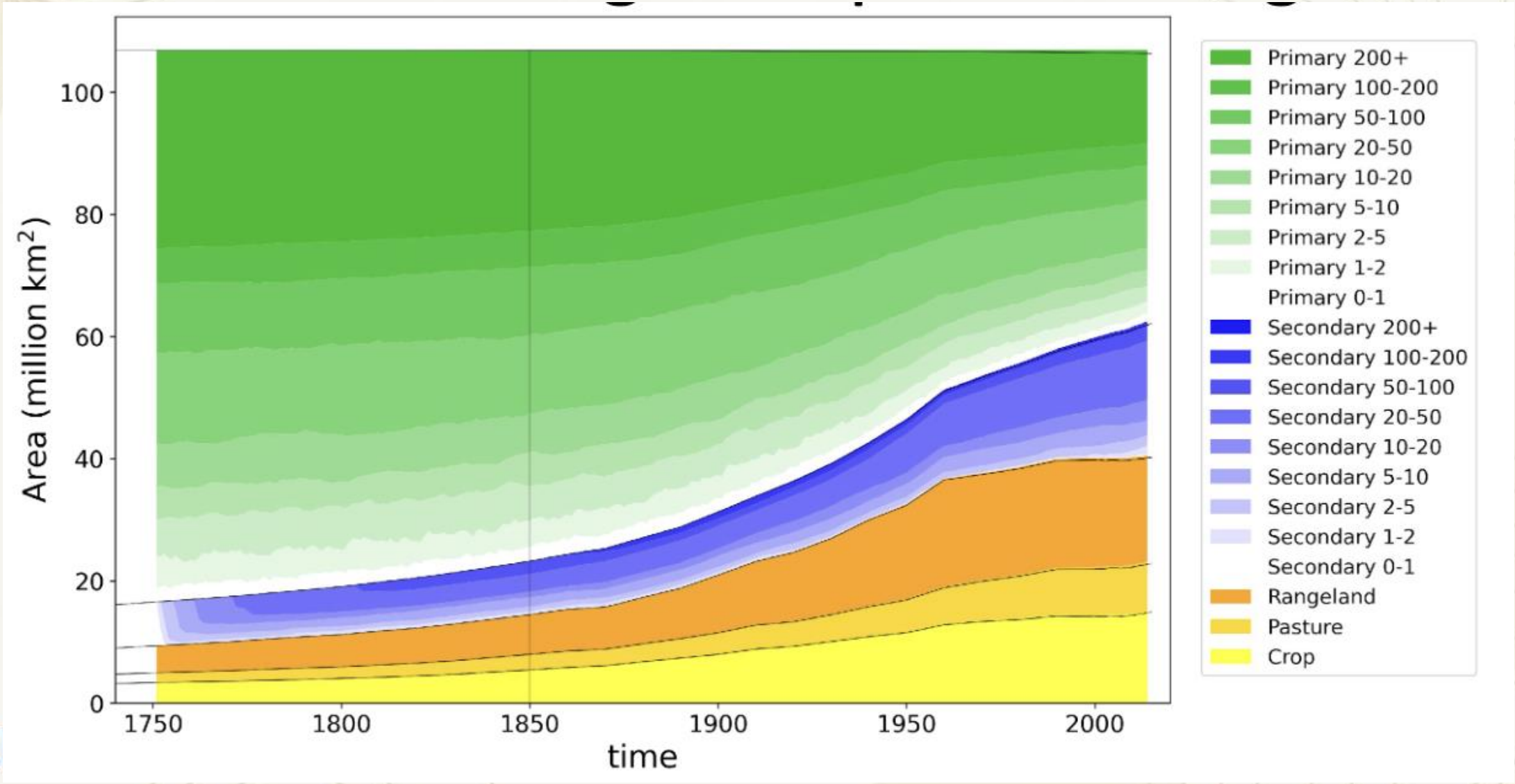
BIG LEAF MODEL

No age classes or land use classes



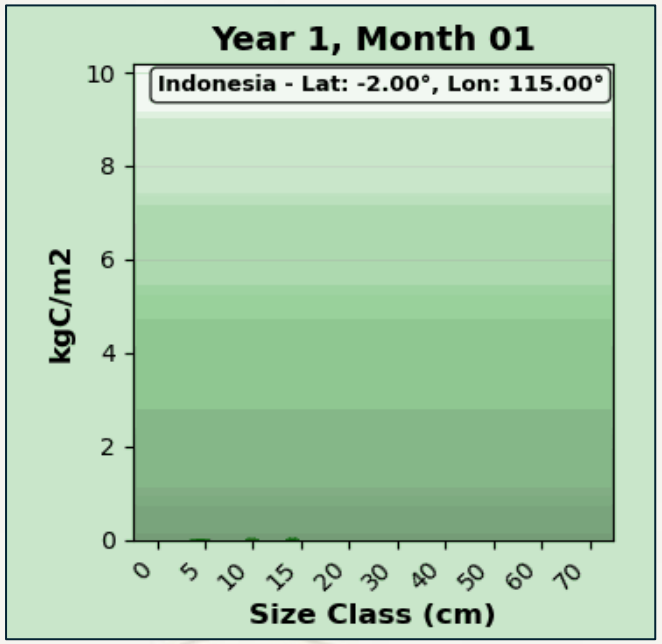
Land use categories in FATES

(Primary, Secondary, Rangeland, Pasture, Crop*)



°CICE

Demographic models have a memory of the state of the ecosystem after harvest, clearcutting etc.



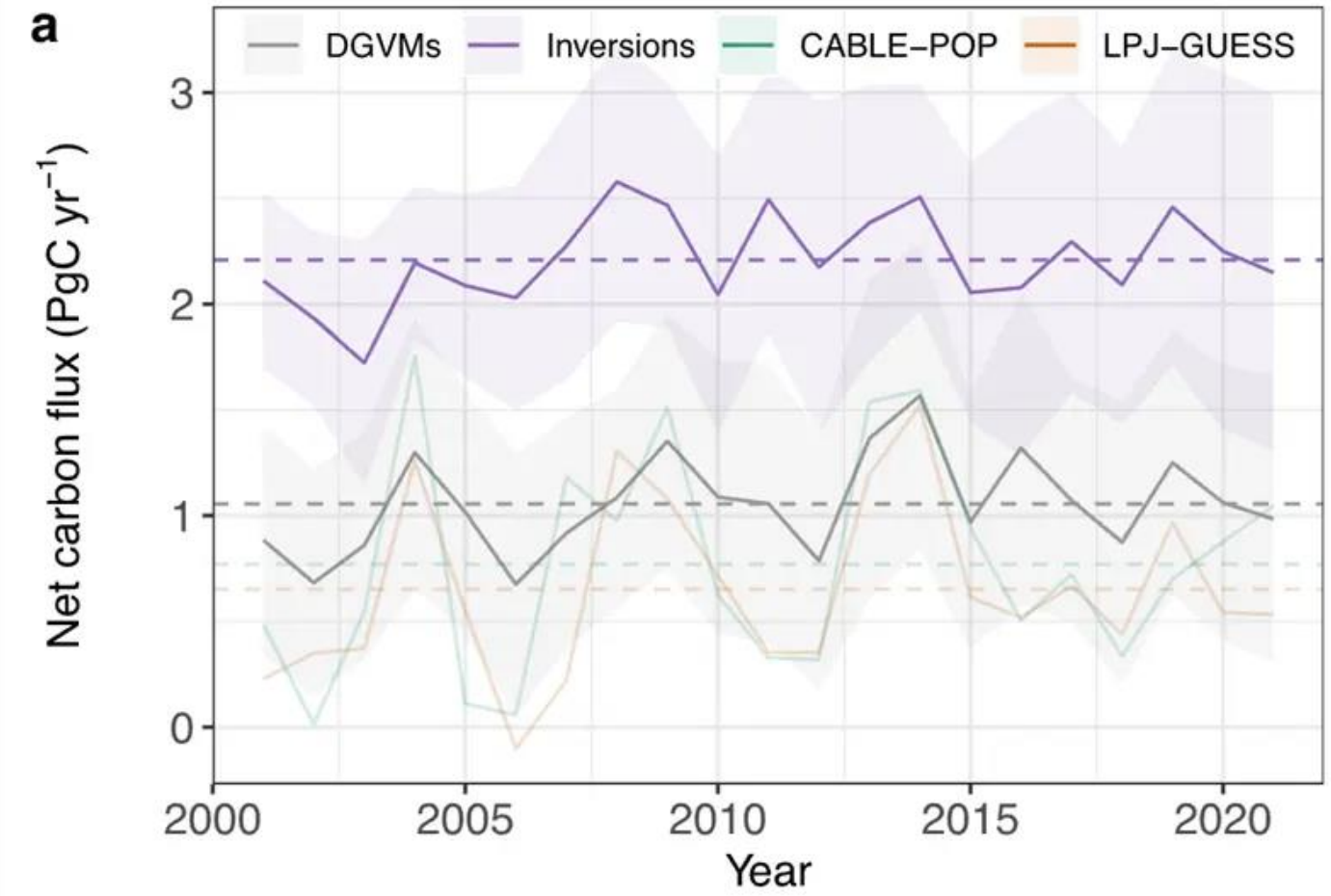
”Big Leaf” models, without demography, are ‘**hedge trimming**’ .Ecosystem can grow back immediately & does not **remember** past land use.



CICERO

Northern latitude carbon sink

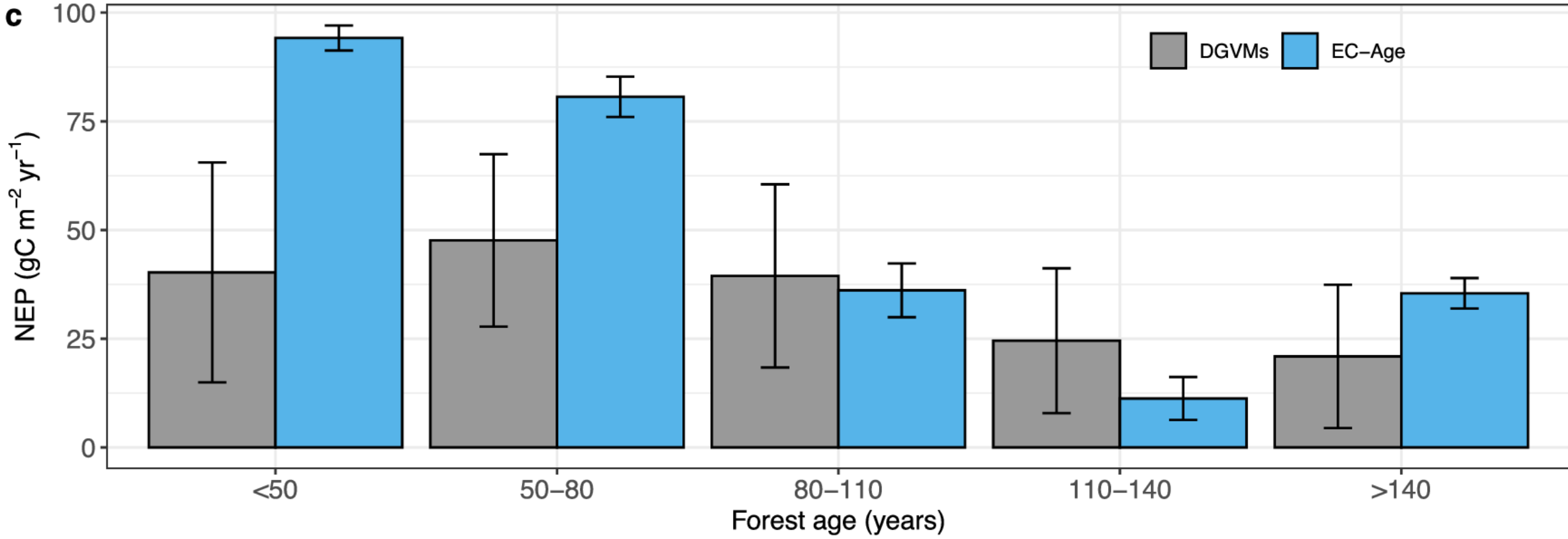
CMIP6 land models **cannot capture** global carbon dynamics **sinks**



O'Sullivan et al. Nature Comunications, 2024

Northern latitude carbon sink

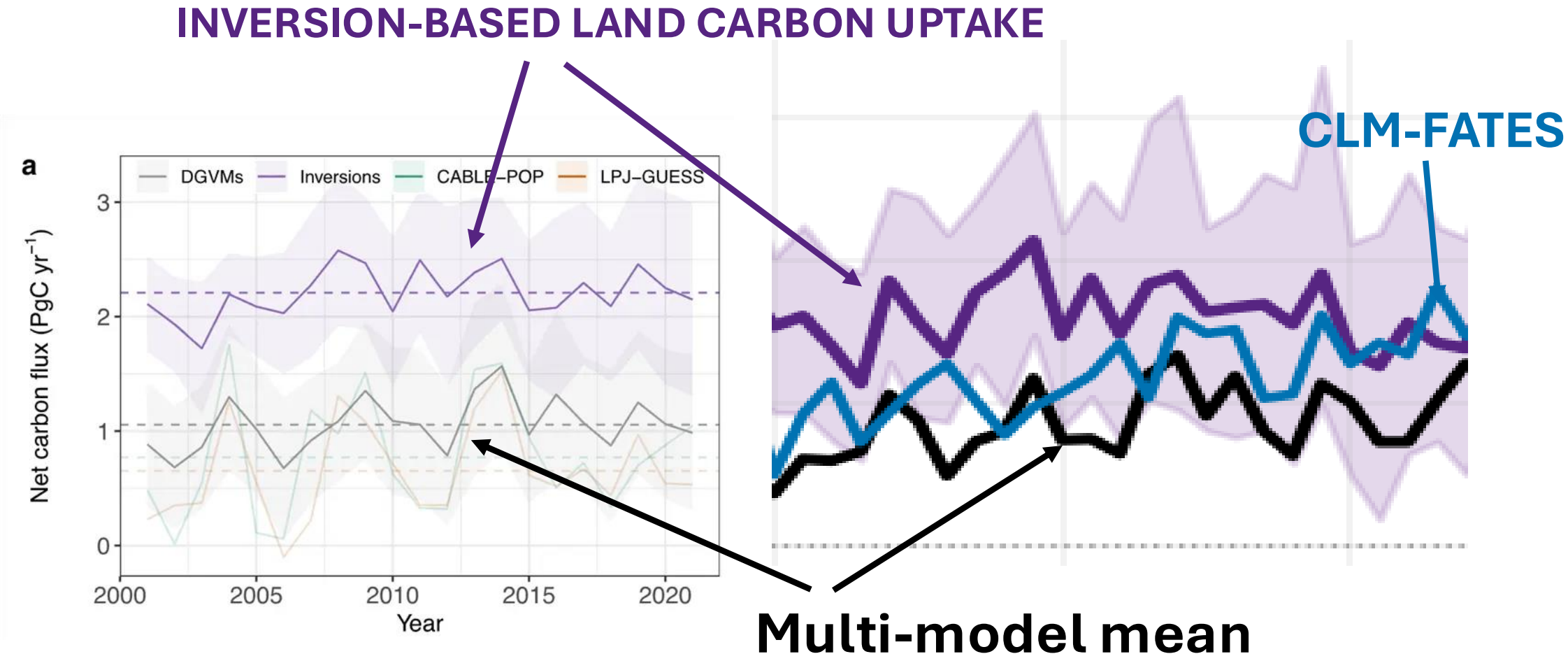
CMIP6 land models **cannot capture** global carbon dynamics **sinks**



°CICERO

O'Sullivan et al. Nature Comunications, 2024

FATES gets us closer to the Northern hemisphere carbon sink



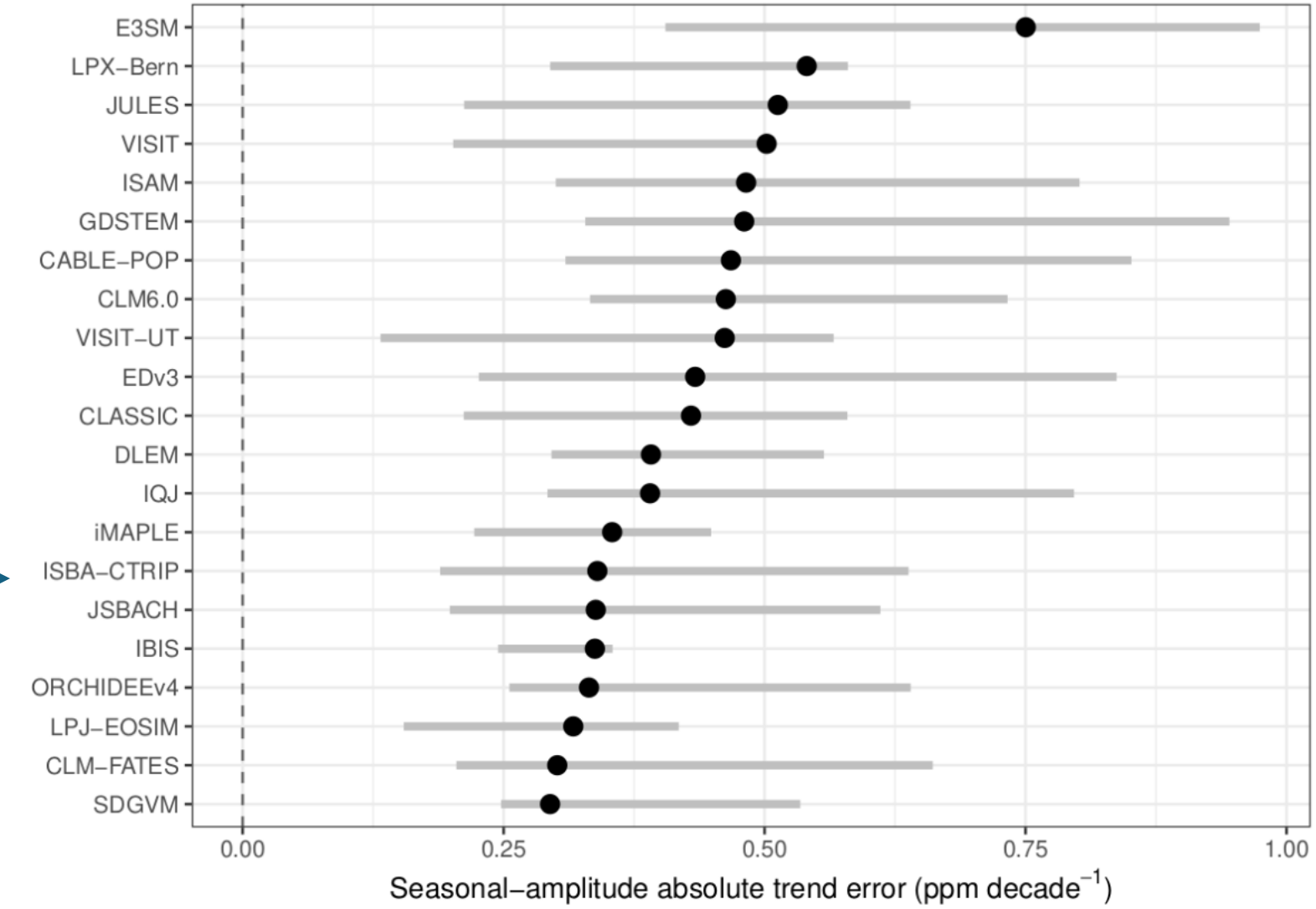
O'Sullivan et al. 2024

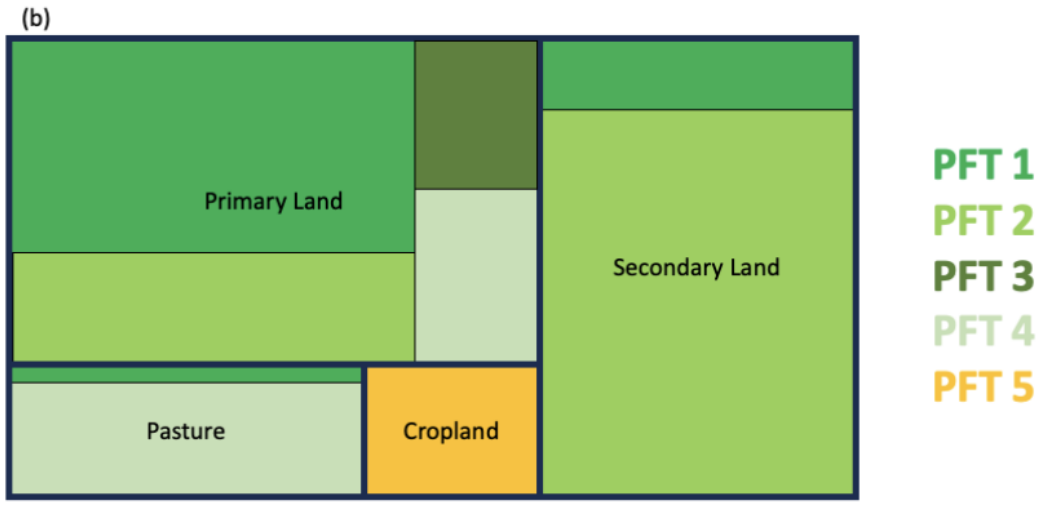
Global Carbon Budget 2026

Absolute error in the trend of the CO_2 seasonal amplitude (ppm decade^{-1})

Global
Carbon
Budget
2026

Trend in ***IAV*** of northern hemisphere CO2



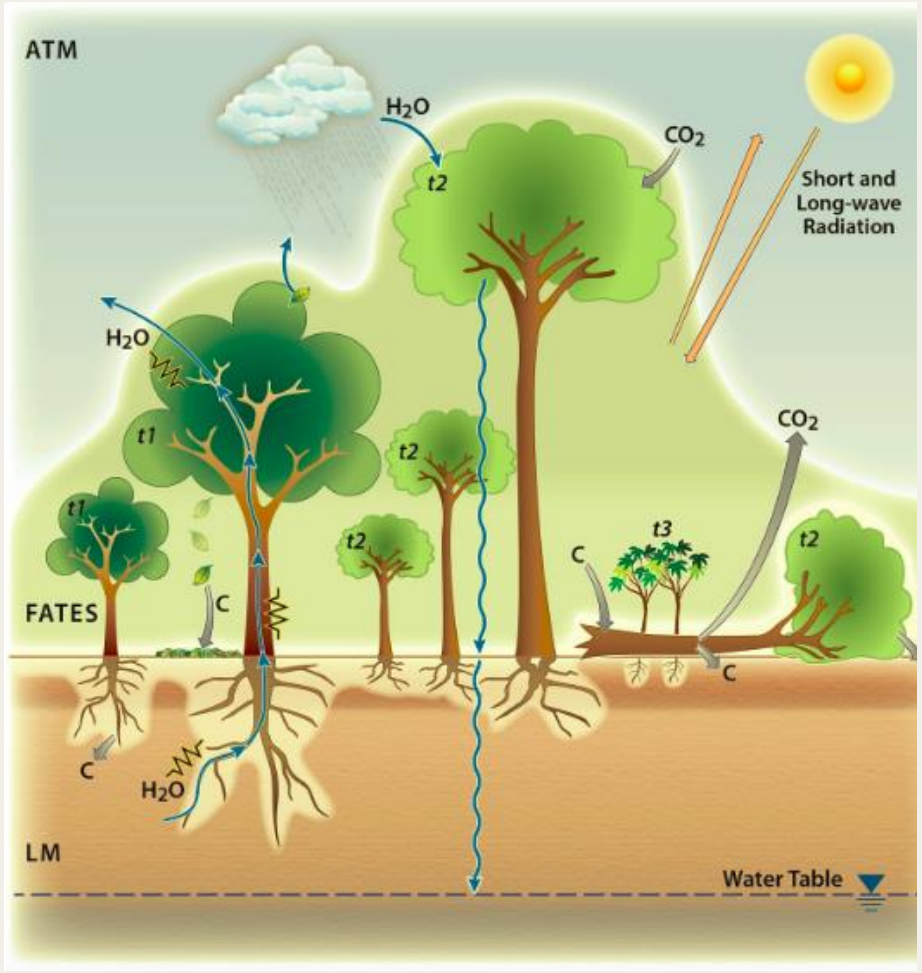


Summary: Representing gross land use change and ecosystem age structure allows us to capture the regrowth of the NH carbon sink

What new things does FATES do in NorESM?

(and why do they matter?)

- Resolves plant size
- Resolves ecosystem age since disturbance
- Resolves gross land use transitions
- **Resolves vegetation mortality**
- Has optimizing LAI



Ecosystem tipping points and vegetation mortality.



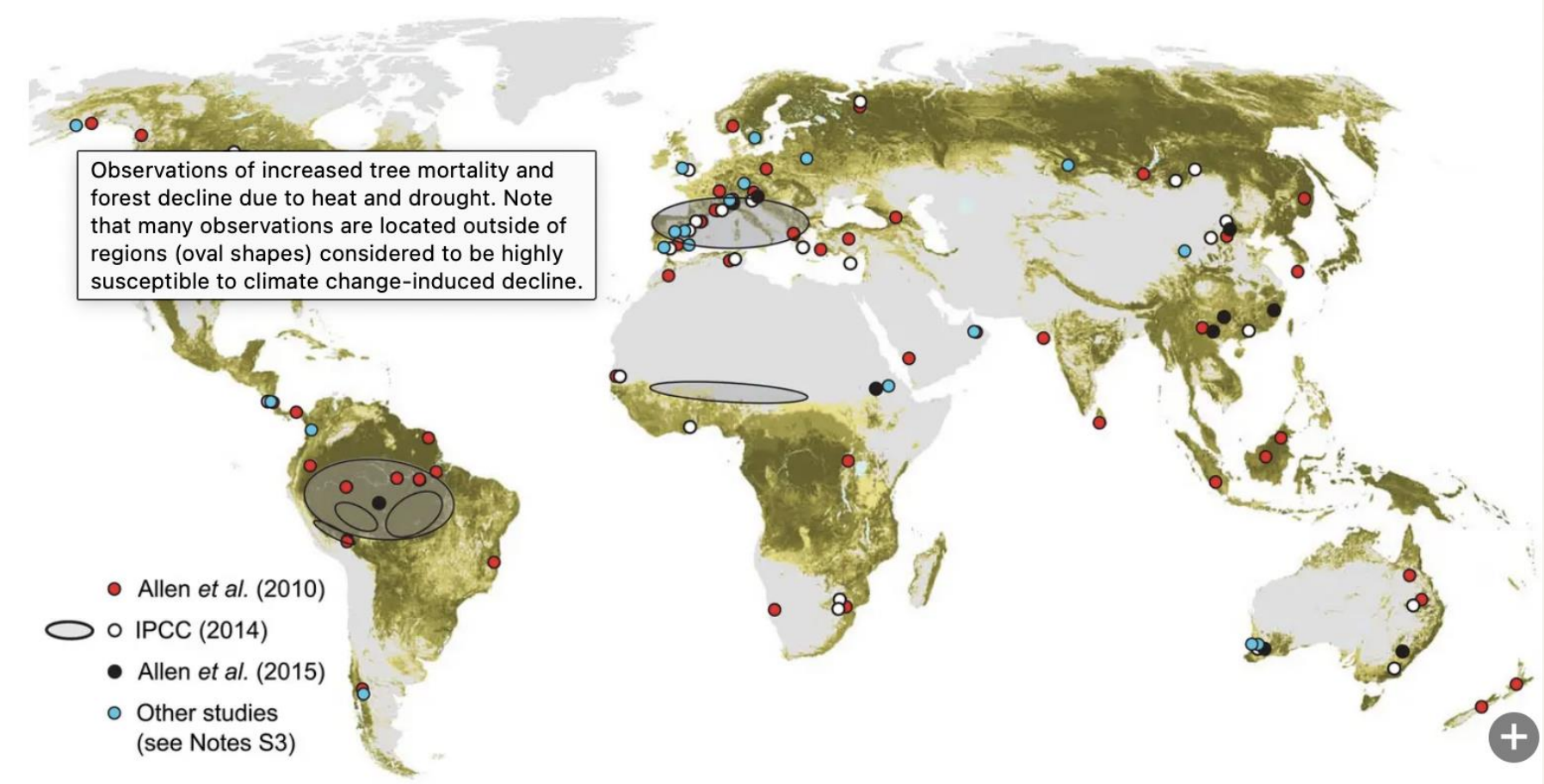
Trees killed by drought (California)



Trees killed by fire (Colorado)

CICERO

Ecosystem tipping points and vegetation mortality.



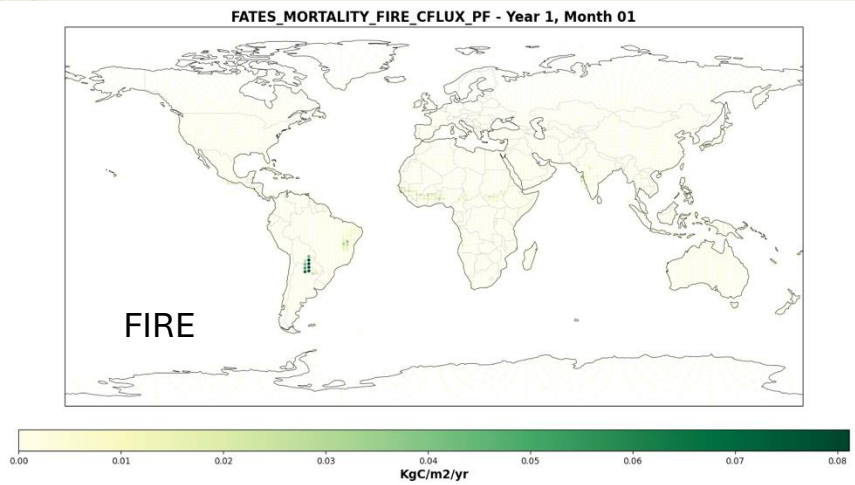
FATES mortality processes

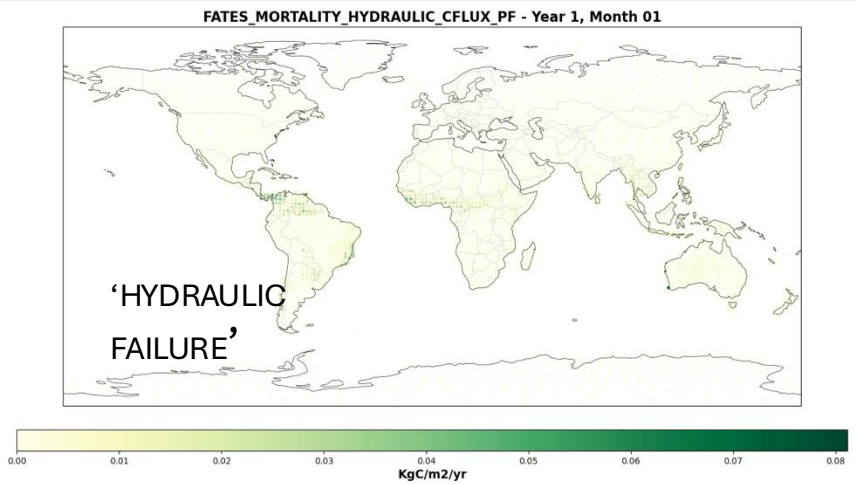
- Background
- Carbon Starvation
- ‘Hydraulic Failure’
- Fire
- Logging
- ‘Impact’
- Freezing
- Size-induced
- Termination

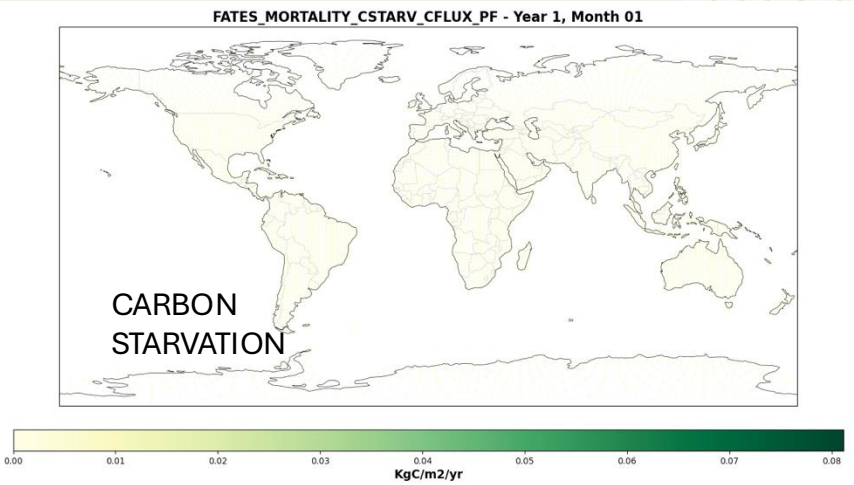
CICERO

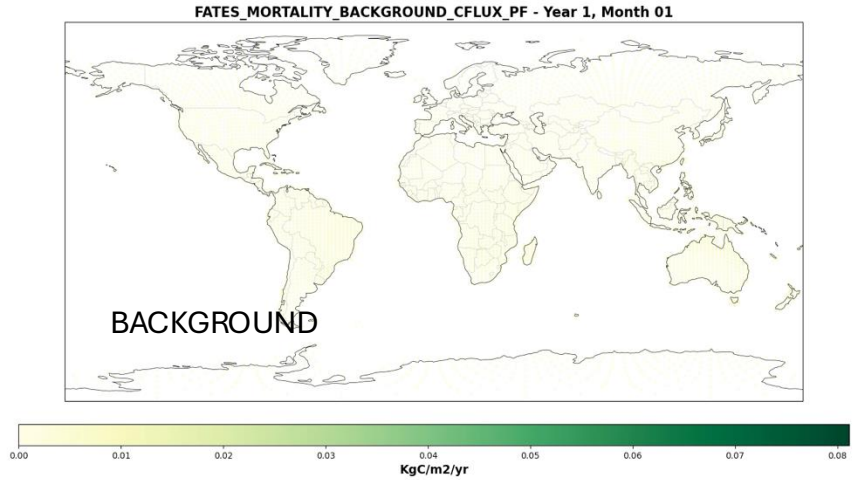
Hartman et al 2021. International Tree Mortality Network

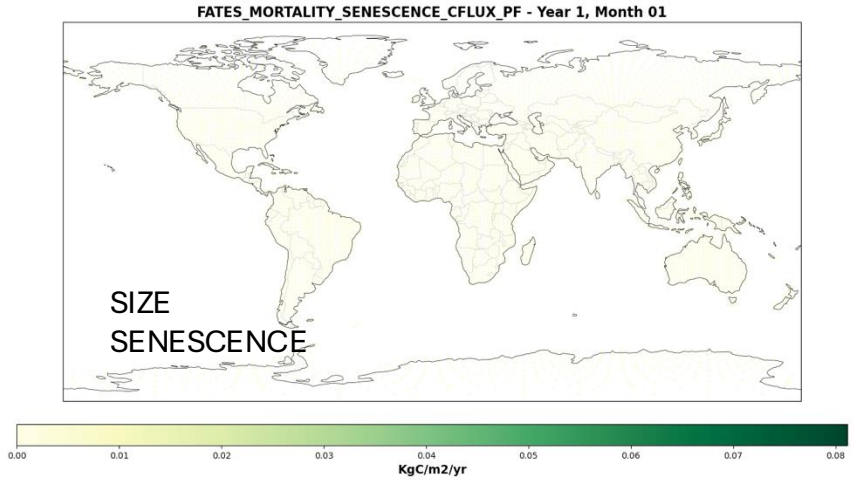
Vegetation mortality processes in FATES.

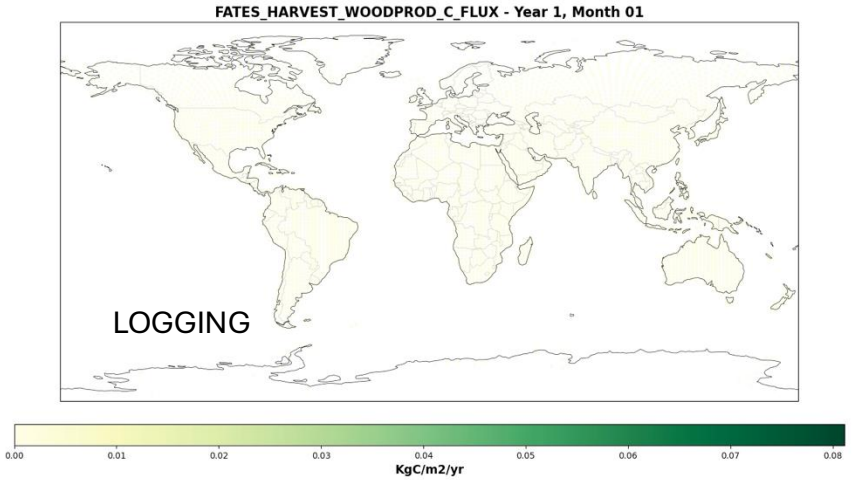






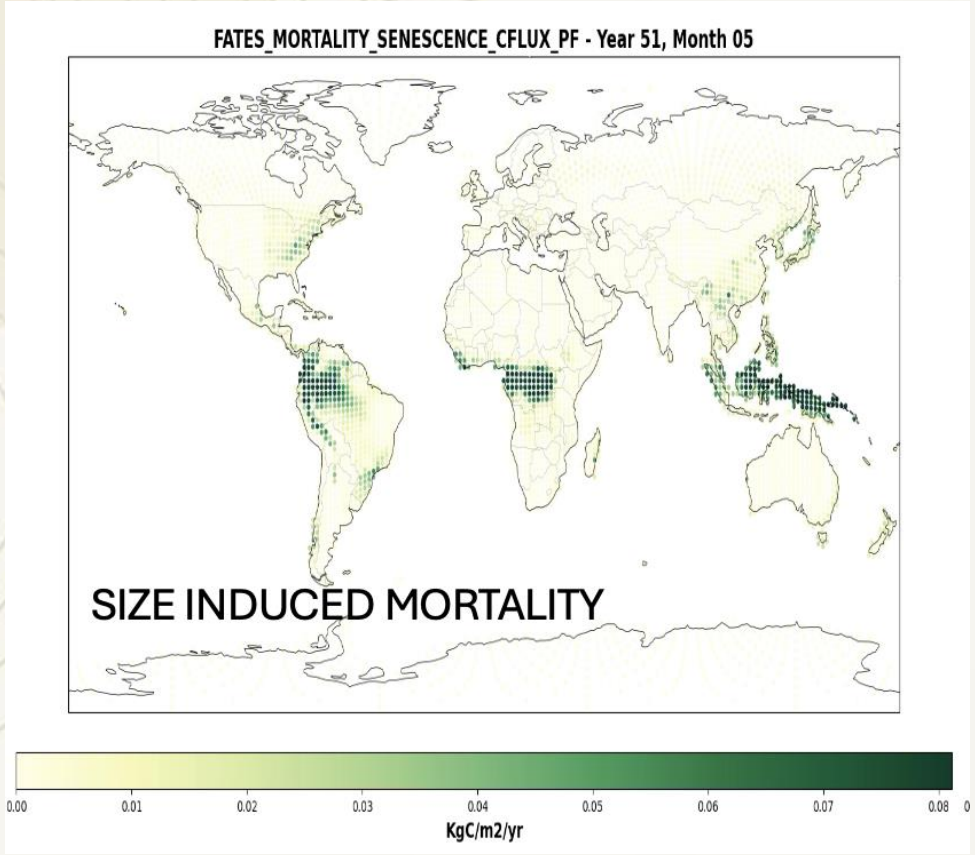






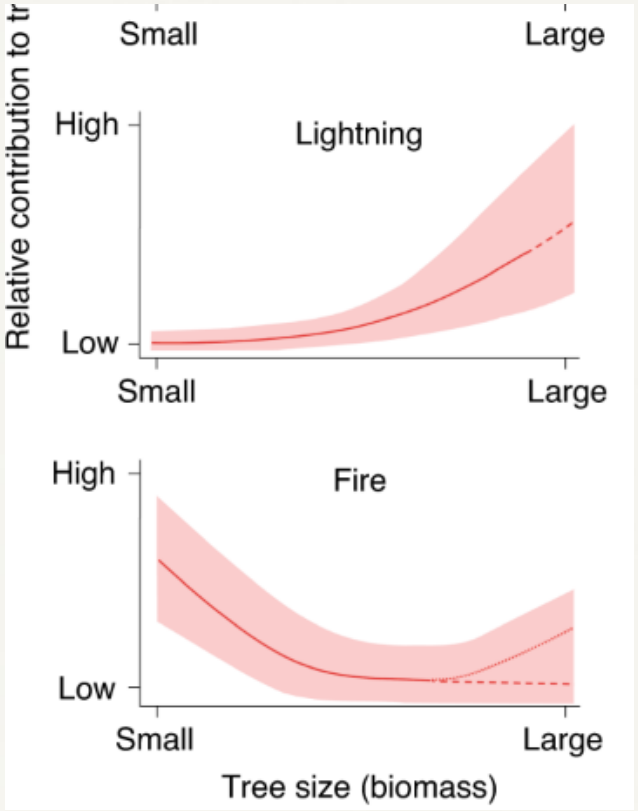
CICERO

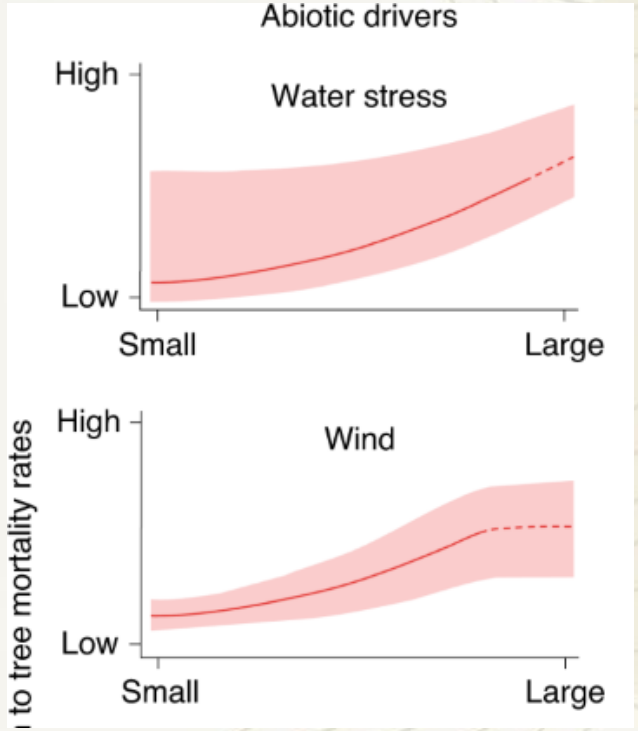
Many methods of plant death scale with size...



Implications of size-dependent tree mortality for tropical forest carbon dynamics

Evan M. Gora & Adriane Esquivel-Muelbert

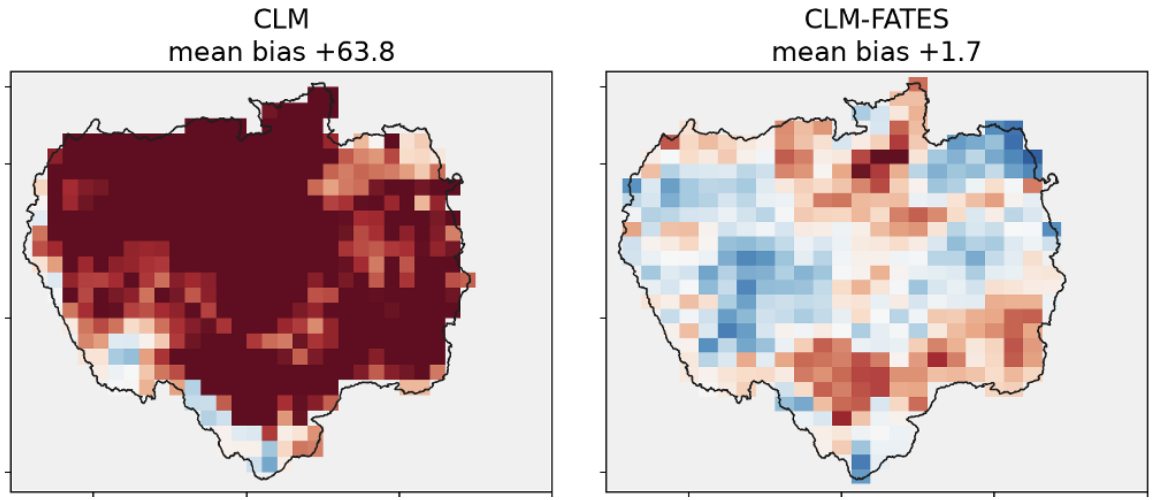


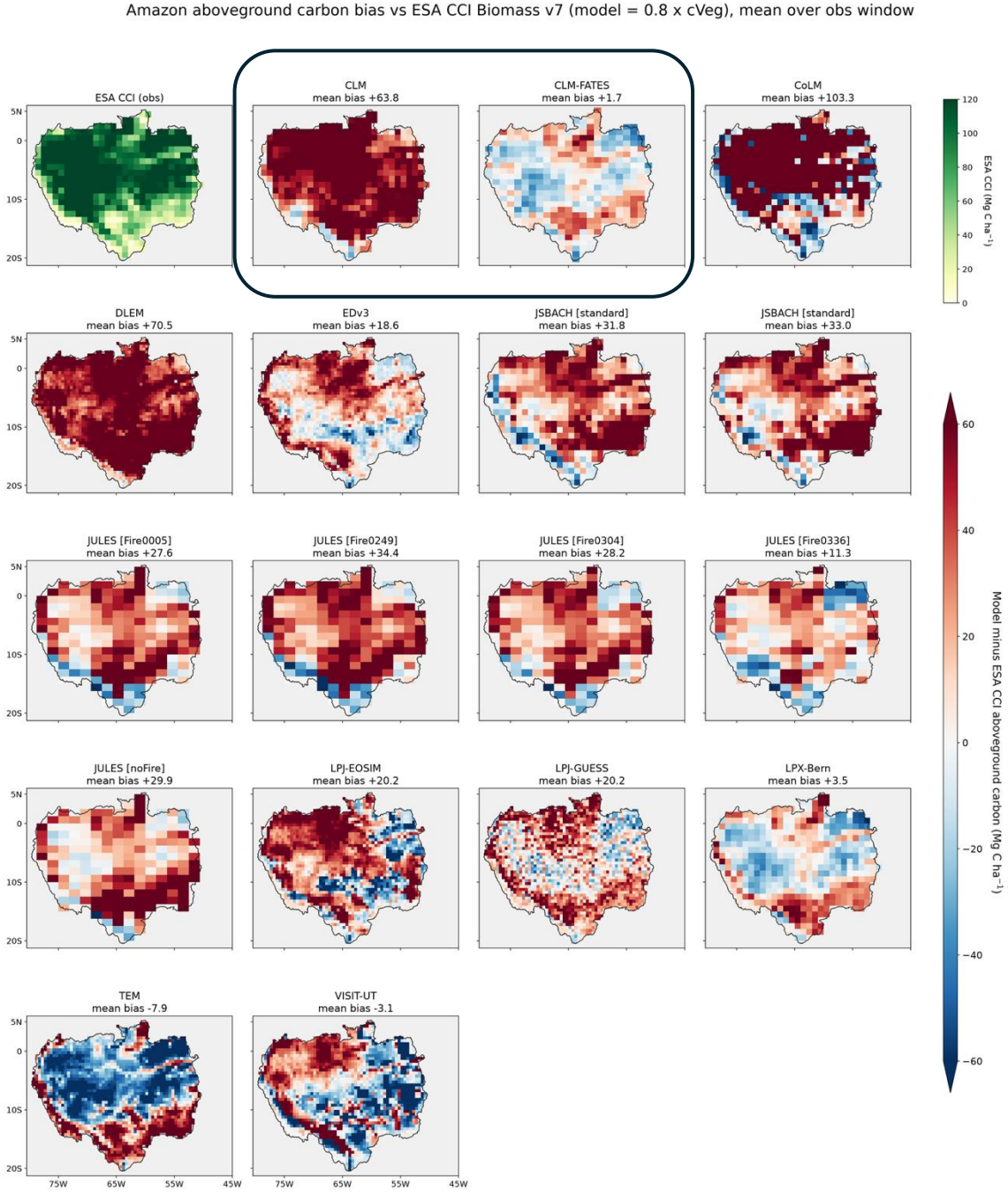


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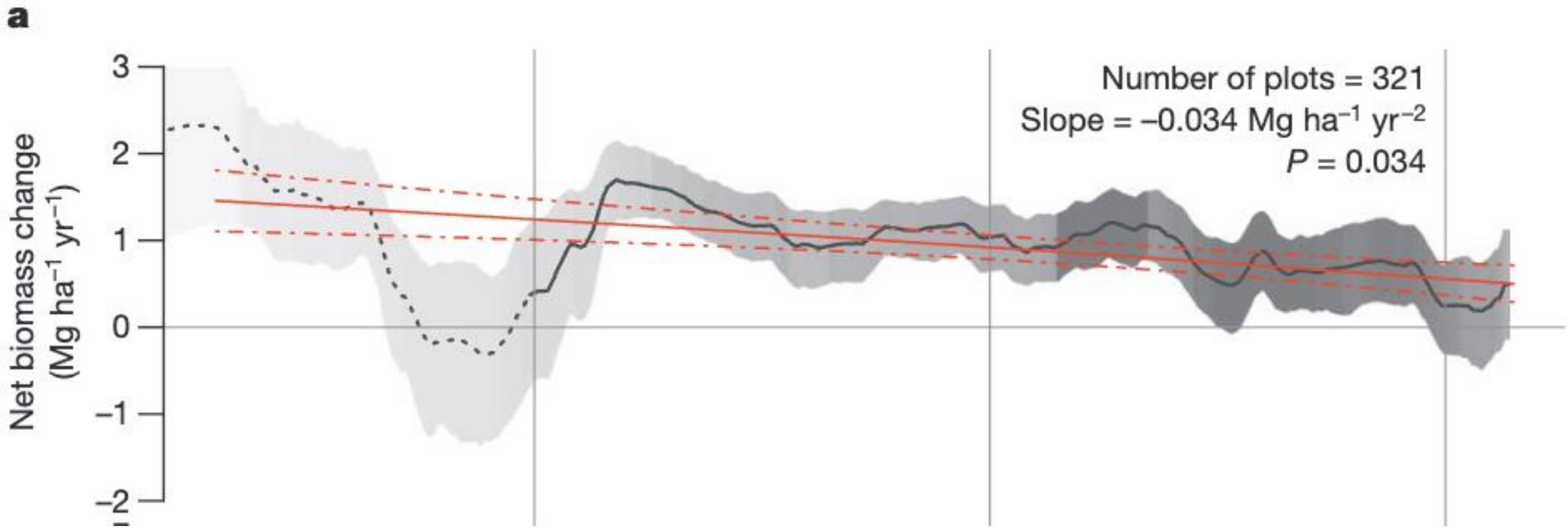
Bias vs biomass change (ESACCI)

- Many models predict higher **gains in Amazon vegetation carbon** than observed.
- **What is it** that causes models to do this?

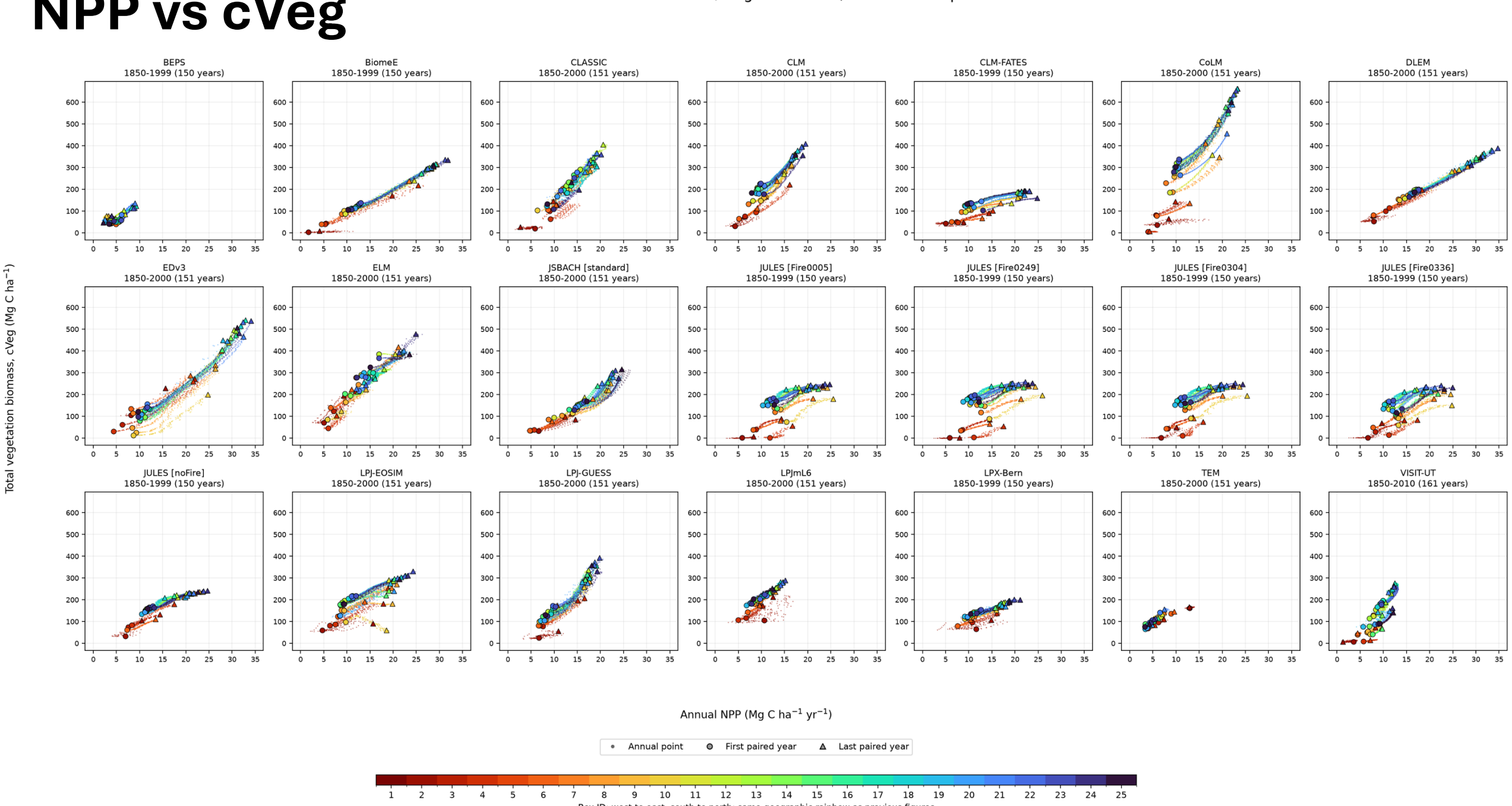




- Biomass change in the Amazon is **trending towards 0**… (Brienen et al. 2015)

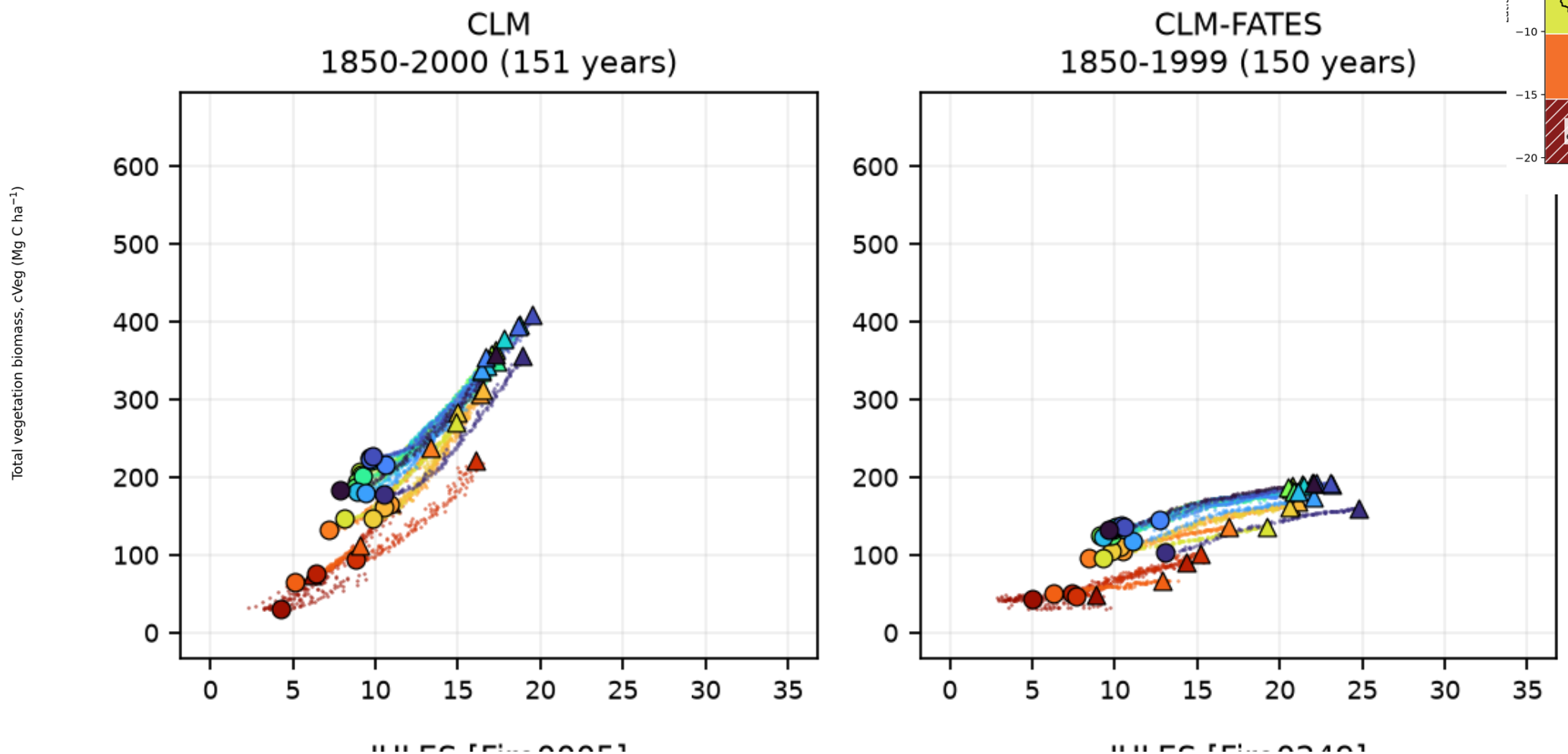


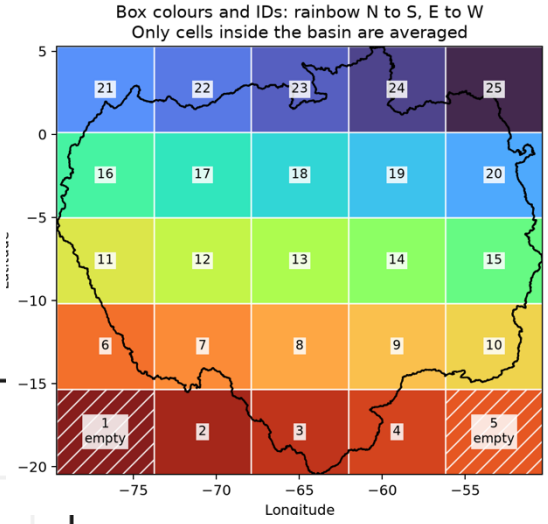
NPP vs cVeg


Amazon 1% CO2 BGC | NPP versus total vegetation biomass
Annual means in 5 x 5 latitude/longitude boxes; full available paired run
BEPS
1850-1999 (150 years)
BiomeE
1850-1999 (150 years)
CLASSIC
1850-2000 (151 years)
CLM
1850-2000 (151 years)
CLM-FATES
1850-1999 (150 years)
CoLM
1850-2000 (151 years)
DLEM
1850-2000 (151 years)
EDv3
1850-2000 (151 years)
ELM
1850-2000 (151 years)
JSBACH [standard]
1850-2000 (151 years)
JULES [Fire0005]
1850-1999 (150 years)
JULES [Fire0249]
1850-1999 (150 years)
JULES [Fire0304]
1850-1999 (150 years)
JULES [Fire0336]
1850-1999 (150 years)
JULES [noFire]
1850-1999 (150 years)
LPJ-EOSIM
1850-2000 (151 years)
LPJ-GUESS
1850-2000 (151 years)
LPJmL6
1850-2000 (151 years)
LPX-Bern
1850-1999 (150 years)
TEM
1850-2000 (151 years)
VISIT-UT
1850-2010 (161 years)
Total vegetation biomass, cVeg (Mg C ha−1)
Annual NPP (Mg C ha−1 yr−1)
Annual point
First paired year
Last paired year

NPP vs cVeg

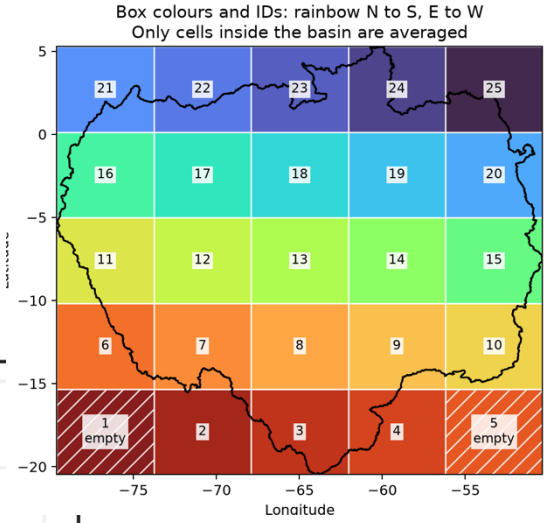
Amazon 1% CO2 BGC | NPP versus total vegetation biomass
Annual means in 5 x 5 latitude/longitude boxes; full available paired run

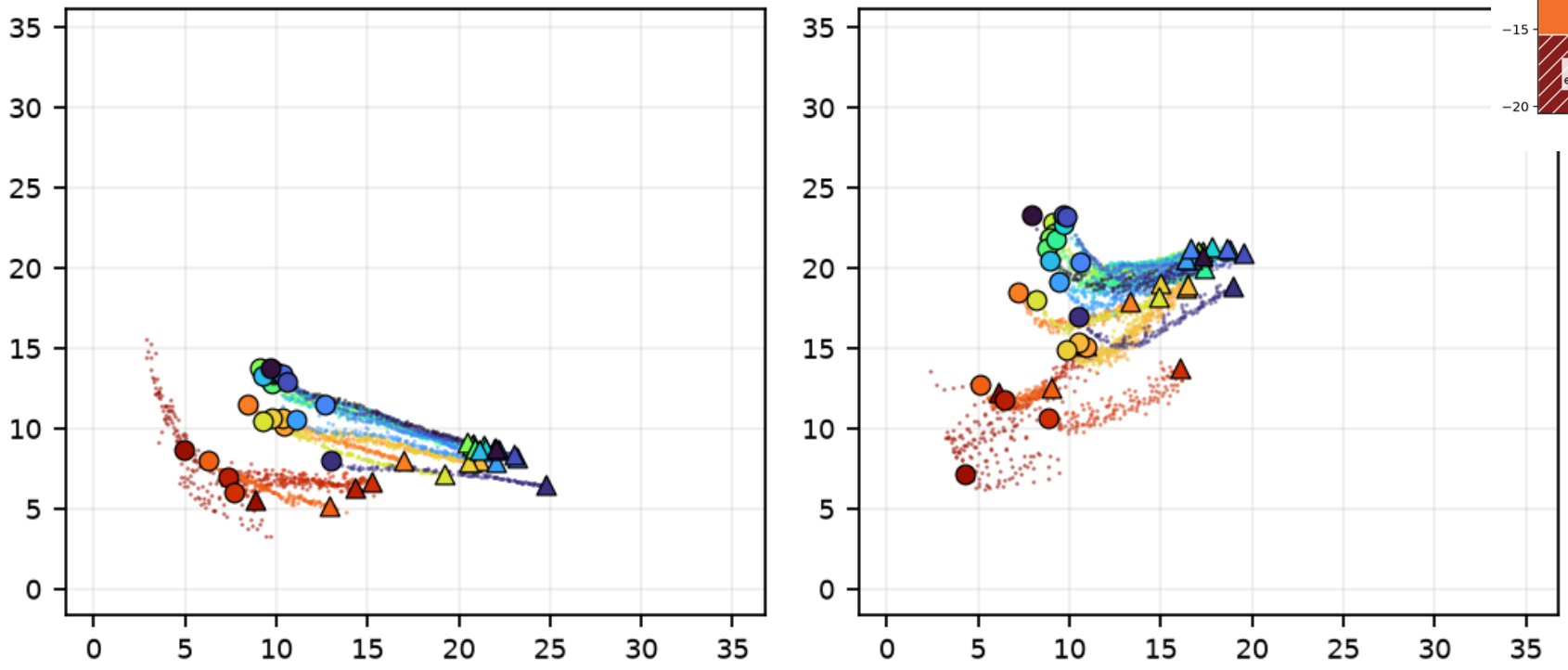




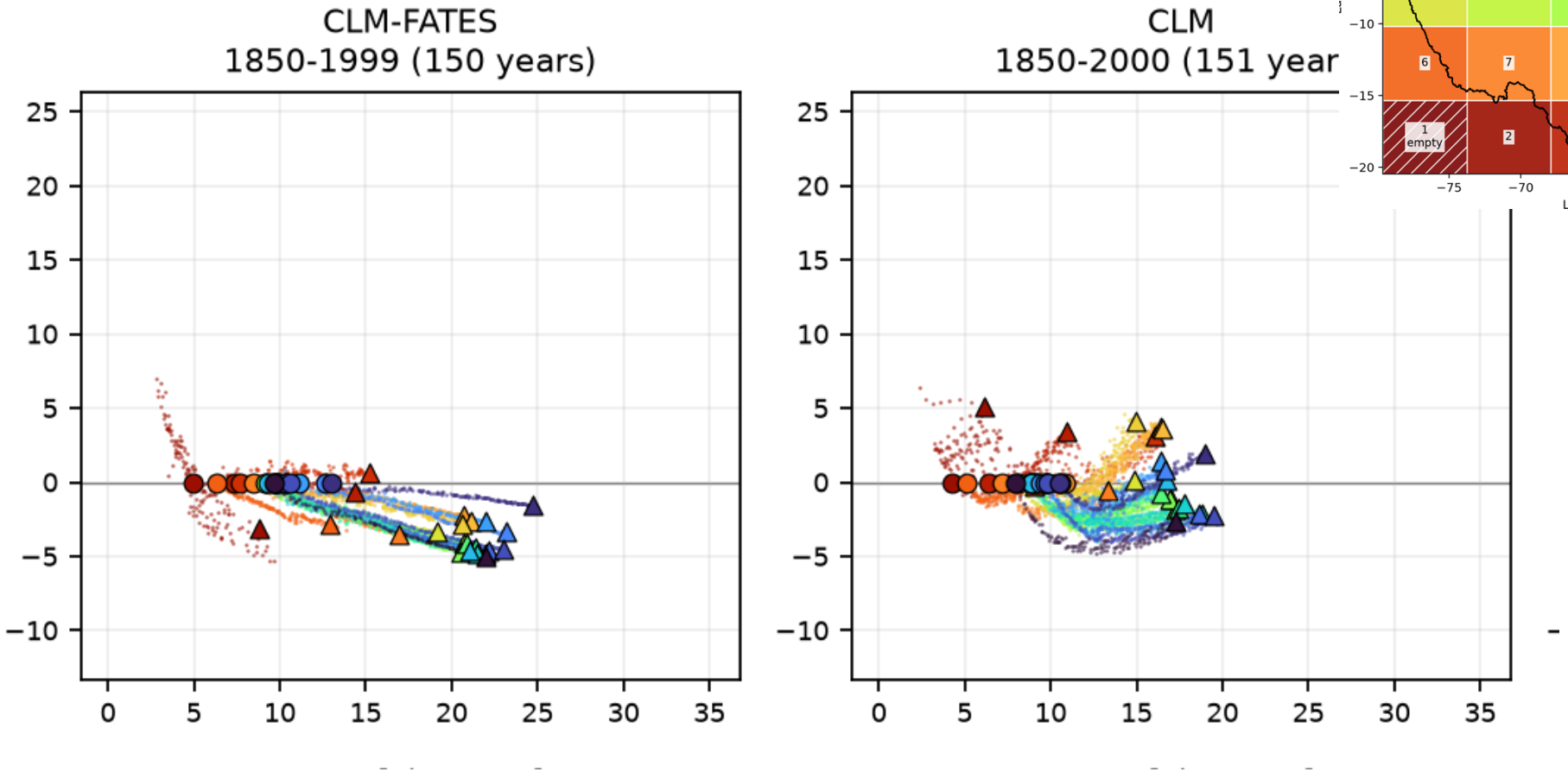
NPP vs turnover

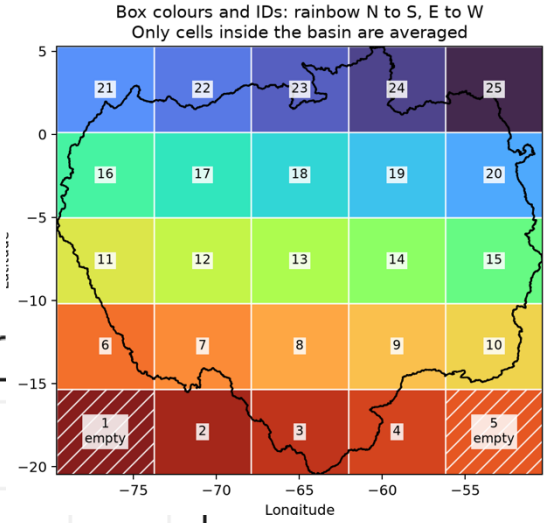
Amazon 1% CO2 BGC | NPP versus total vegetation biomass
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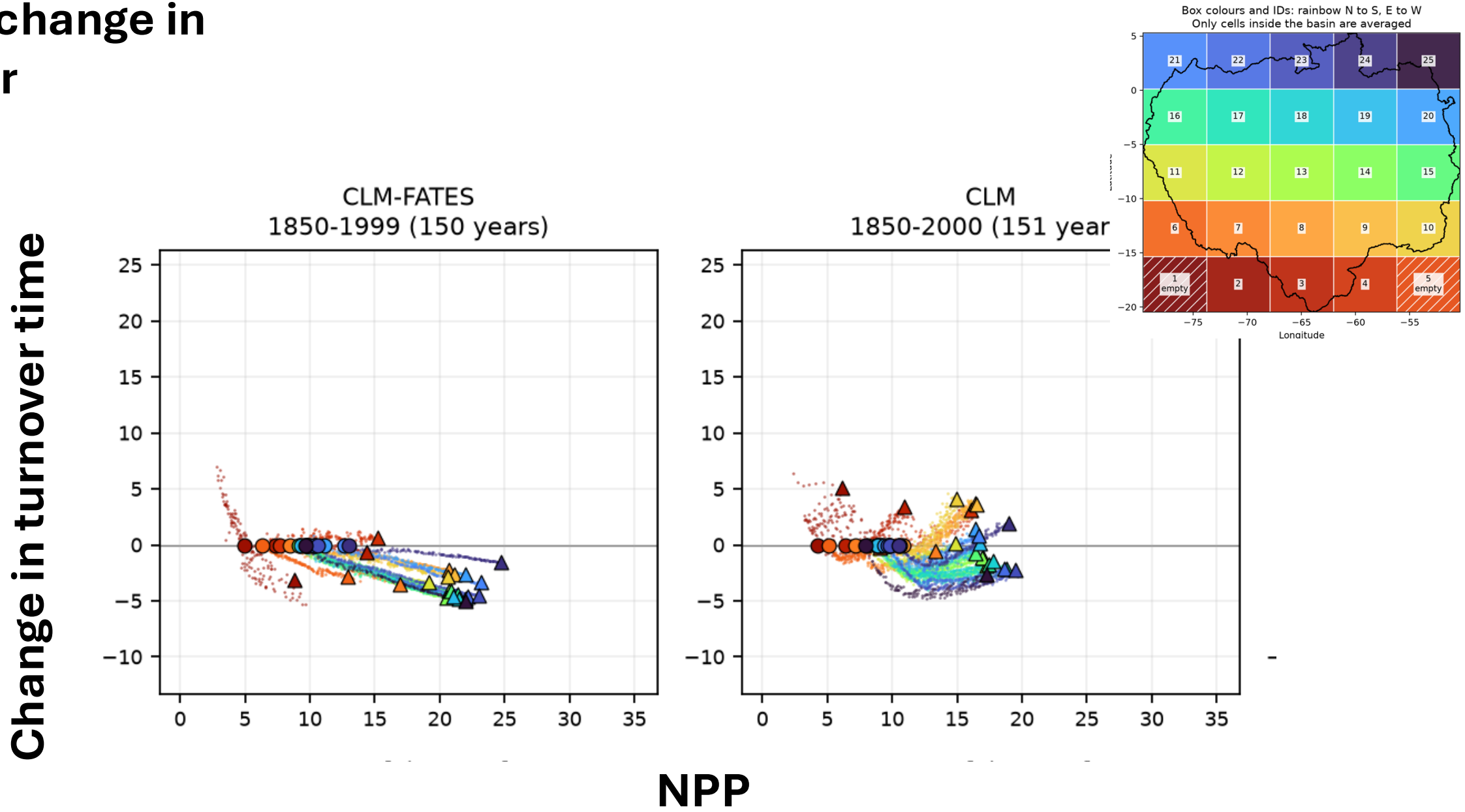


NPP vs change in turnover





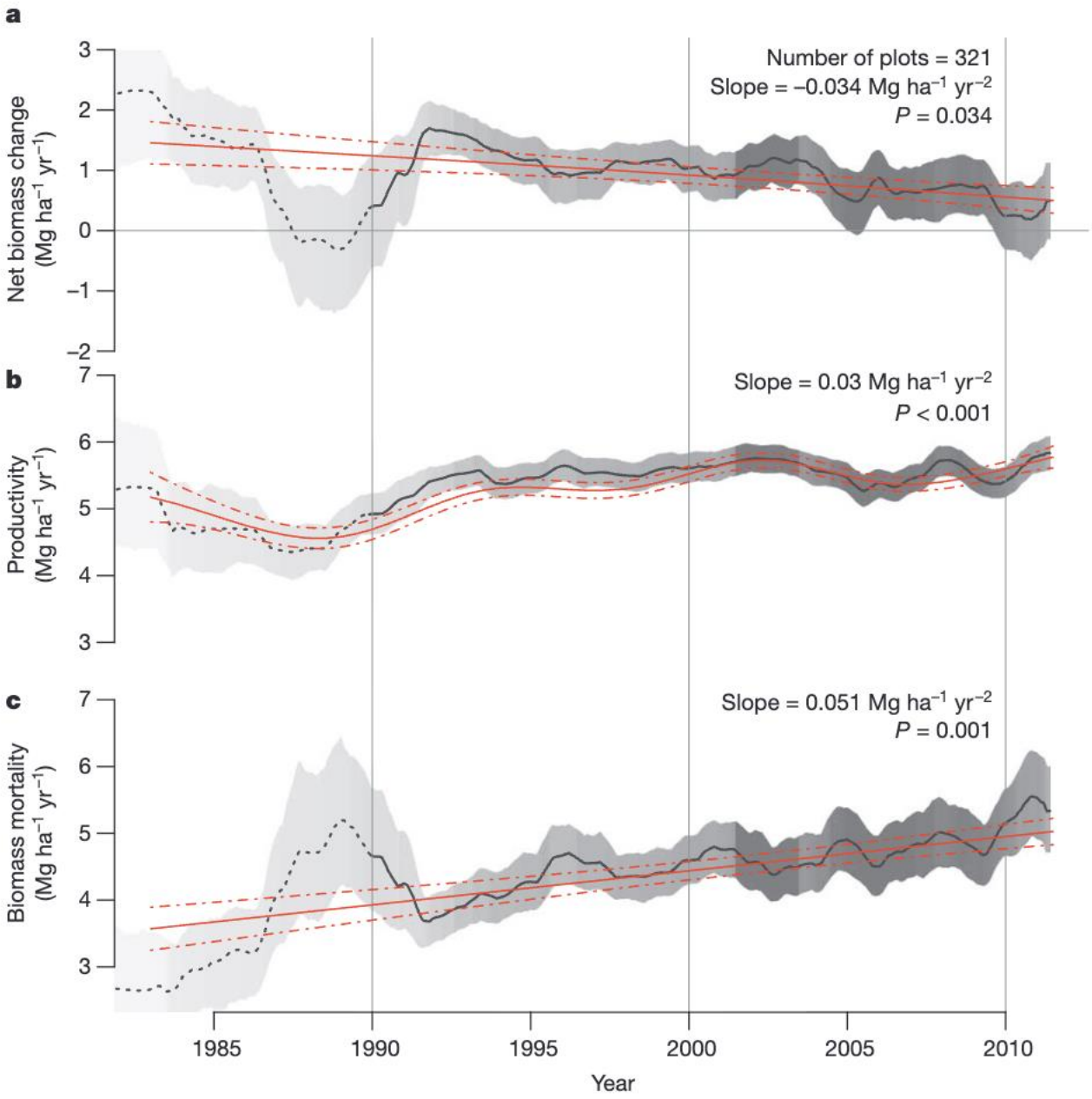
NPP vs change in turnover



Models where trees **die faster** when they **grow faster** have **less biomass**

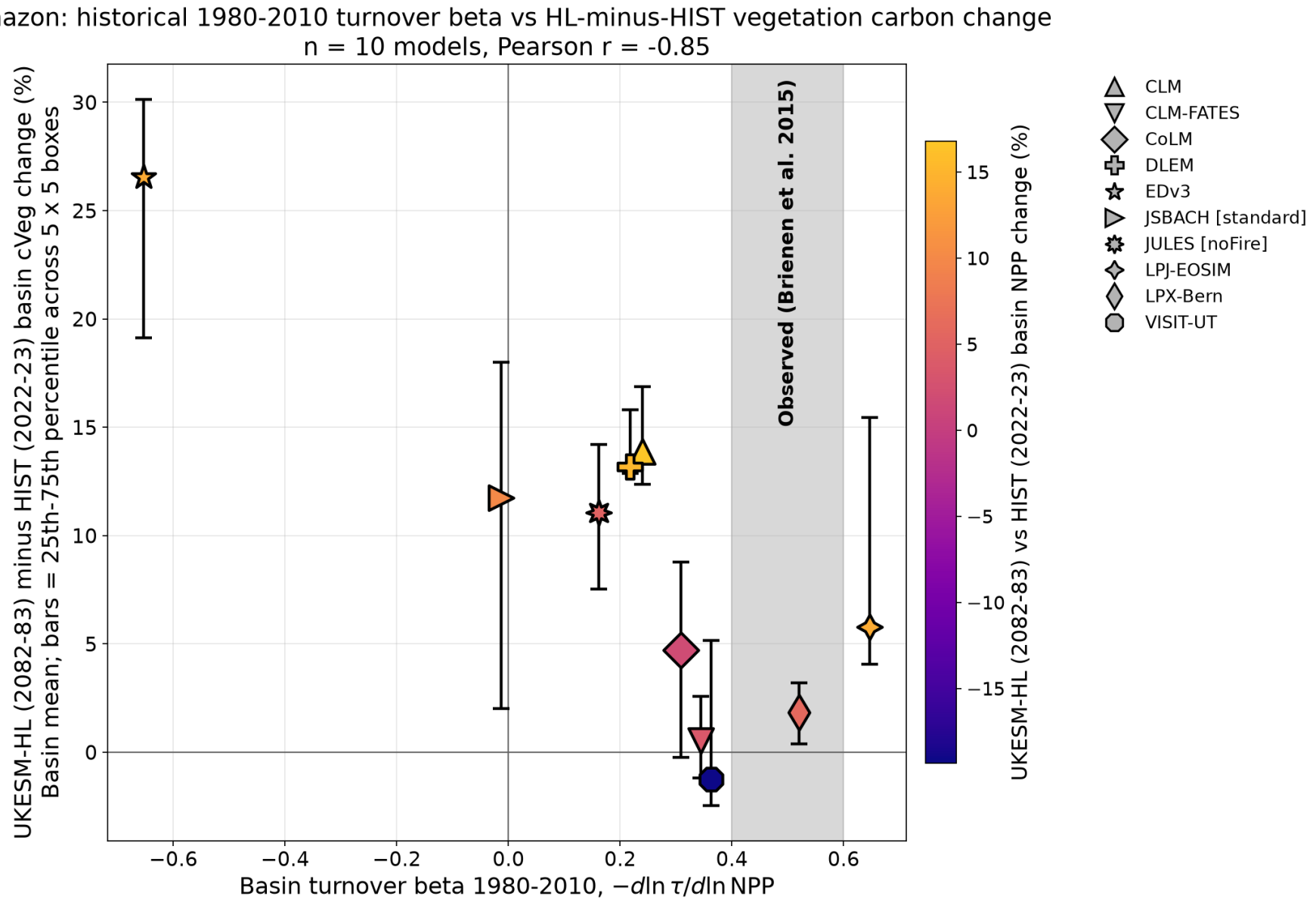
But there are **observations** of vegetation turnover under **increasing CO2..**

Brienen et al. 2015 ***RAINFOR*** forest inventory plot network observations



Observations of turnover elasticity **do not support** models that predict high biomass accumulation in the Amazon

What are we to make of the models that keep all of their big trees? How can we decide if they are right?



Summary: representation of **size-structured mortality**

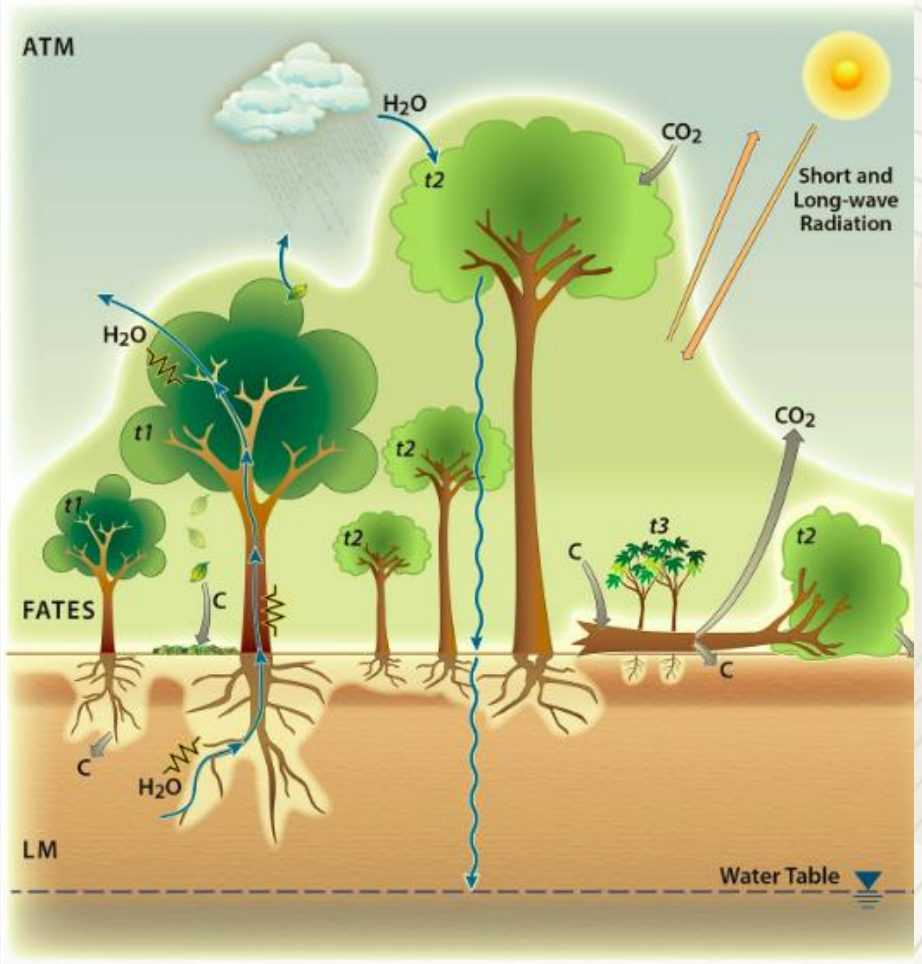
- Mortality of large trees in FATES **accelerates turnover**
- The impact on carbon uptake is **v. large**
- Observations support **increases** in turnover
- **Large sink** in tropical forest ,carbon not supported
- **Ecological dynamics are critical to** carbon balance

.

What new things does FATES do in NorESM?

(and why do they matter?)

- Resolves plant size
- Resolves ecosystem age since disturbance
- Resolves gross land use transitions
- Resolves vegetation mortality
- **Has optimizing LAI**



°CICERO

What is optimizing LAI?

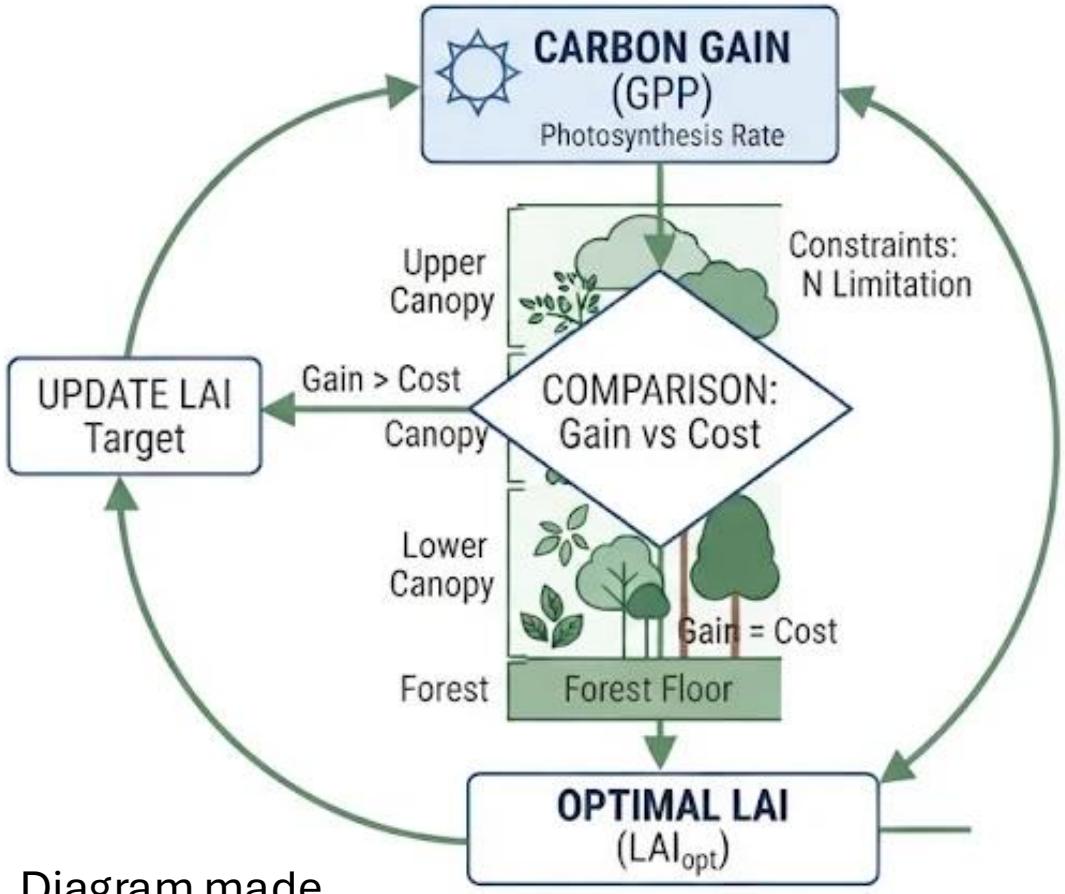


Diagram made with AI

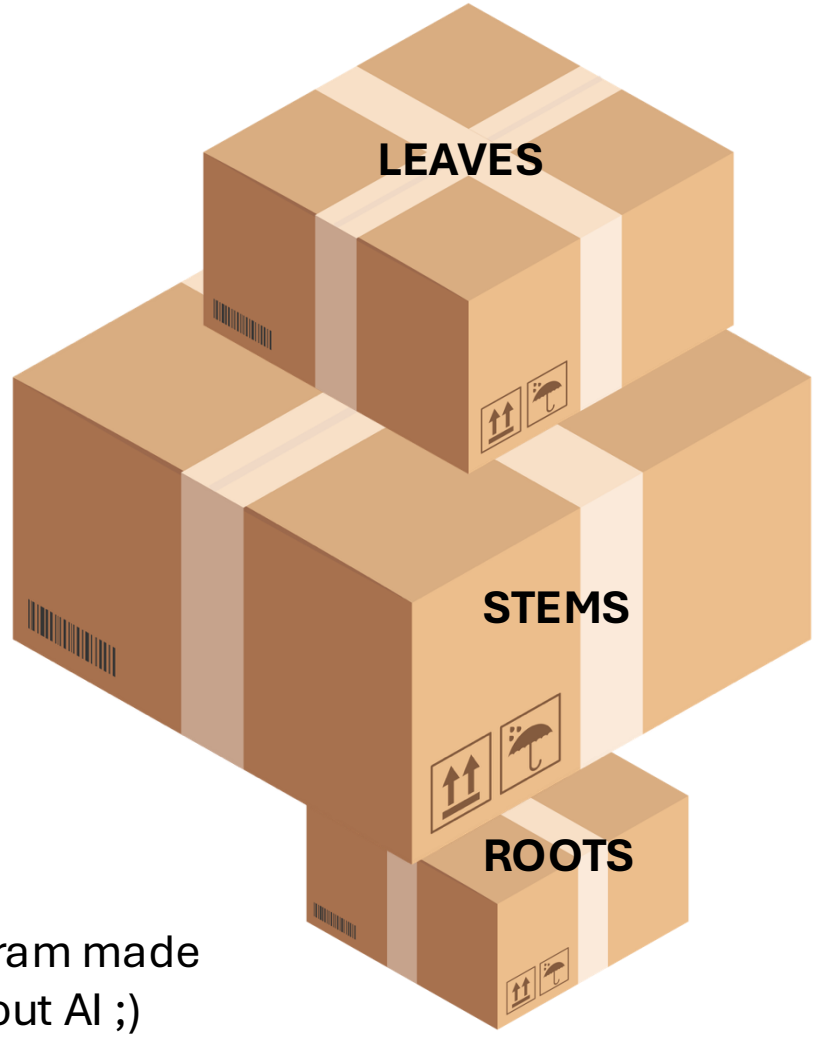
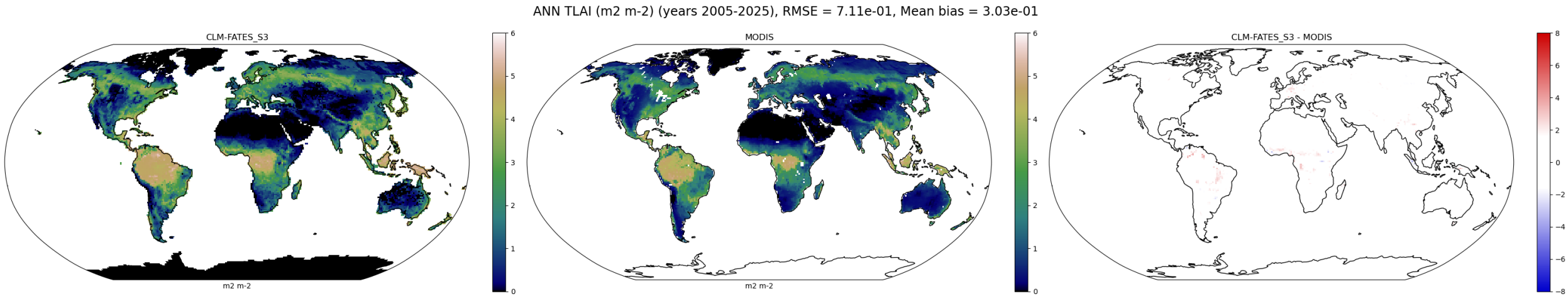


Diagram made without AI ;)

Optimizing LAI does an OK job

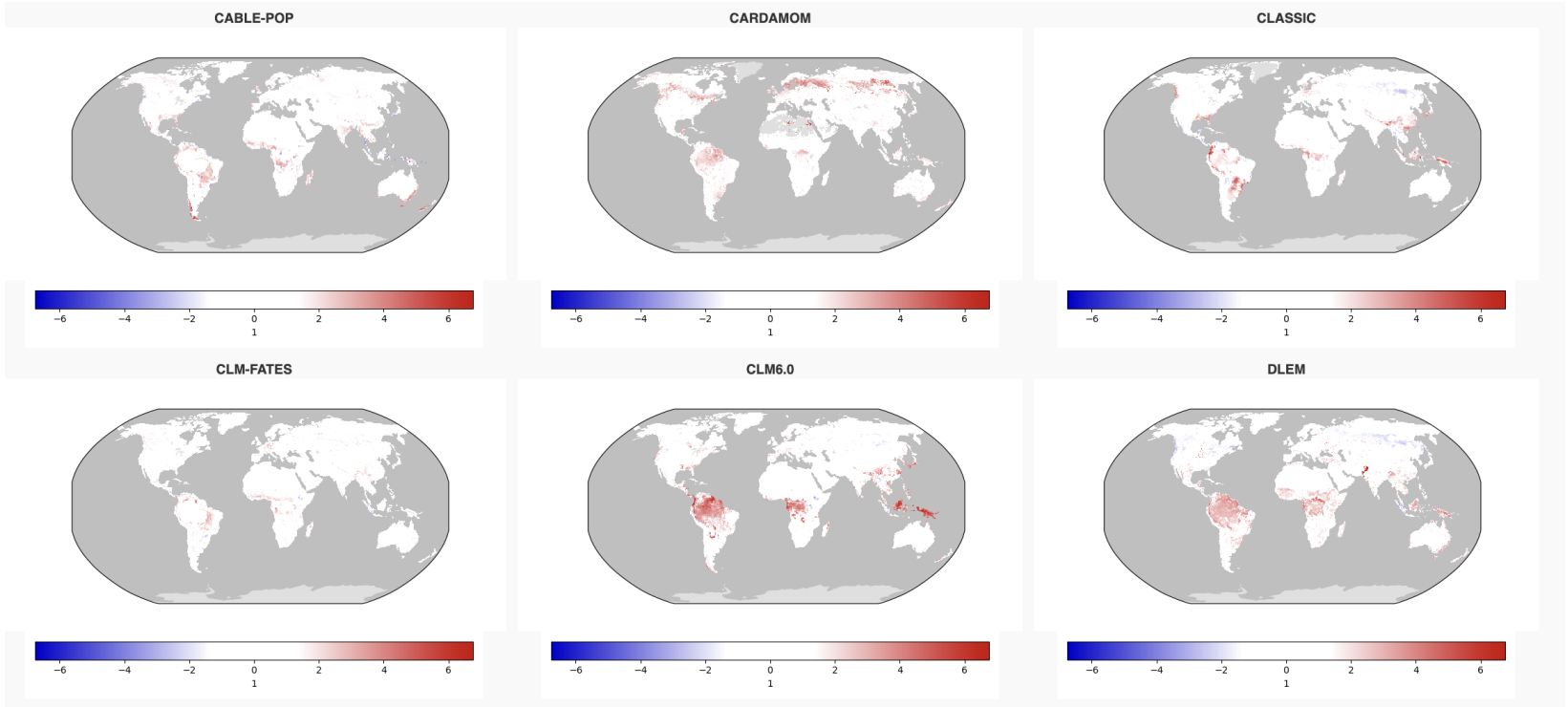


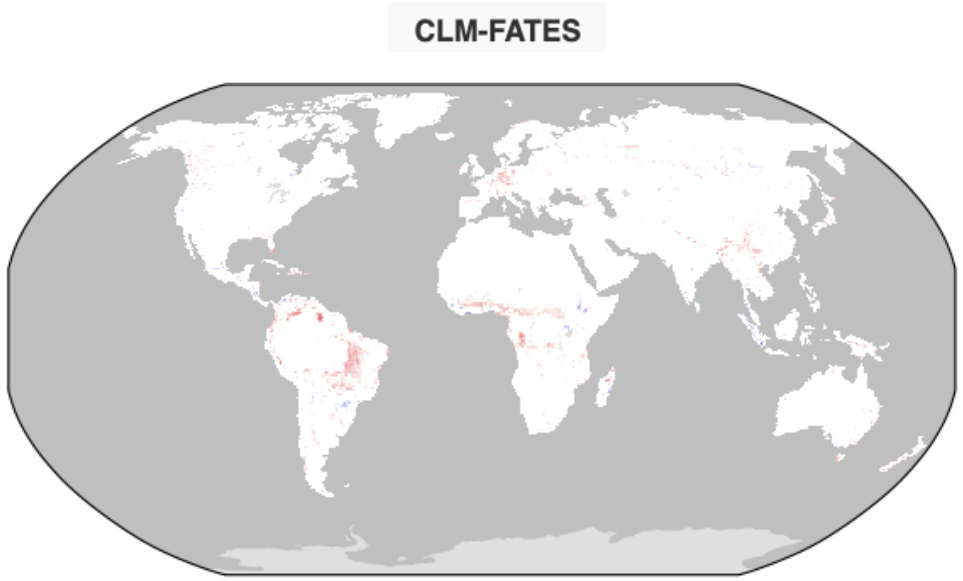
TRENDY 2026

https://gws-access.jasmin.ac.uk/public/land surf_rdg/pmcguire/ILAMB_output _TRENDYv15/GCP_270926a4nC

Optimizing LAI does an OK job

MODIS LAI

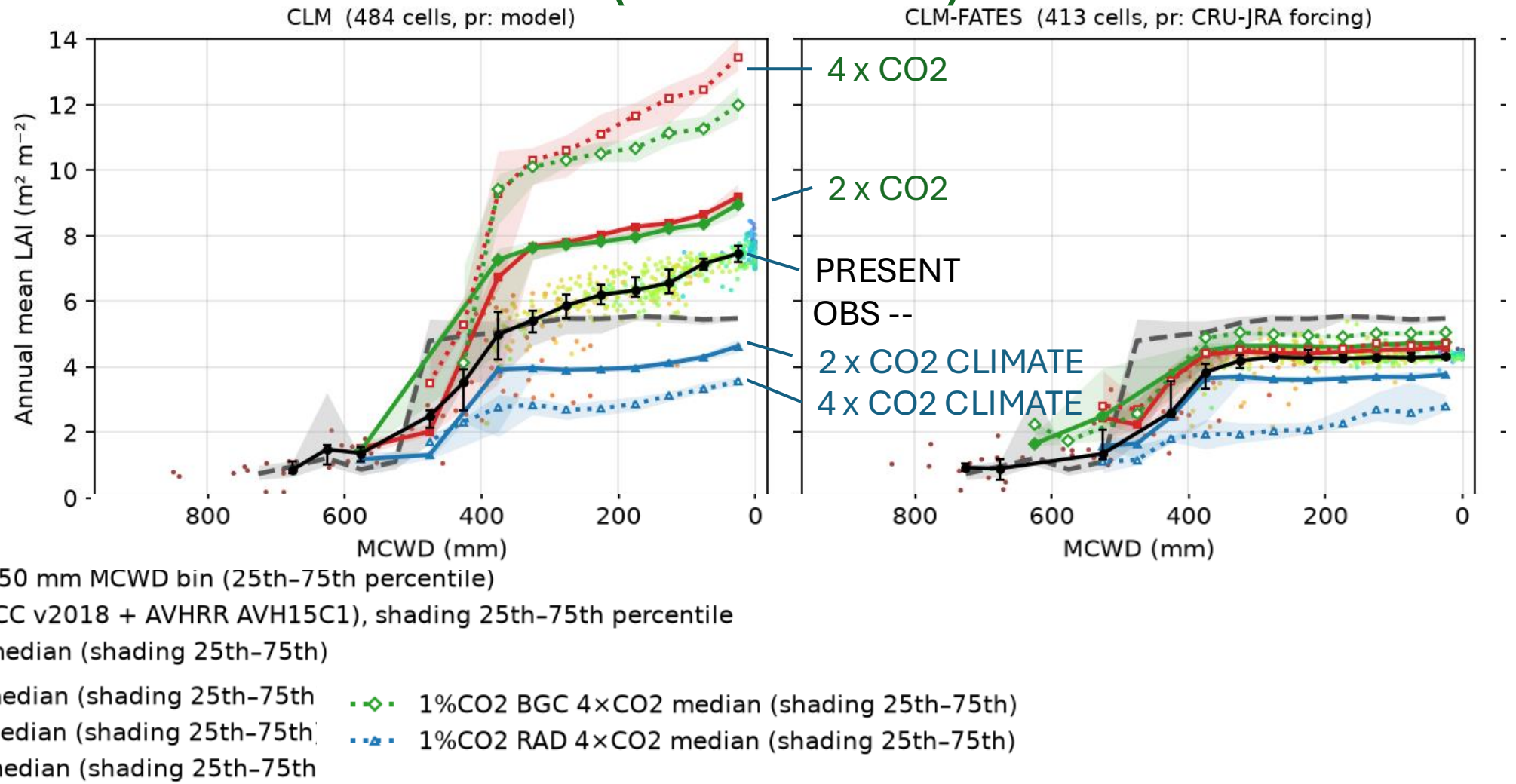




Optimizing LAI has **consequences** for future model behaviour

Amazon Basin:
Max. Cumulative Water Deficit (drought stress)
vs.
LAI (leaf area index)

- Leaf area index in FATES, as in real life, does not increase with more rainfall



What does FATES NOT do in NorESM?

On by default:

- land use change
- selective logging
- size and age structure
- grazing
- dynamic plant mortality pathways
- size-structured fire-veg interactions
- multi-layered photosynthesis & radiation
- seed bank dynamics

Optional but not yet default:

plant hydraulics
nutrient cycling
seed dispersal
crown damage
vegetation competition & dynamics

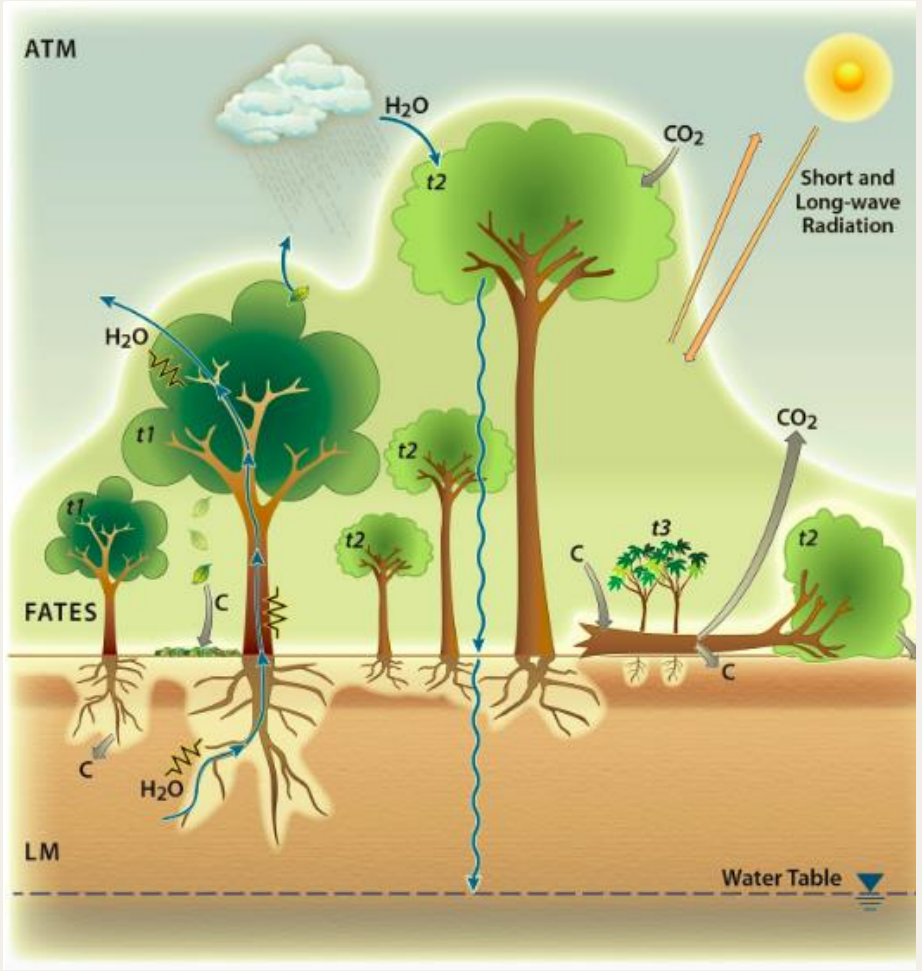
Not yet included

- crop harvest & phenology
- Mycorrhizae
- Insects
- BECCS (bioenergy carbon capture & storage)

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Summary

1. CLM-FATES performs very well in global benchmarking analysis
2. CLM-FATES is capturing the Northern hemisphere carbon uptake better than previous models
3. CLM-FATES accelerates turnover in tropical forests, in line with observations



Plans...

1. FATES will expand into testing global **nitrogen** cycling
2. Implementation of **BECCS**
3. Further **calibration** to regrowth curves and canopy structure
4. **Mortality** intercomparison project (AI4PEX)

Opportunities

1. Non-default **plant hydraulics** model to be tested
2. We still need **crops, insects, windthrow**, etc
3. Coupling to **hillslope** & **multi-layer** physics
4. FATES has many advanced capabilities (**PFT competition, seed dispersal**, etc. to play with)

Resouces

- **FATES code:** https://github.com/NGEET/fates
- **Documentation:** https://fates-users-guide.readthedocs.io/projects/tech-doc/en/latest/
- **Users Guide:** https://fates-users-guide.readthedocs.io/en/latest/
- **Mailing List:** https://groups.google.com/g/fates_model
- **Diagnostics Tool:** https://github.com/NorESMhub/xesmf_clm_fates_diagnostic
- rosie.fisher@cicero.oslo.no.
- rosieafisher.com

FATES: the Functionally Assembled Terrestrial Ecosystem Simulator: history

Assessing uncertainties in a second-generation dynamic vegetation model caused by ecological scale limitations

Rosie Fisher[1], Nate McDowell[1], Drew Purves[2], Paul Moorcroft[3], Stephen Sitch[4], Peter Cox[5,6], Chris Huntingford[7], Patrick Meir[8] and F. Ian Woodward[9]

2010

Taking off the training wheels: the properties of a dynamic vegetation model without climate envelopes, CLM4.5(ED) 2015

R. A. Fisher[1], S. Muszala[1], M. Verteinstein[1], P. Lawrence[1], C. Xu[2], N. G. McDowell[2], R. G. Knox[3], C. Koven[3], J. Holm[3], B. M. Rogers[4], A. Spessa[5,6], D. Lawrence[1], and G. Bonan[1]

Benchmarking and parameter sensitivity of physiological and vegetation dynamics using the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) at Barro Colorado Island, Panama

Charles D. Koven[1], Ryan G. Knox[1], Rosie A. Fisher[2,3], Jeffrey Q. Chambers[1,4], Bradley O. Christoffersen[5], Stuart J. Davies[6], Matteo Detto[7,8], Michael C. Dietze[9], Boris Faybishenko[1], Jennifer Holm[1], Maoyi Huang[10], Marlies Kovenock[11], Lara M. Kueppers[1,12], Gregory Lemieux[1], Elias Massoud[13], Nathan G. McDowell[10], Helene C. Muller-Landau[6,7], Jessica F. Needham[1], Richard J. Norby[14], Thomas Powell[1], Alistair Rogers[15], Shawn P. Serbin[15], Jacquelyn K. Shuman[2], Abigail L. S. Swann[11,16], Charuleka Varadharajan[1], Anthony P. Walker[14], S. Joseph Wright[7], and Chonggang Xu[17]

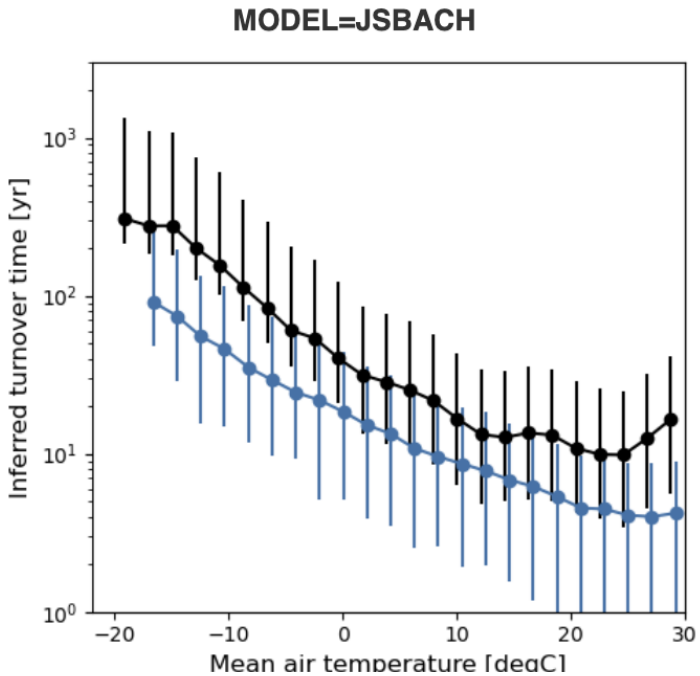
2020

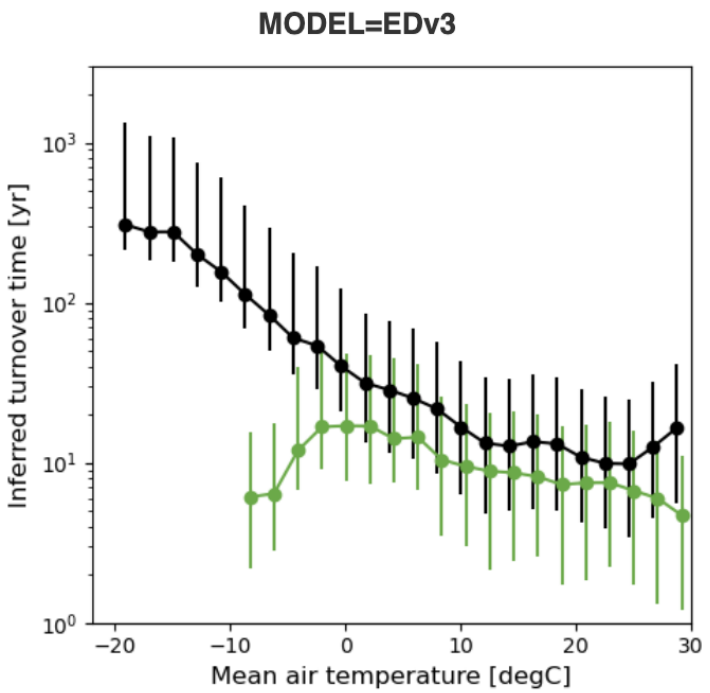
°CICERO

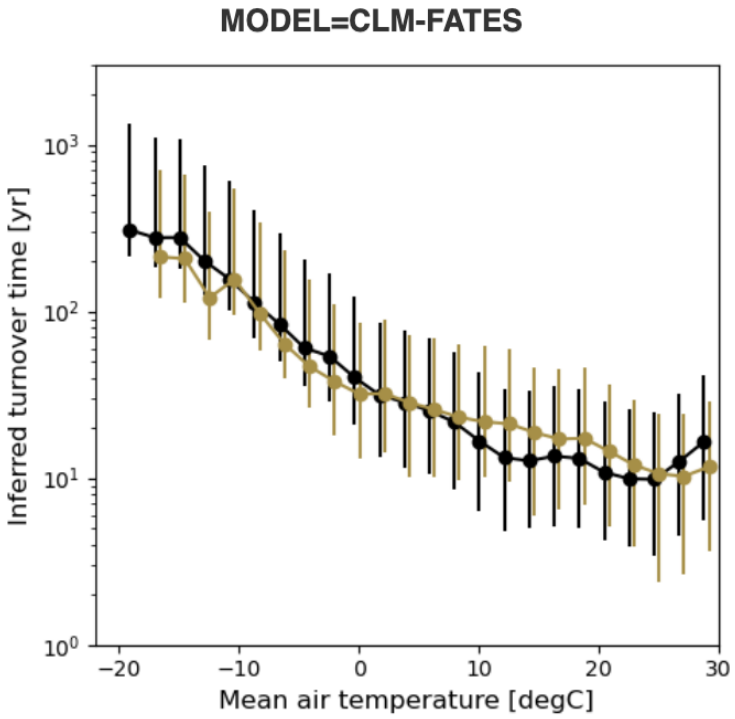
TRENDY 2026

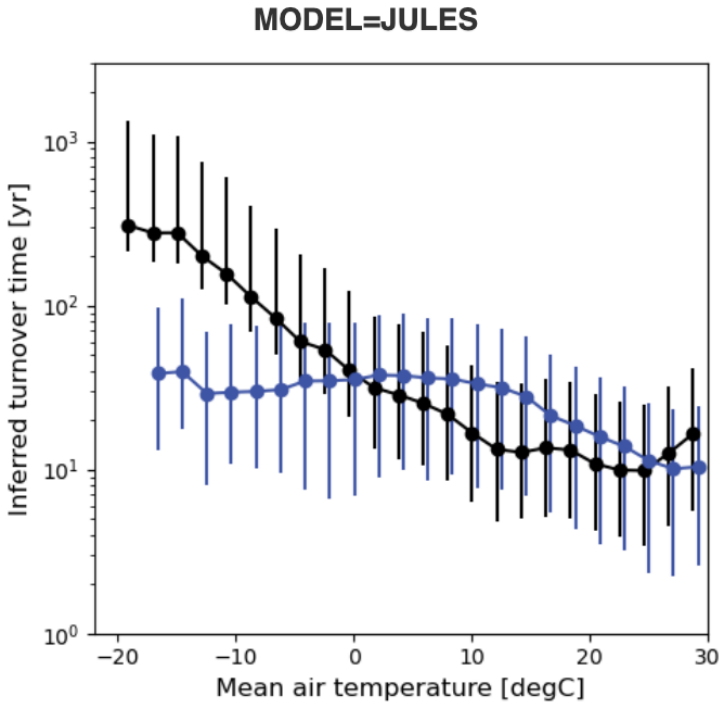
https://gws-access.jasmin.ac.uk/public/landsurf_rdg/pmcguire/ILAMB_output_TRENDYv15/GCP_270926a4nC

'Koven' soil Turnover metric

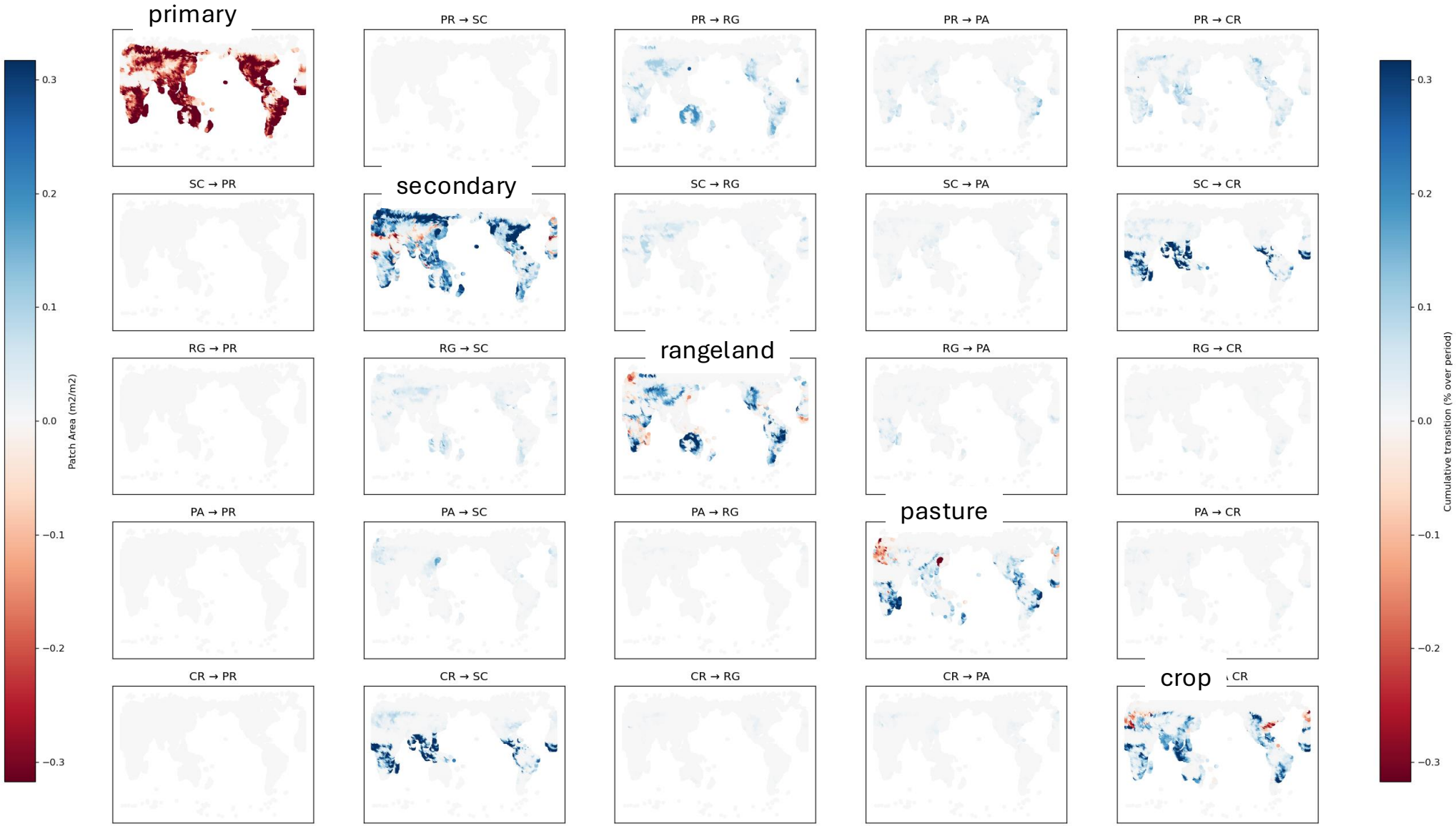






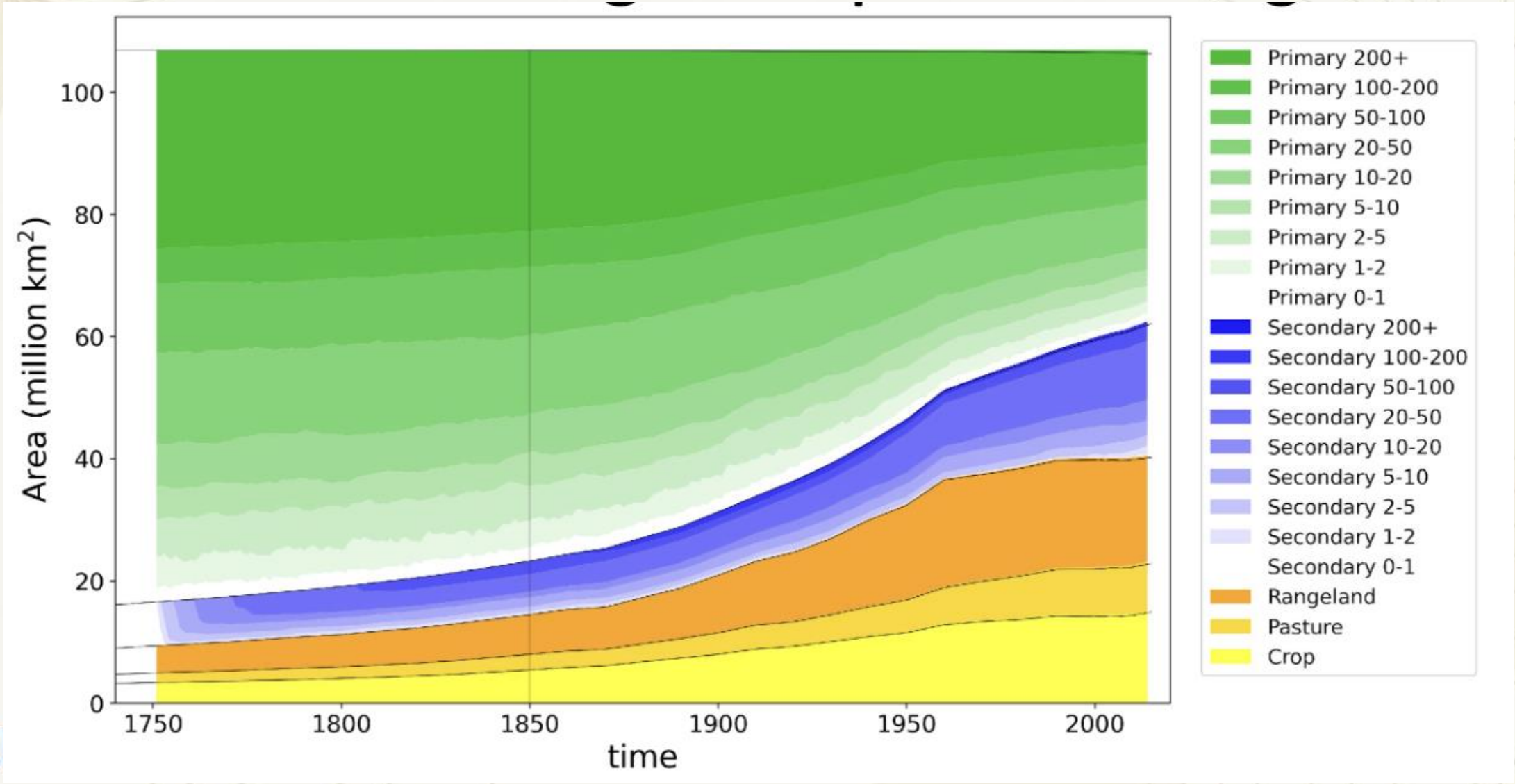


Cumulative gross transitions and net change. 1900-2020



Land use categories in FATES

(Primary, Secondary, Rangeland, Pasture, Crop*)



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