Land Modeling II: Biogeochemistry and Ecosystems

Adrianna Foster, *Will Wieder, Dave Lawrence, Andy Wood, Bill Sacks, Danica Lombardozzi, Daniel Kennedy, Erik Kluzek, Gordon Bonan, Guoqiang Tang, Jackie Shuman, Katie Dagon, Keith Oleson, Naoki Mizukami, Peter Lawrence, Sam Levis, Sam Rabin, Sean Swenson, Teagan King… and many more!*

NCAR

11 August 2023

CESM Tutorial

NSF

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Land biogeochemistry in CESM

Why?

How?

Uncertainties and future directions

Land biogeochemistry in CESM

Why?

Climate impacts vegetation

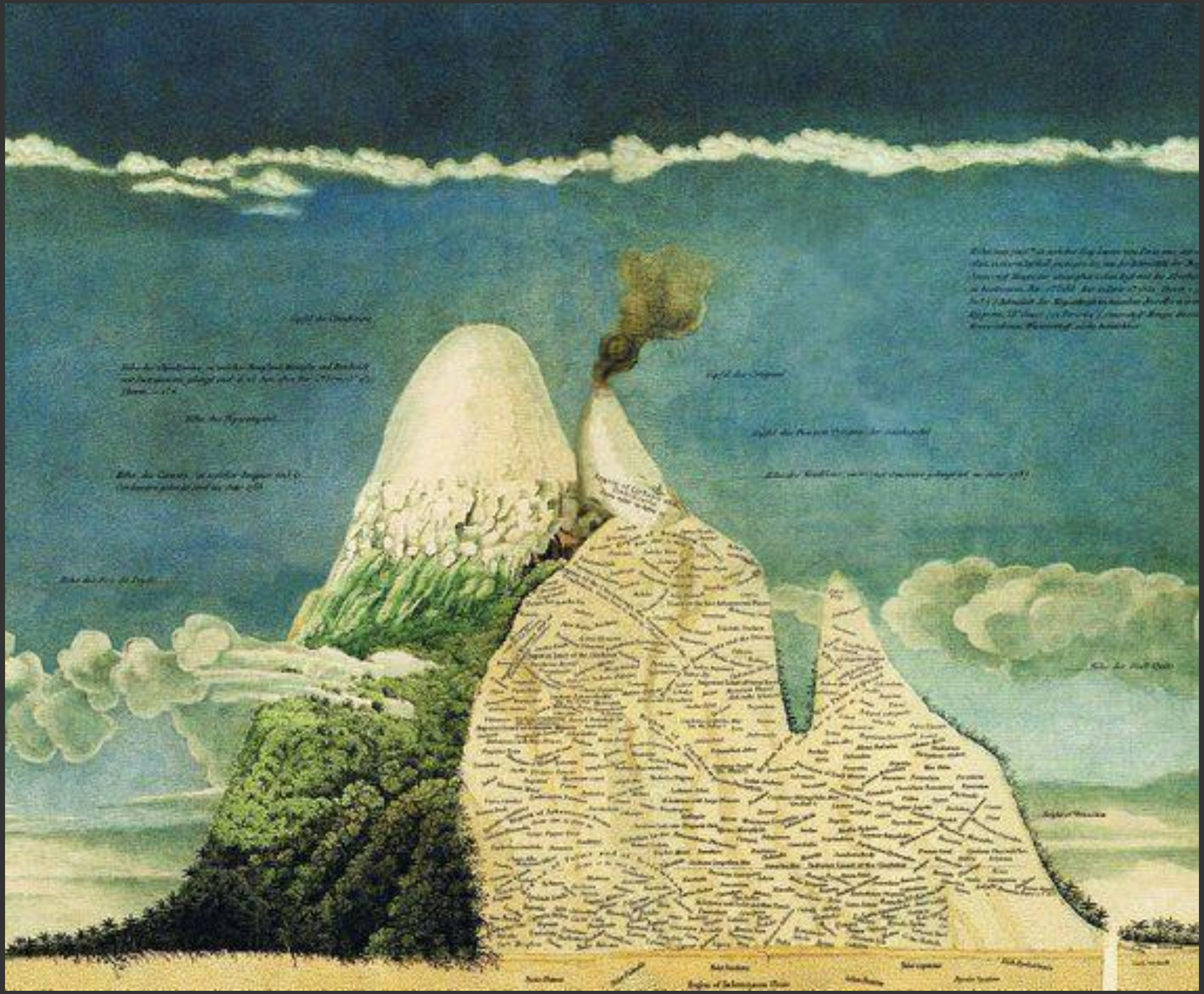
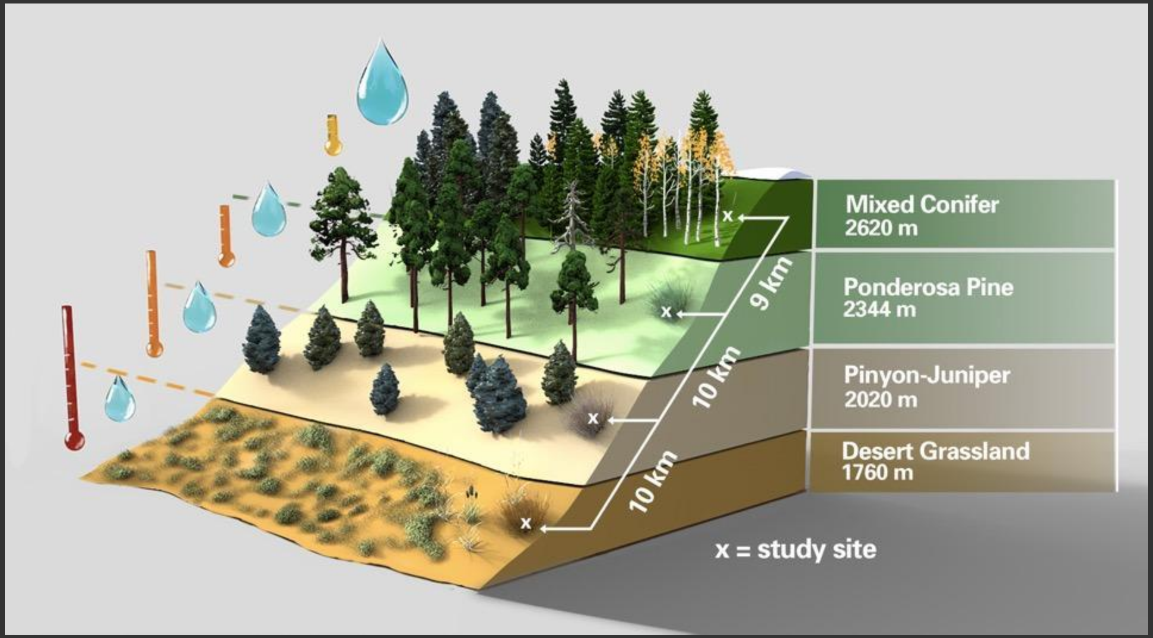
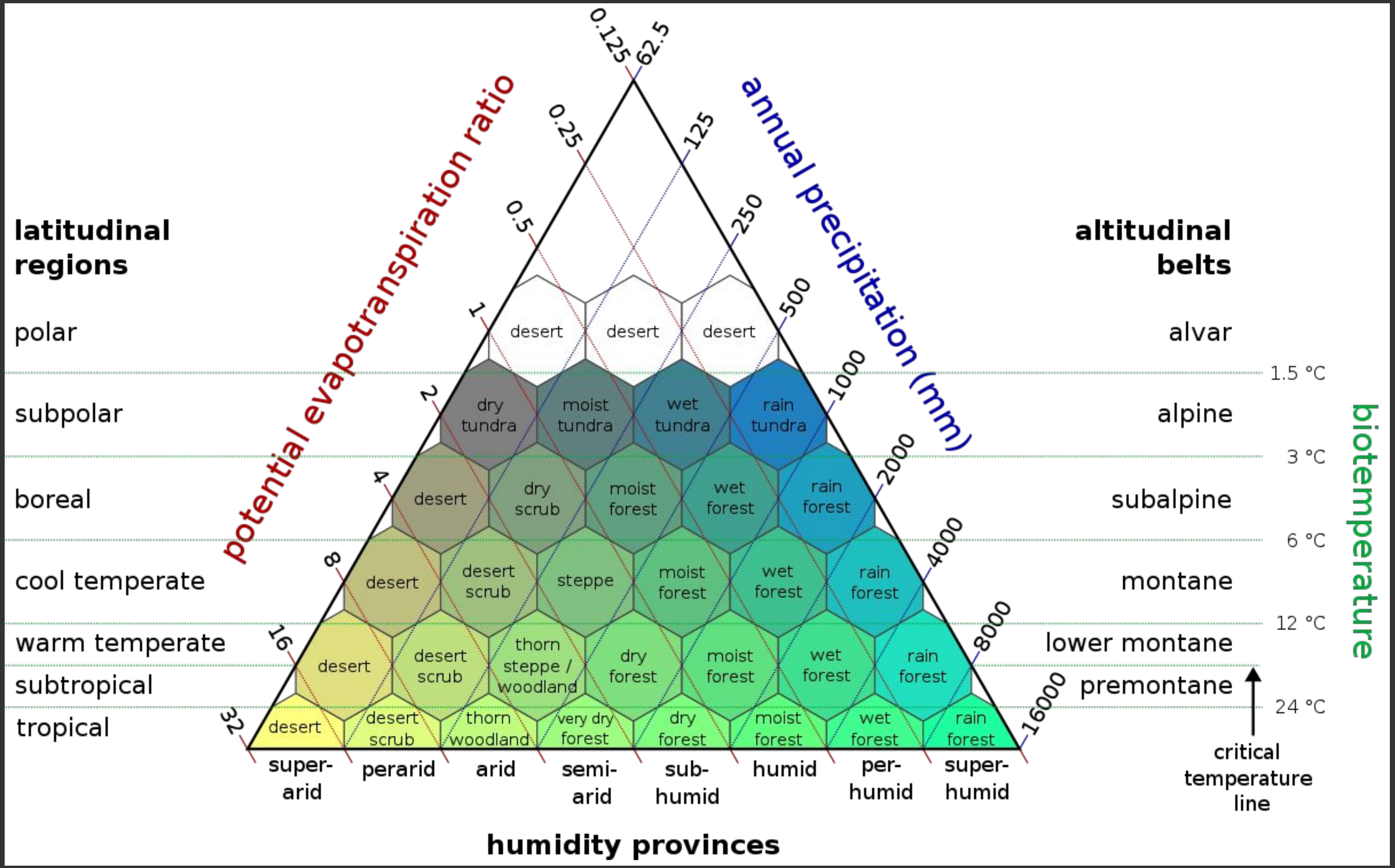


*Tableau des Régions é*quinoxiales from Humboldt (1807)



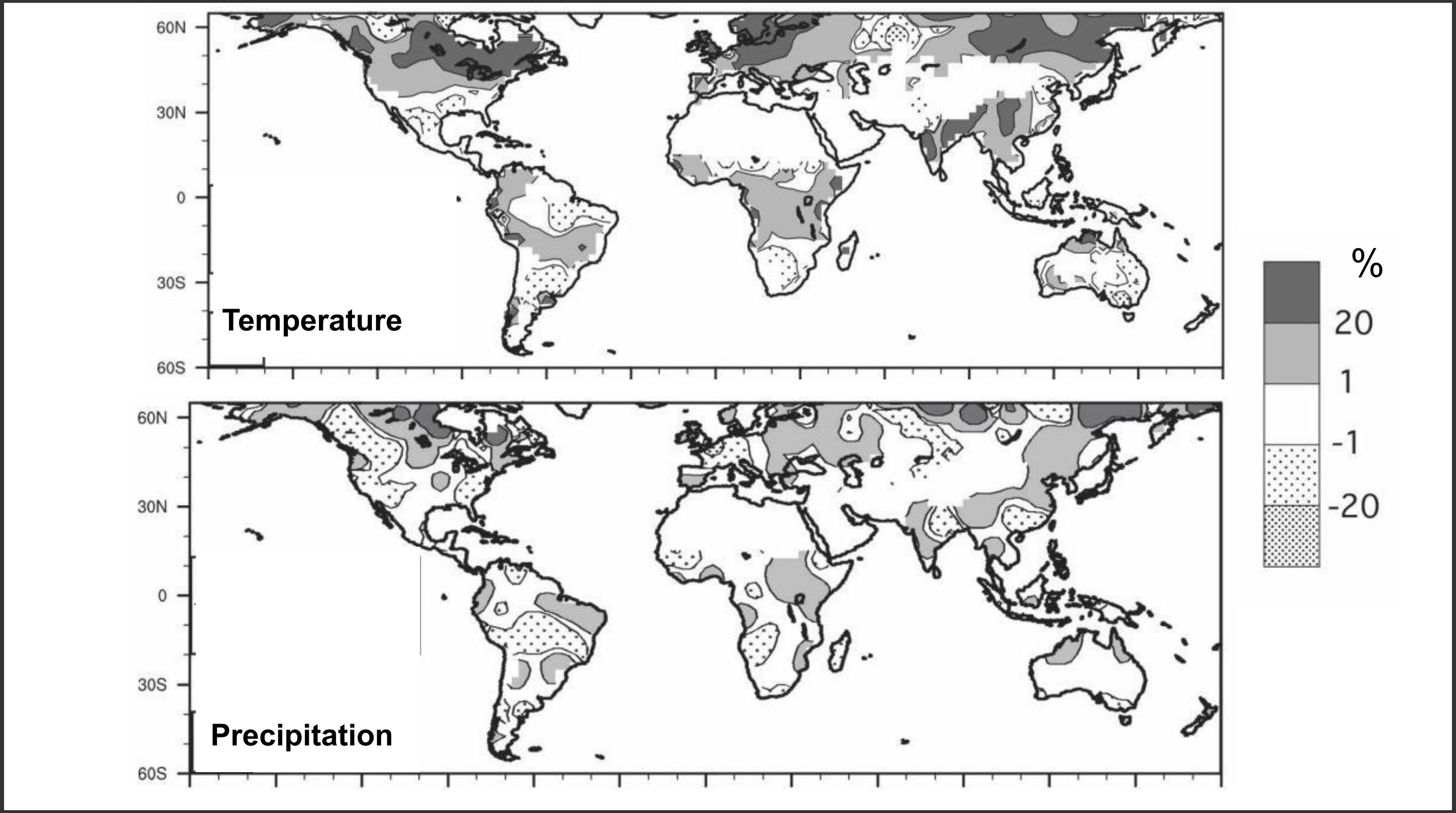
Morrissey et al. (2019) *Nature Ecology and Evolution*

Climate impacts vegetation



Holdridge life zones

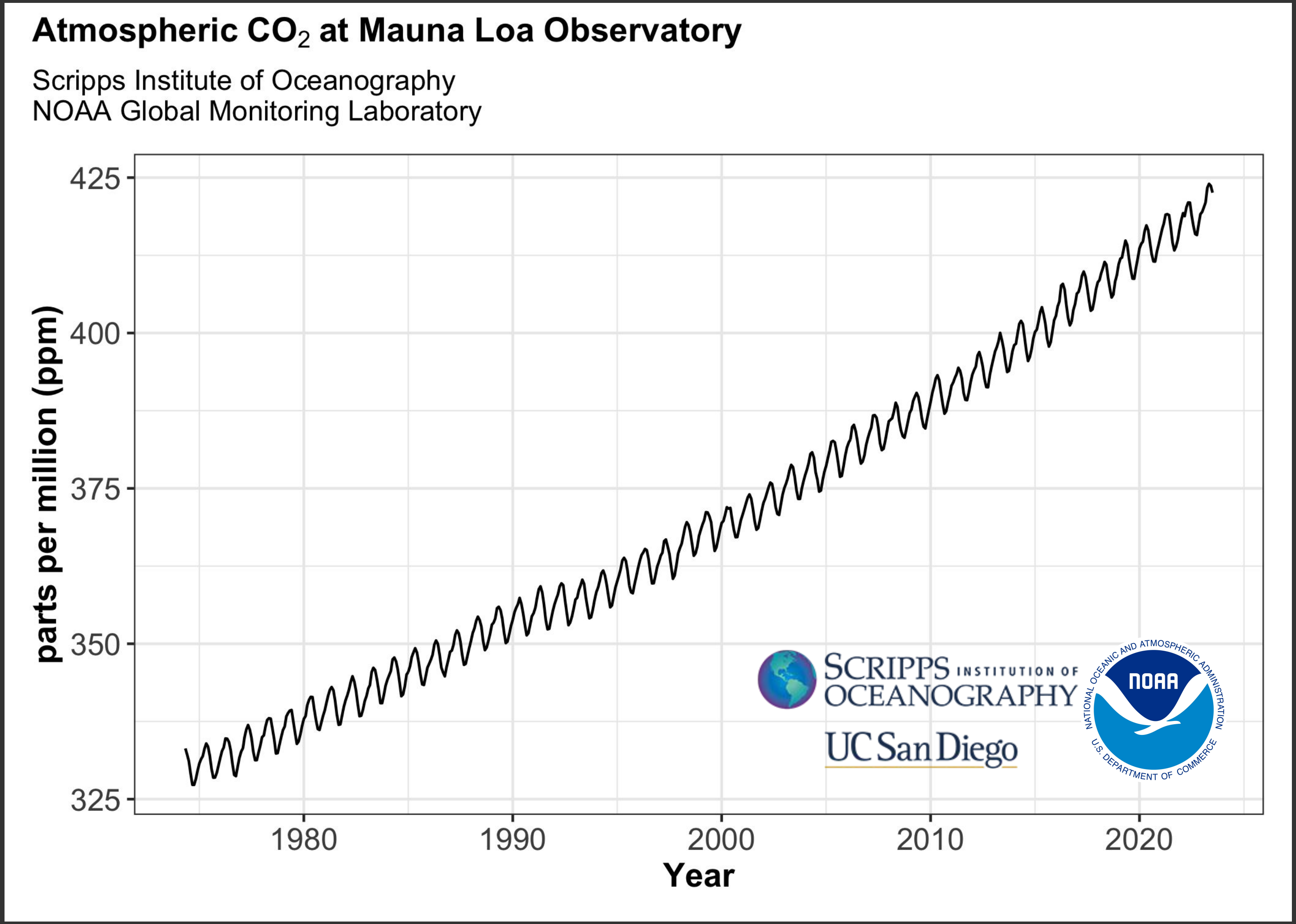
Vegetation impacts climate



Short time scales – dominated by albedo and evapotranspiration

Liu et al. 2006 *Journal of Climate*

Vegetation impacts climate

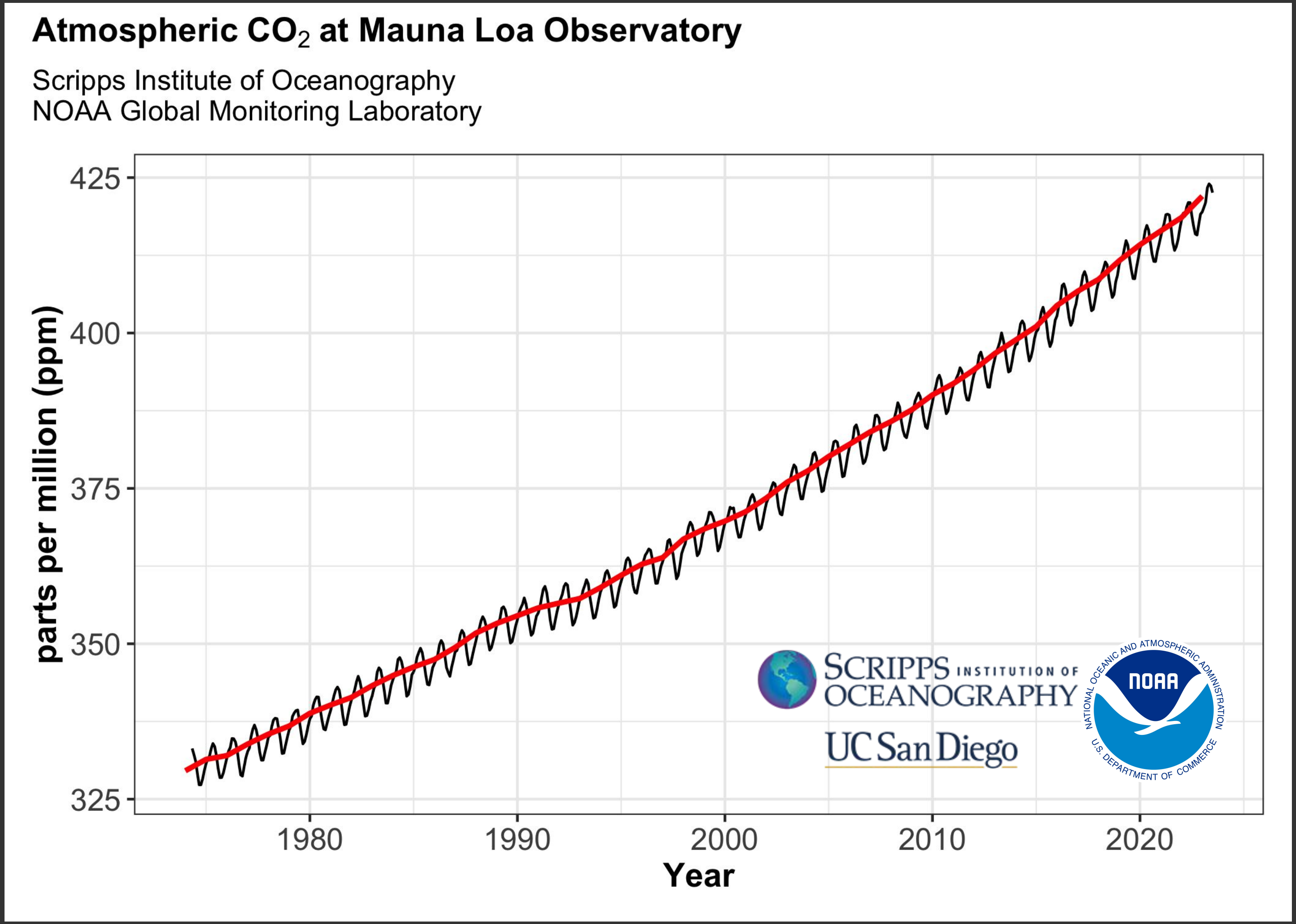


https://gml.noaa.gov/ccgg/trends/mlo.html

Longer time scales

fate of carbon

Vegetation impacts climate



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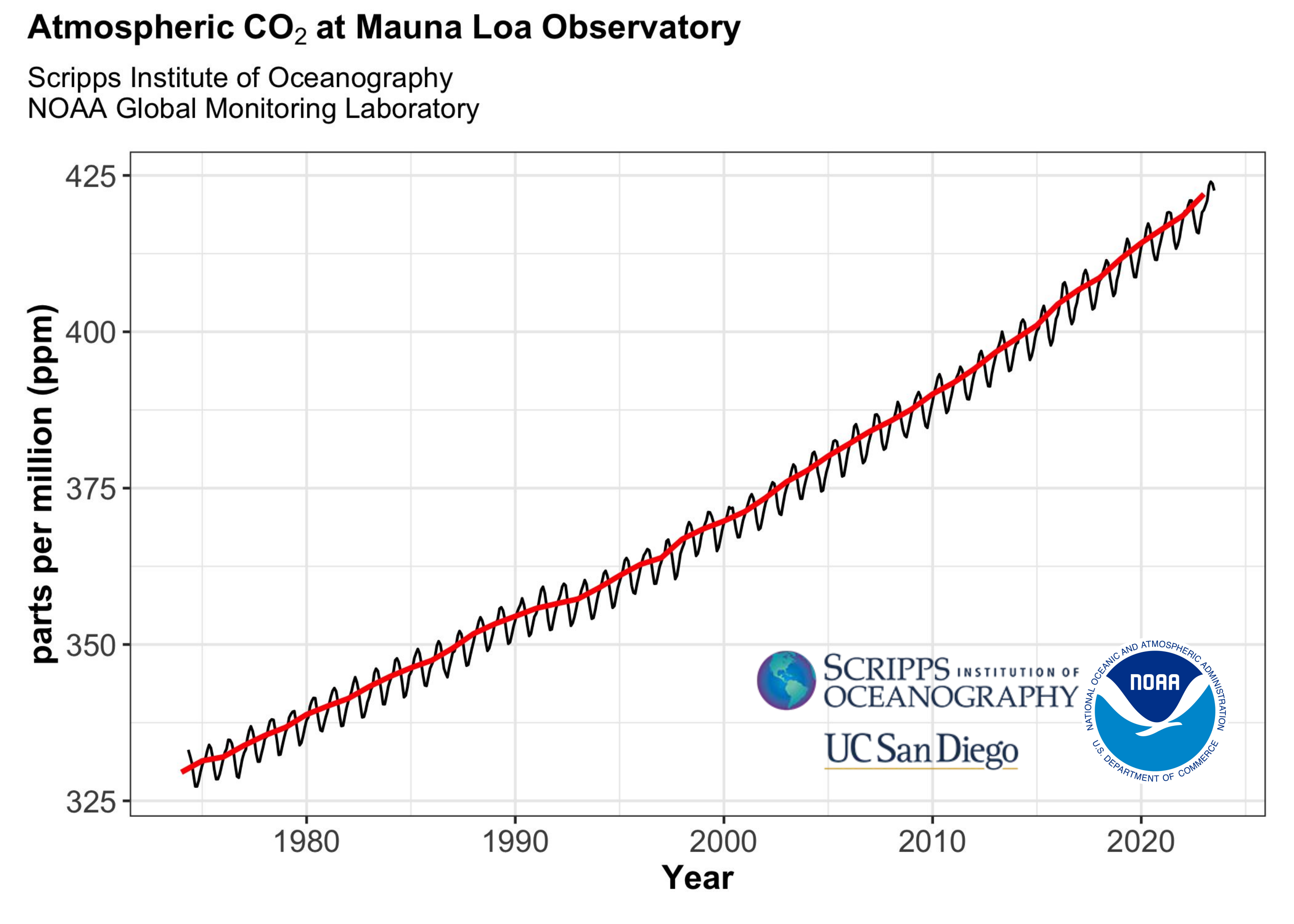
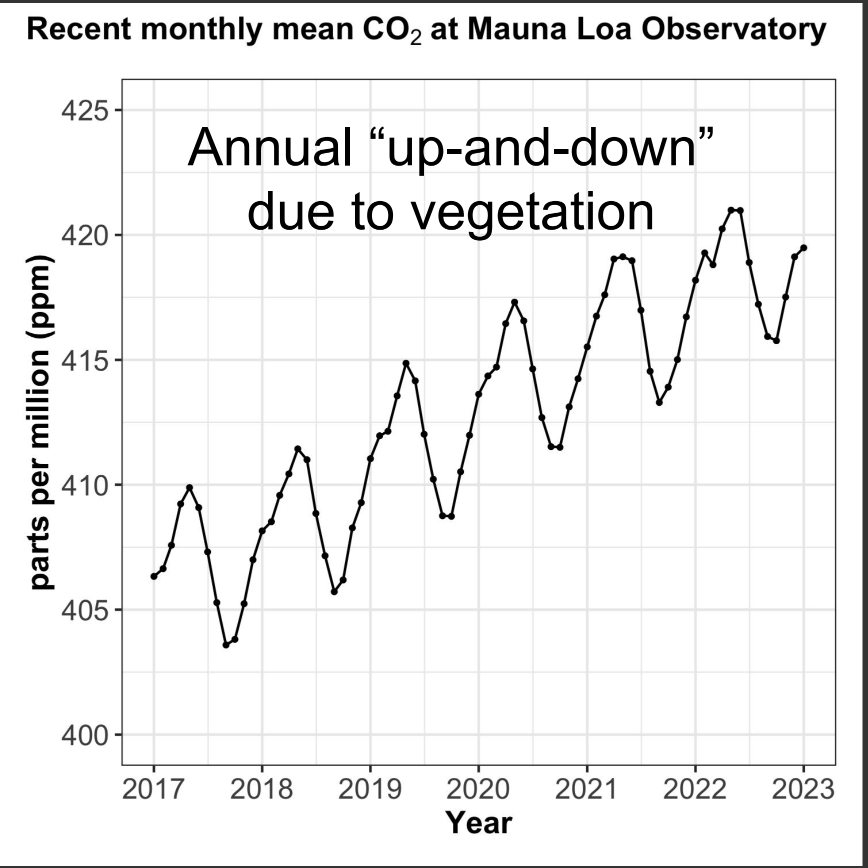
Upward trend due to human activities

Vegetation impacts climate





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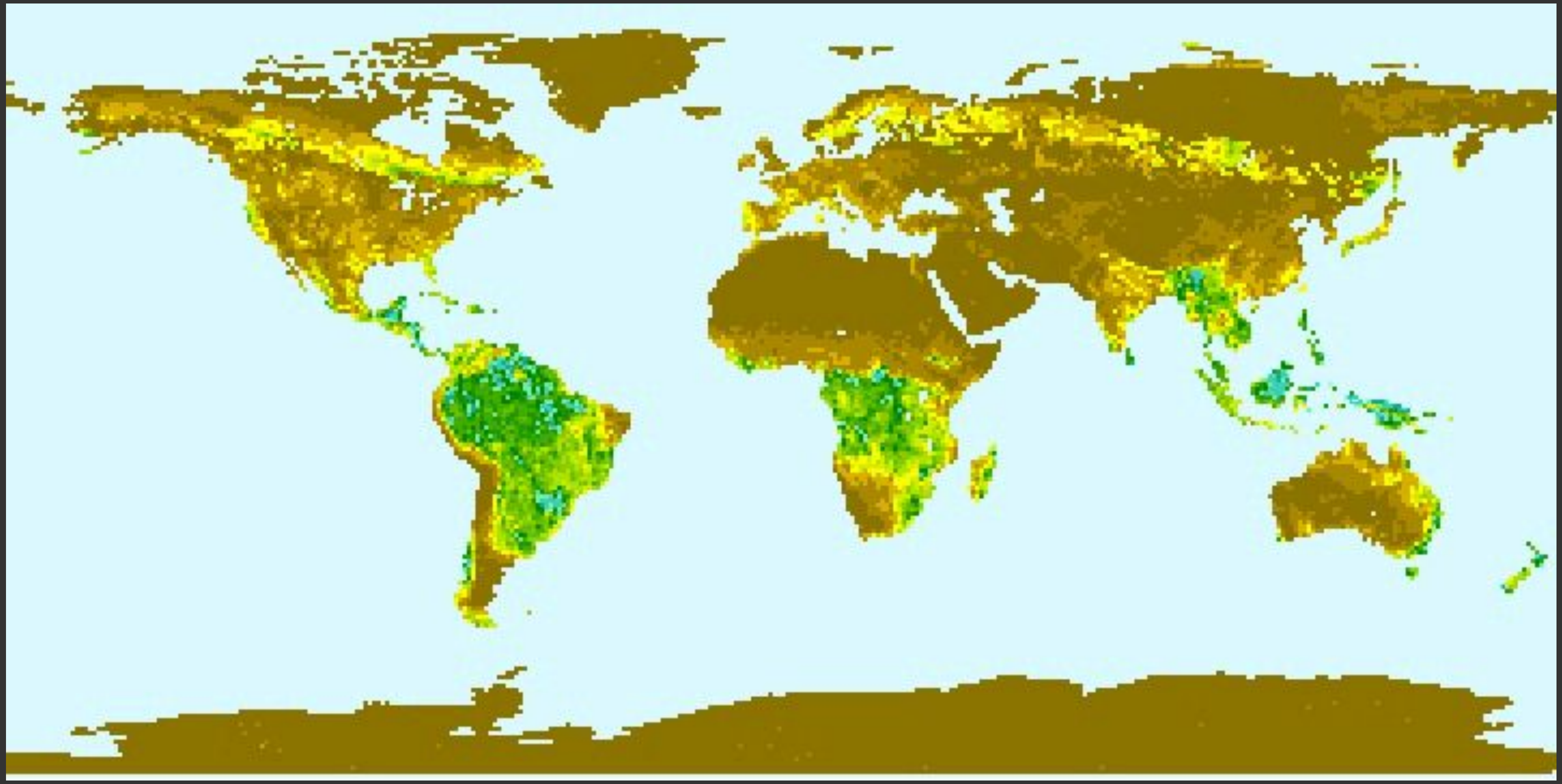
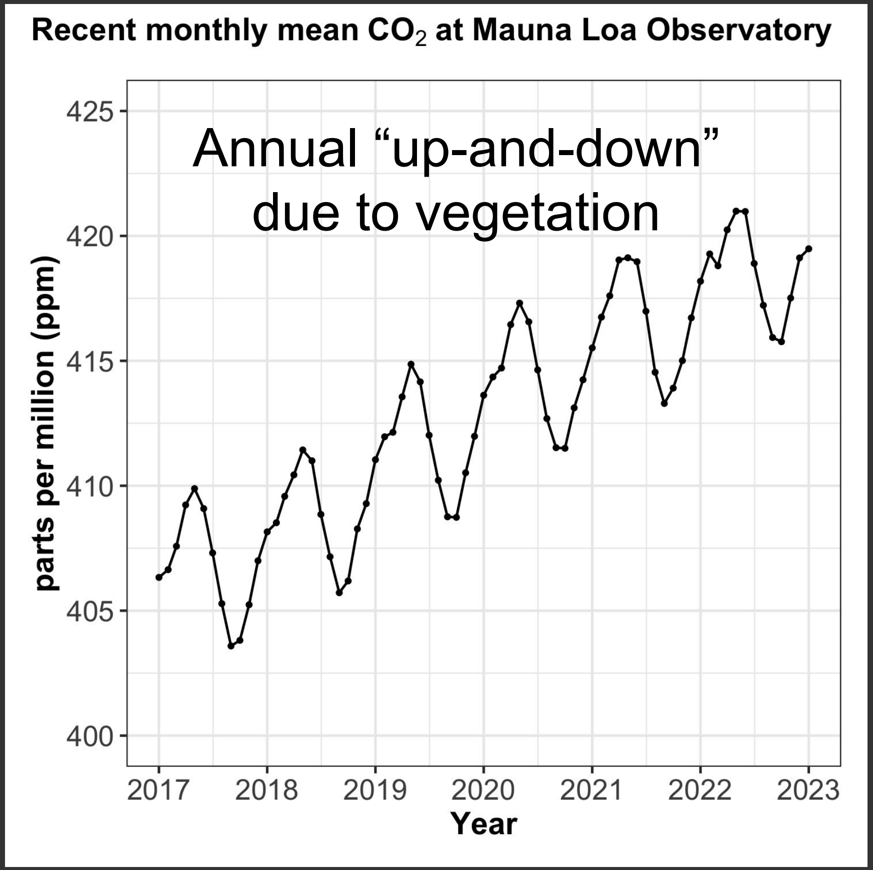
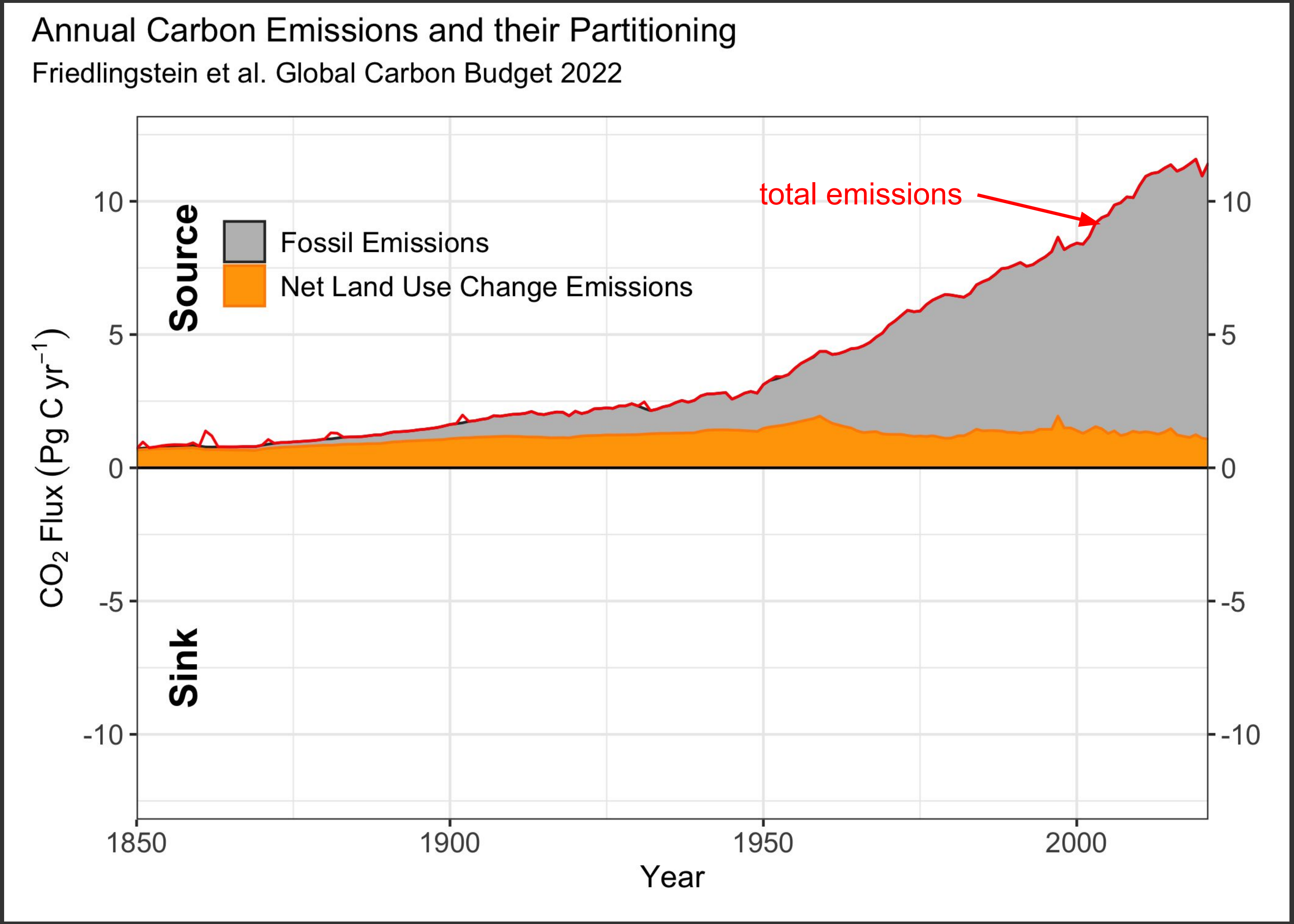
Vegetation impacts climate

MODIS NDVI





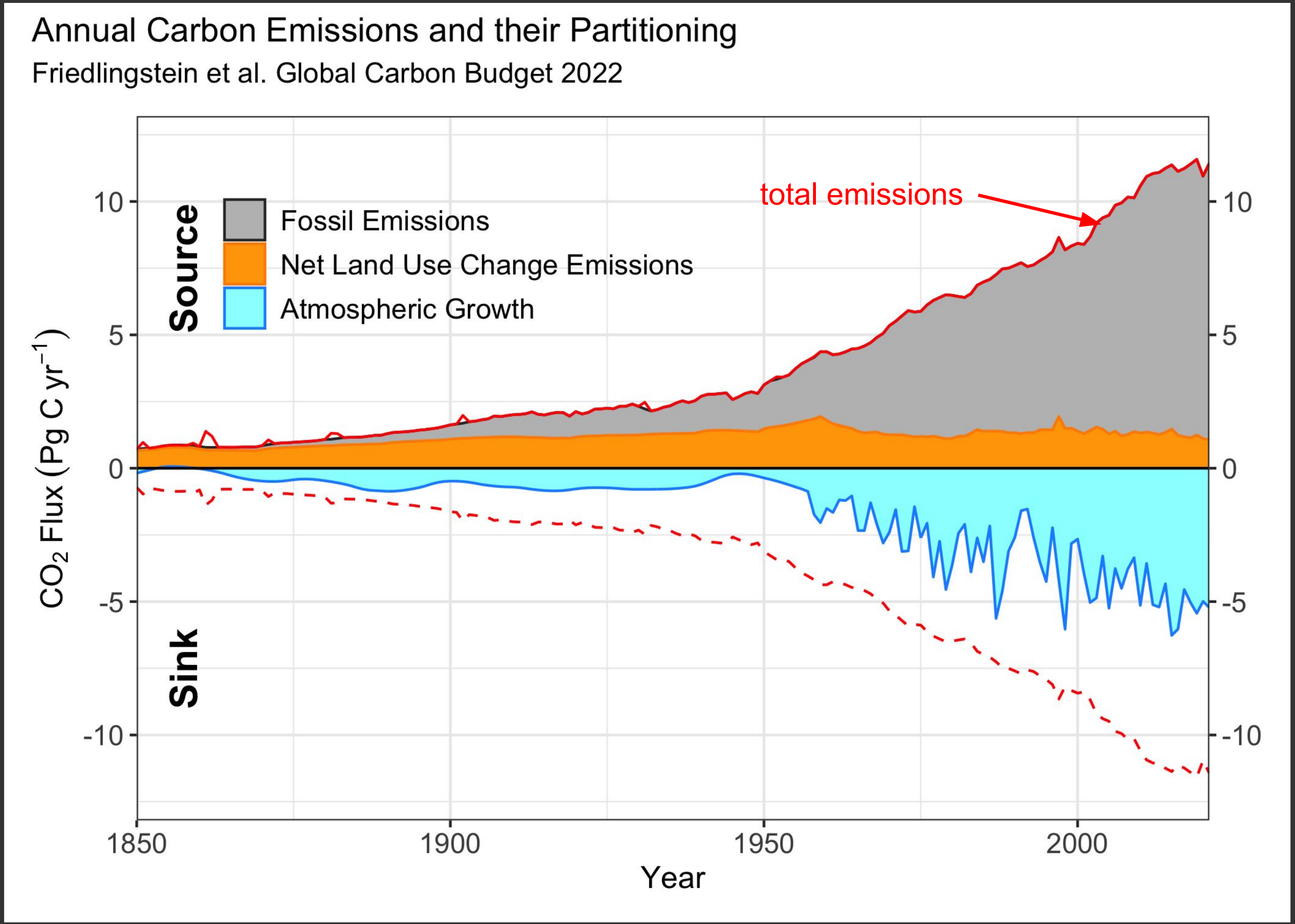
Annual C emissions



Energy statistics and cement production data

Land use and land use change data

Where are these emissions going?



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Atmospheric CO_2 – observations

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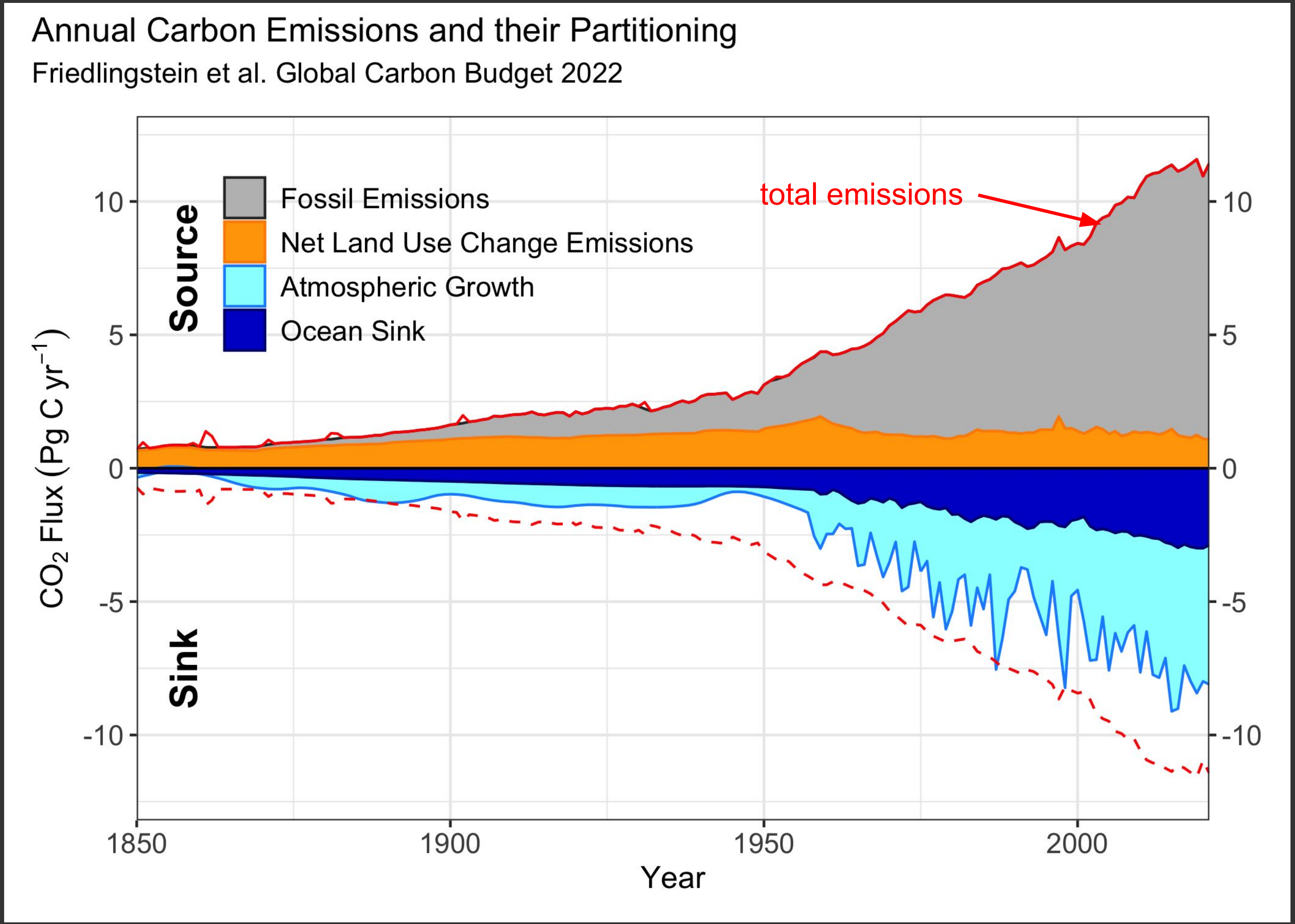

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Ocean sink – ocean biogeochemistry models, data products

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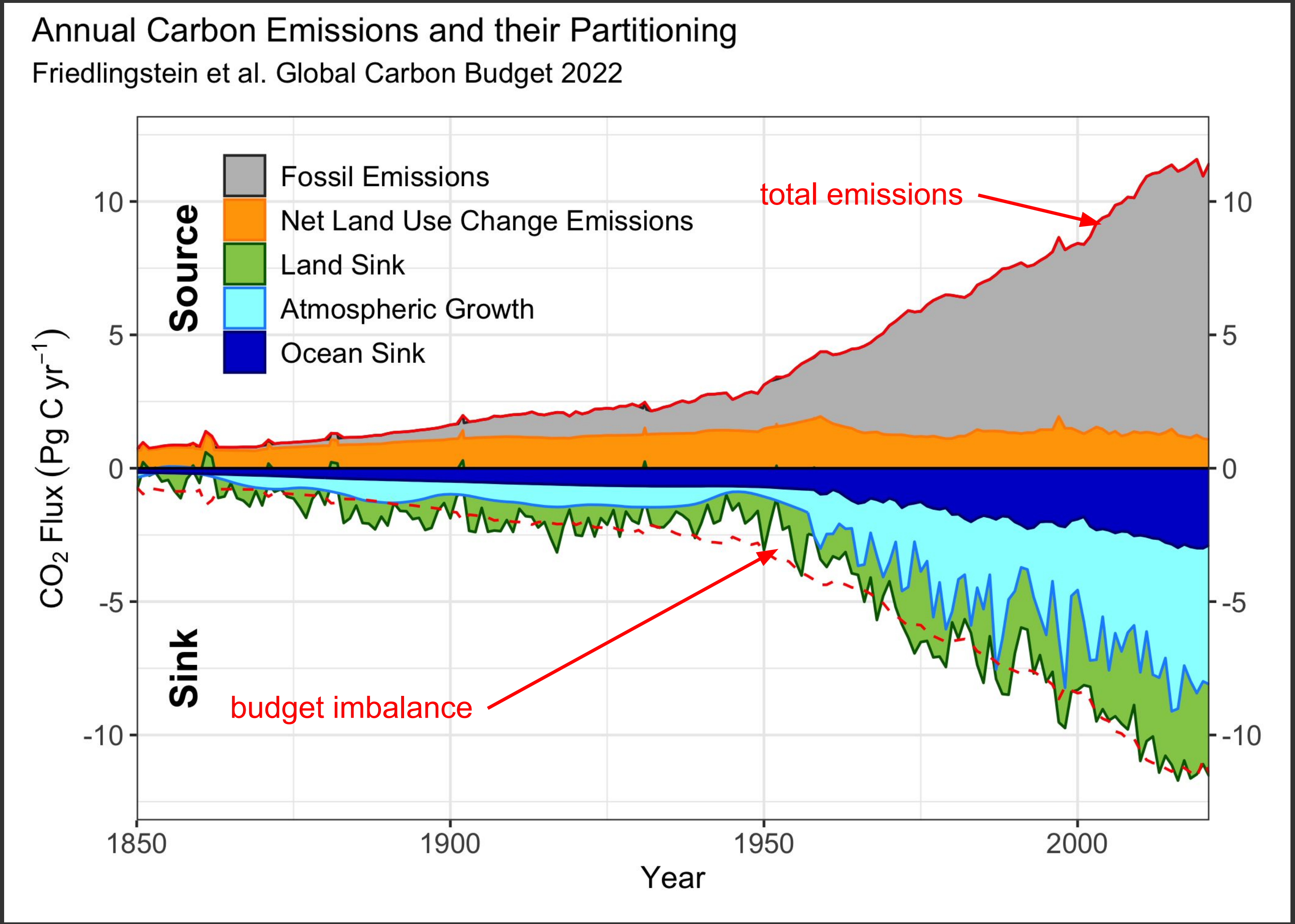

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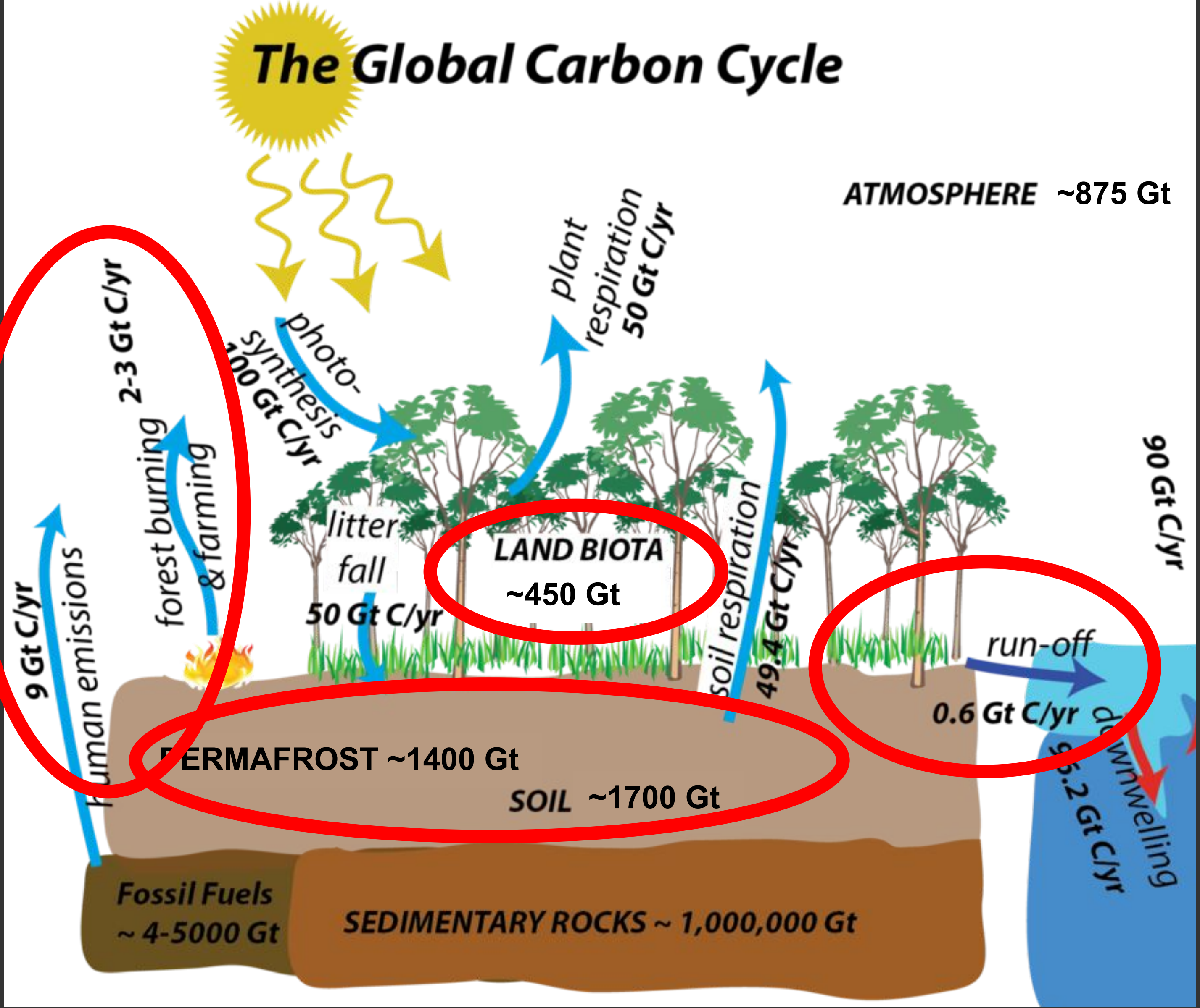
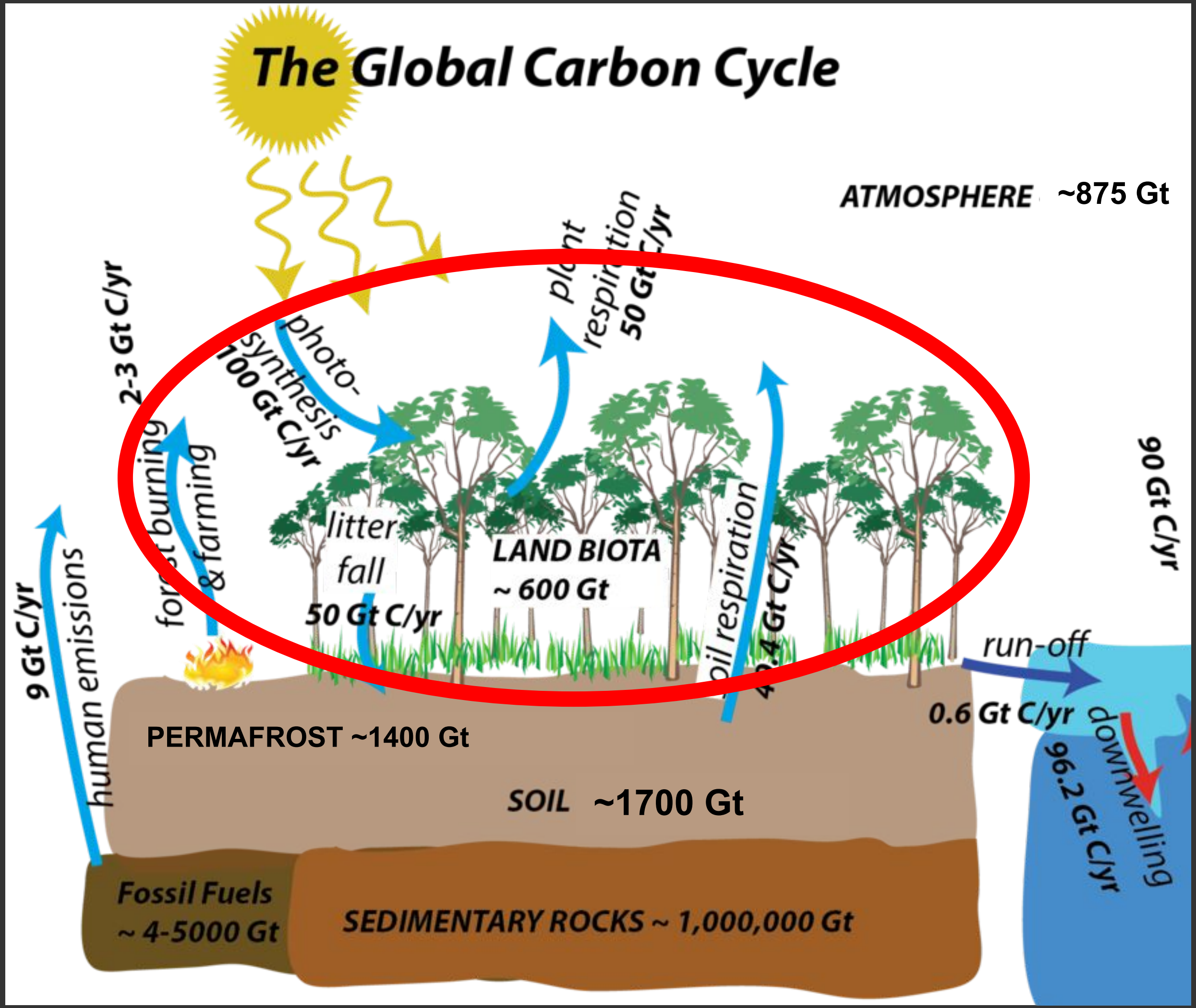
Land sink – global vegetation models



https://serc.carleton.edu/integrate/teaching_materials/earth_modeling/student_materials/unit9_article1.html

Huge pools
Large fluxes
Sink = small residual



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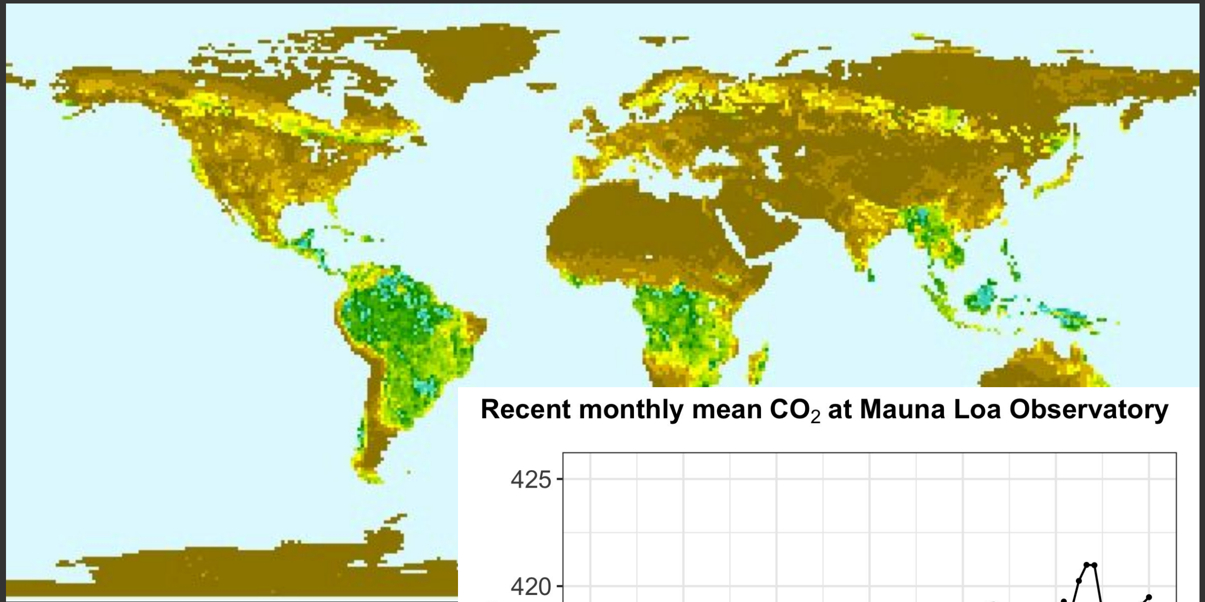
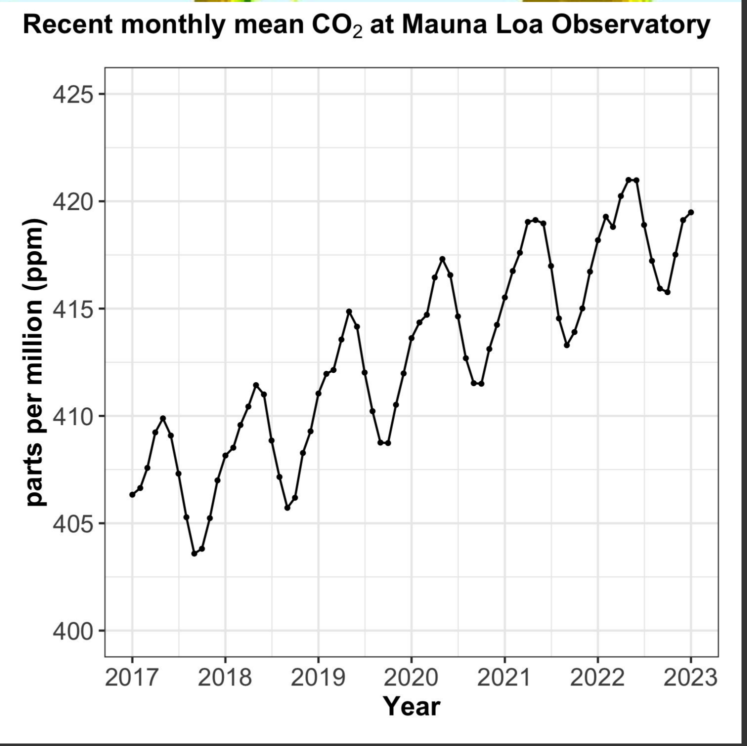
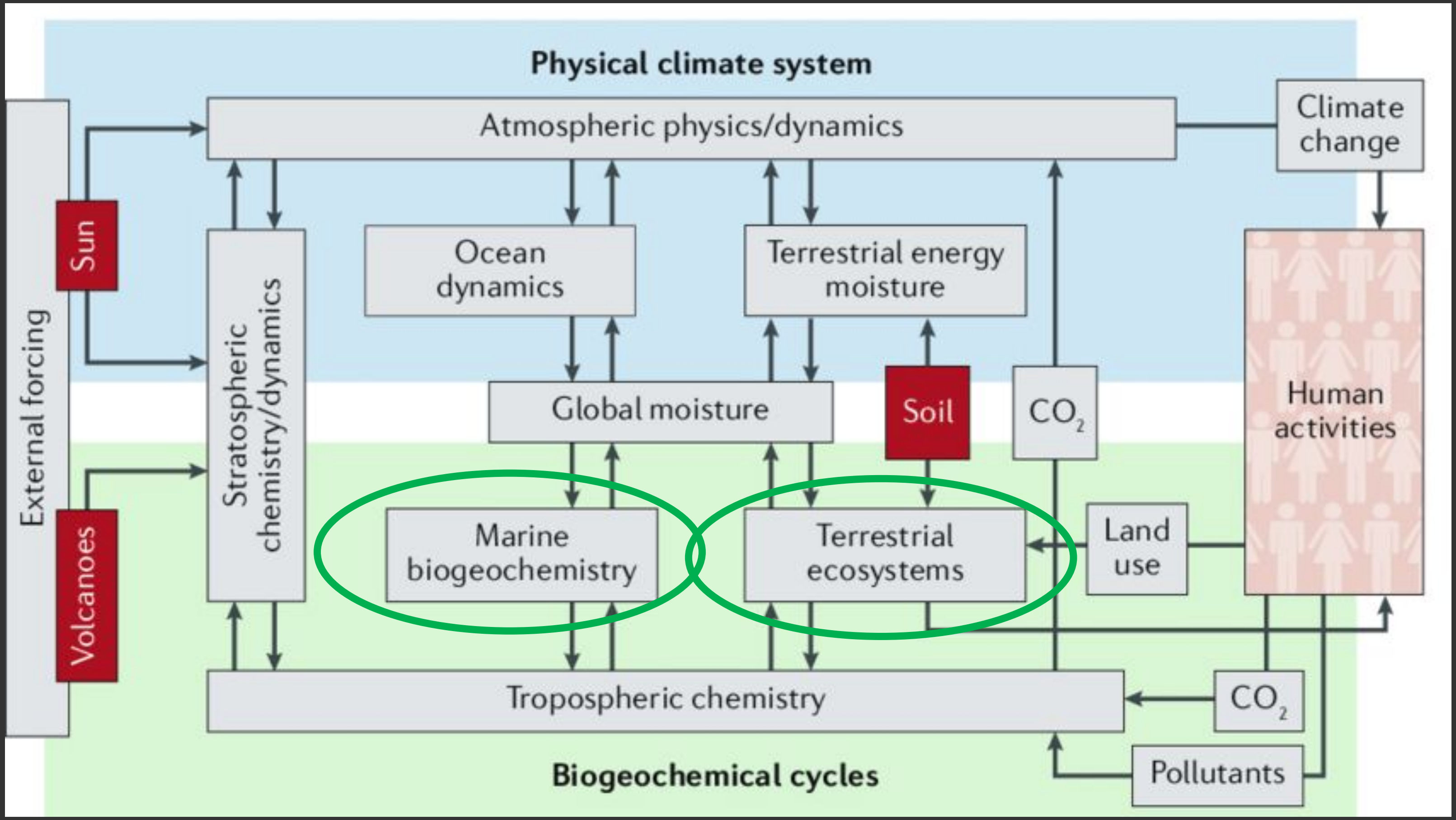




Land biogeochemistry in CESM

Why?

How?



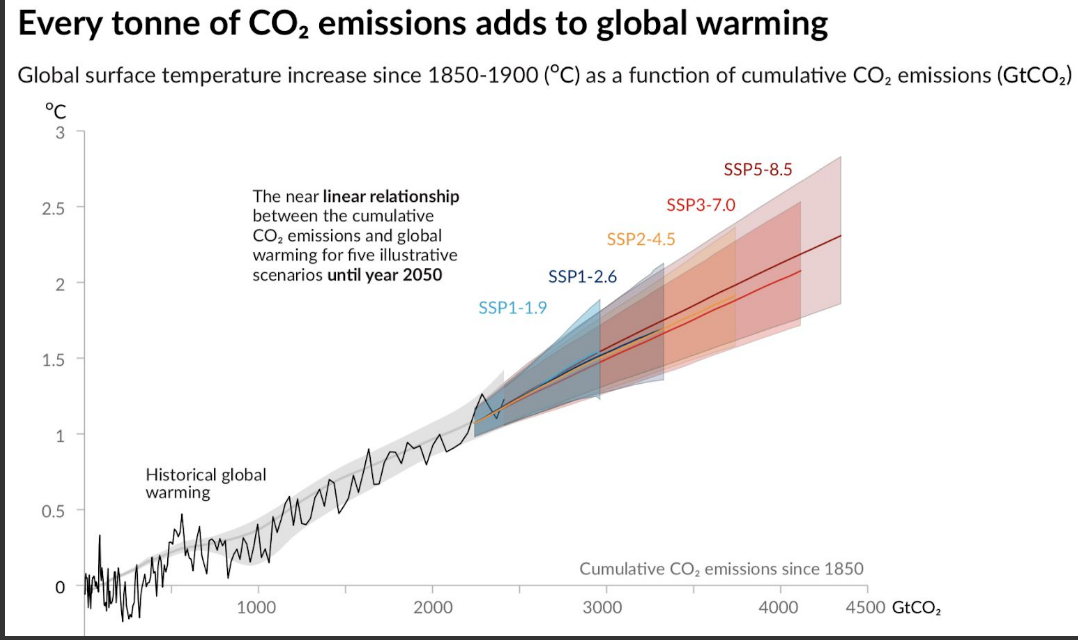
"Bretherton diagram" showing the concept of an Earth System Model

Full-Form Earth System Models: Coupled Carbon-Climate Interaction Experiment (the “Flying Leap”)

by Inez Fung, Peter Rayner, and Pierre Friedlingstein; Edited by Dork Sahagian

IGBP Newsletter, May 2000. The flying leap proposal was to make atmospheric CO2 a prognostic variable in climate models

A. Swann, BGCWG



NCAR and CESM were key players in the development of the concept and creation of the first coupled carbon cycle models.

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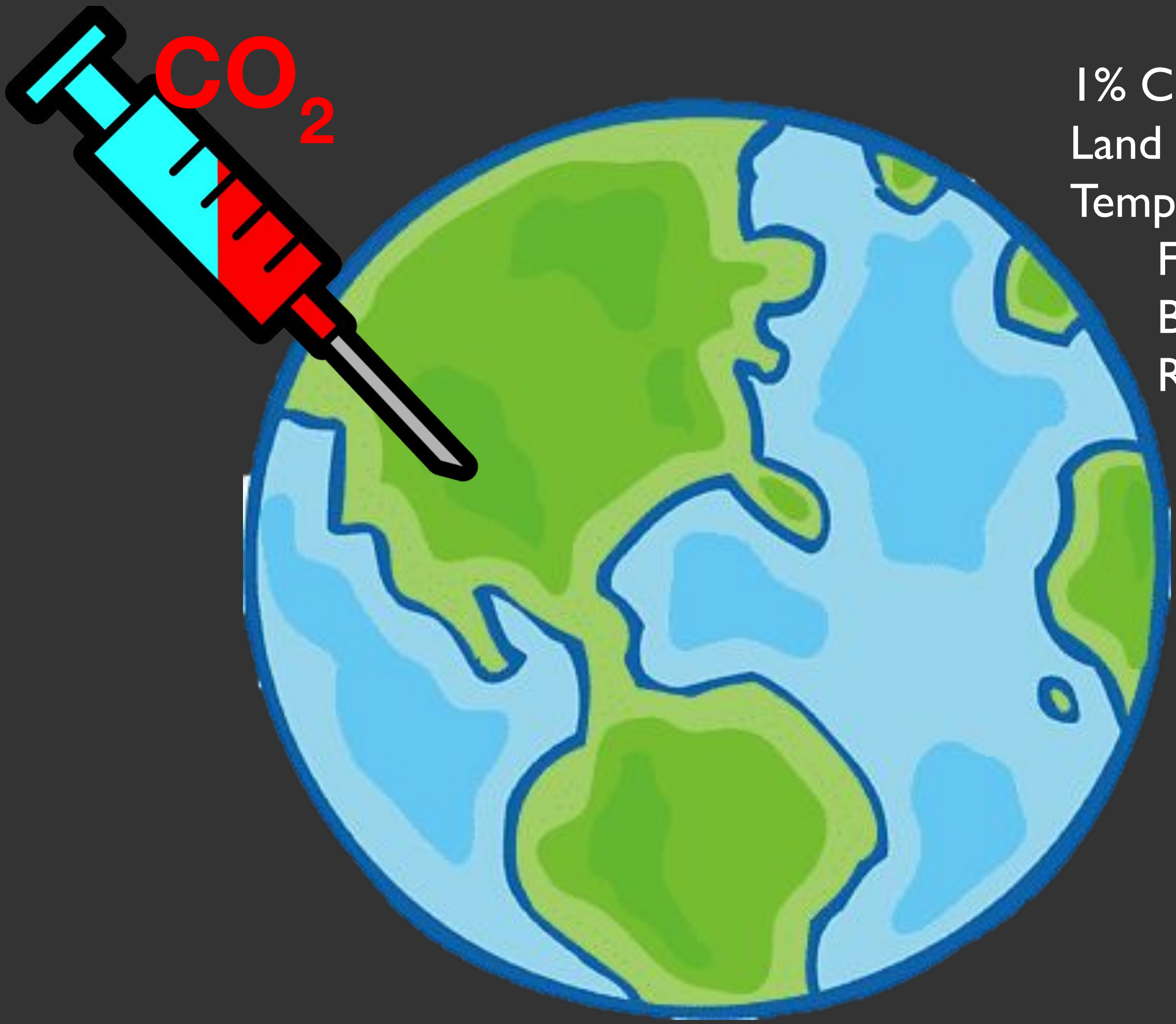
NCAR and CESM were key players in the development of the concept and creation of the first coupled carbon cycle models.

+ Coupled C-N biogeochemistry, CESM1
+ Explicit crop management, CESM2

Idealized experiments

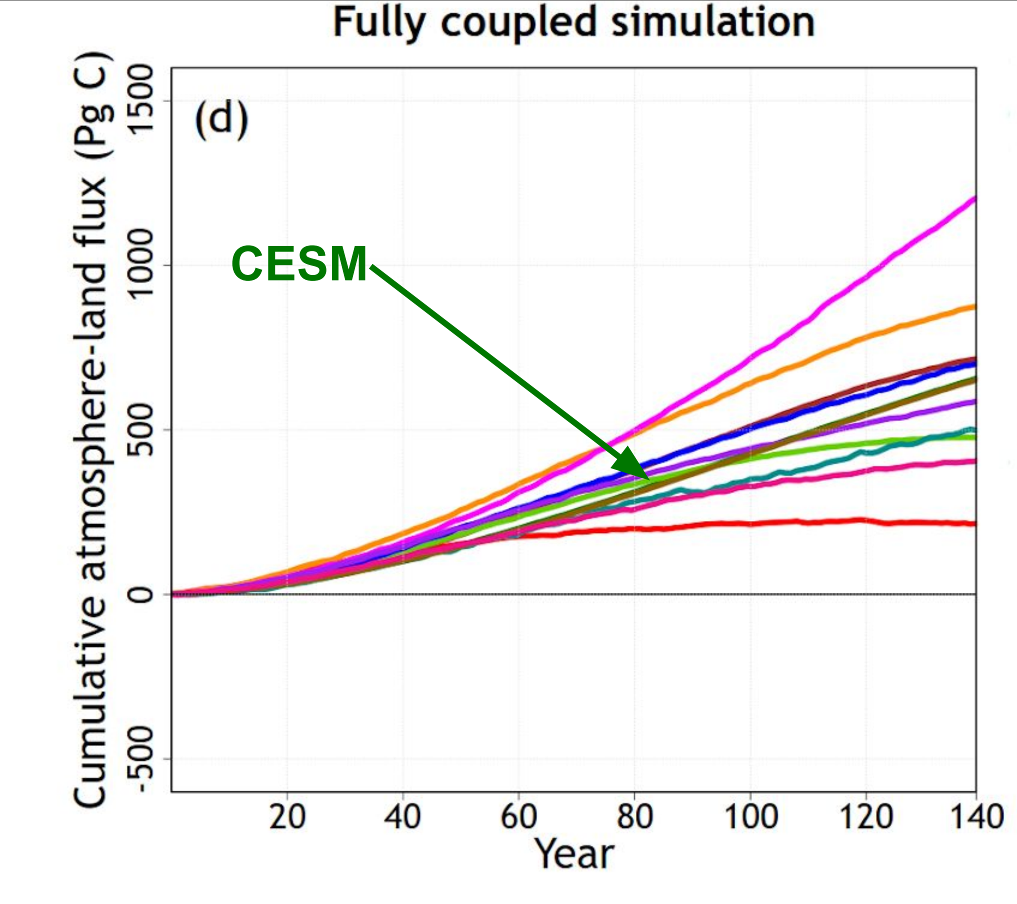


1% CO2 / year
Land & Ocean uptake
Temperature change
- Fully coupled
- Biogeochemically coupled
- Radiatively coupled

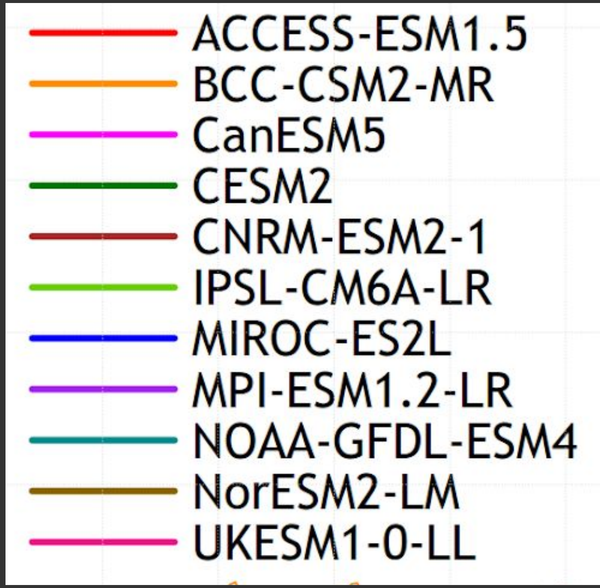
Arora et al. 2020

Idealized experiments

Cumulative land CO_2 sink

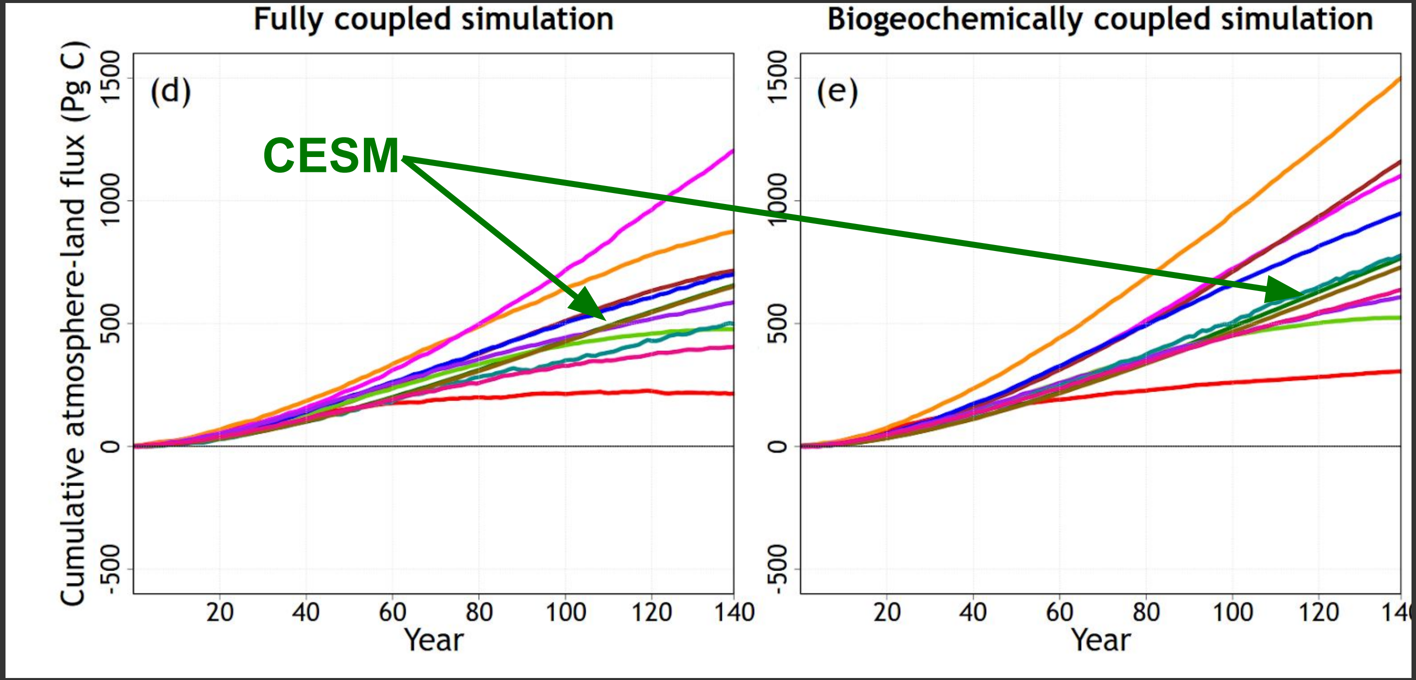


CMIP6 models



Arora et al. 2020

Cumulative land CO_2 sink



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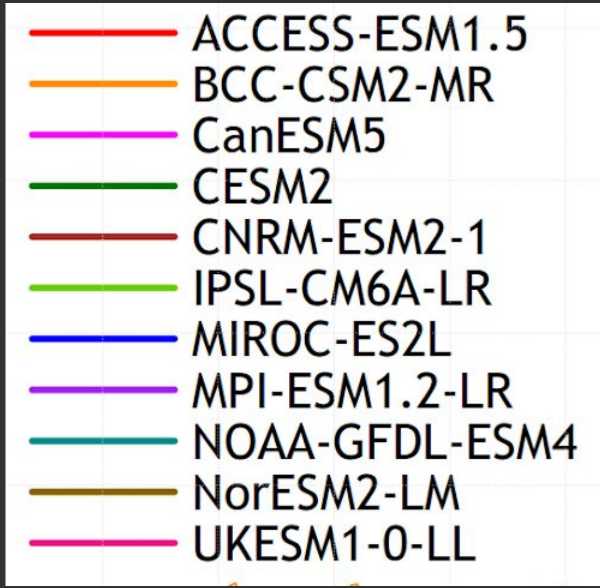

Arora et al. 2020

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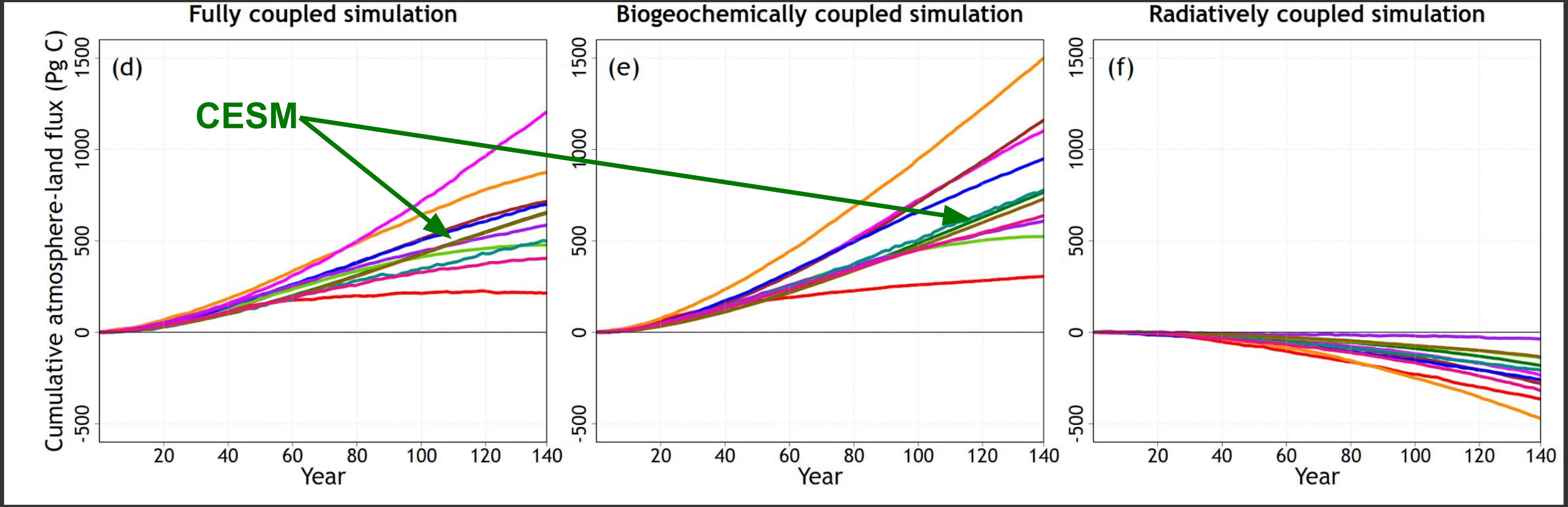
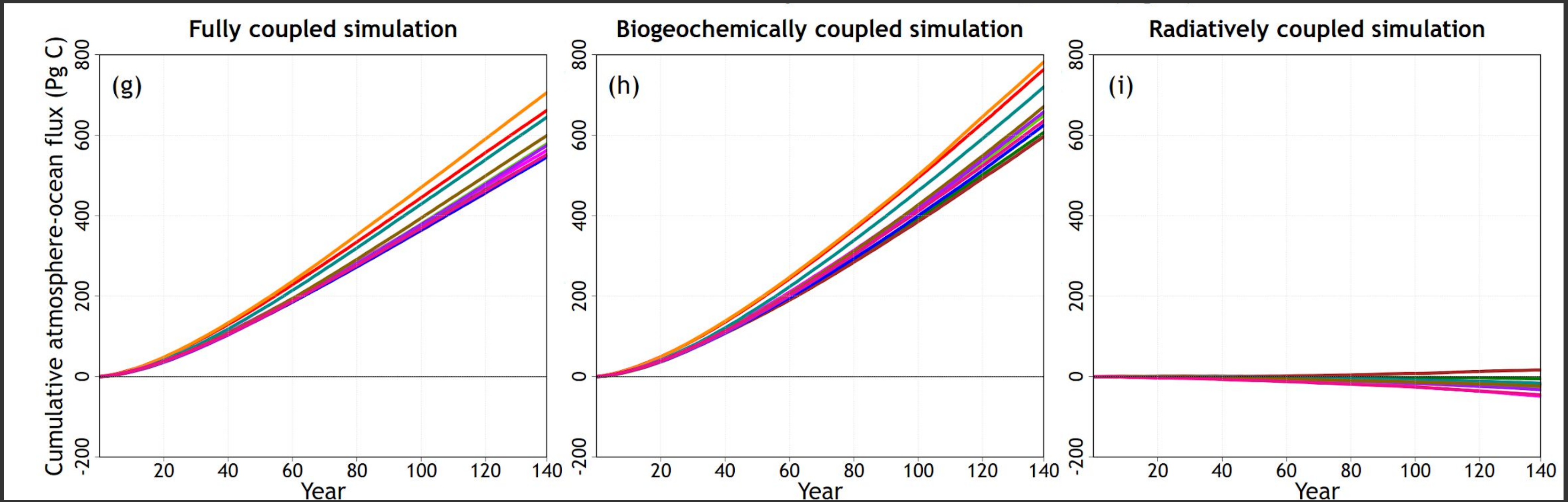


Arora et al. 2020

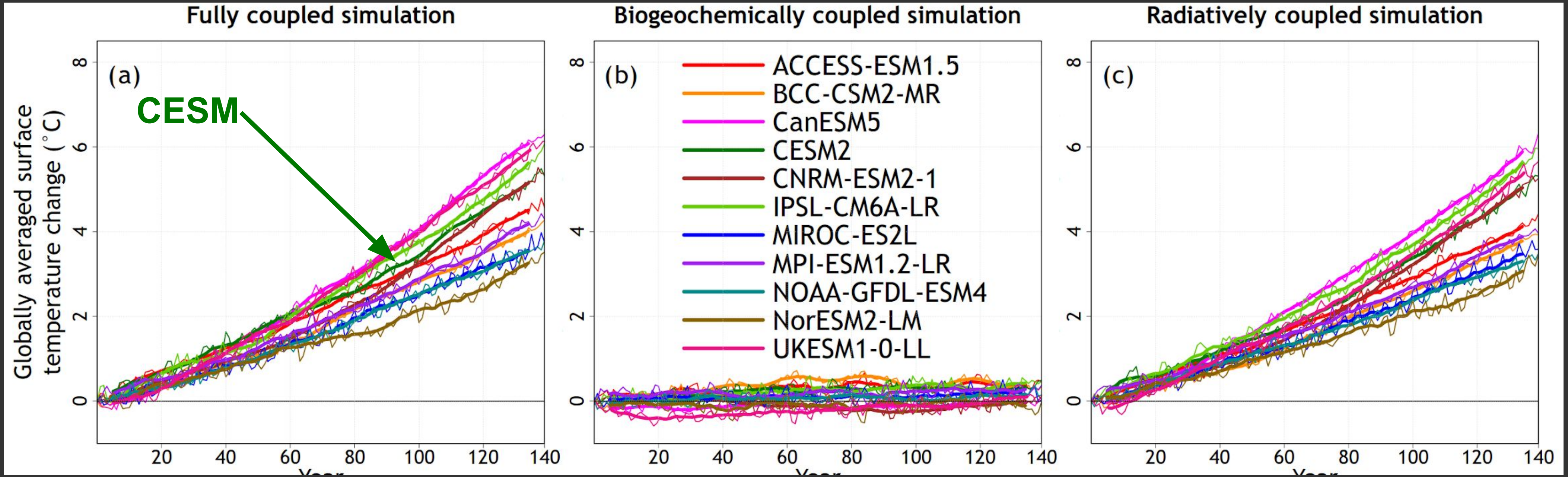
Cumulative ocean CO_2 sink



Arora et al. 2020

Idealized experiments

Global average surface temperature change (ºC)



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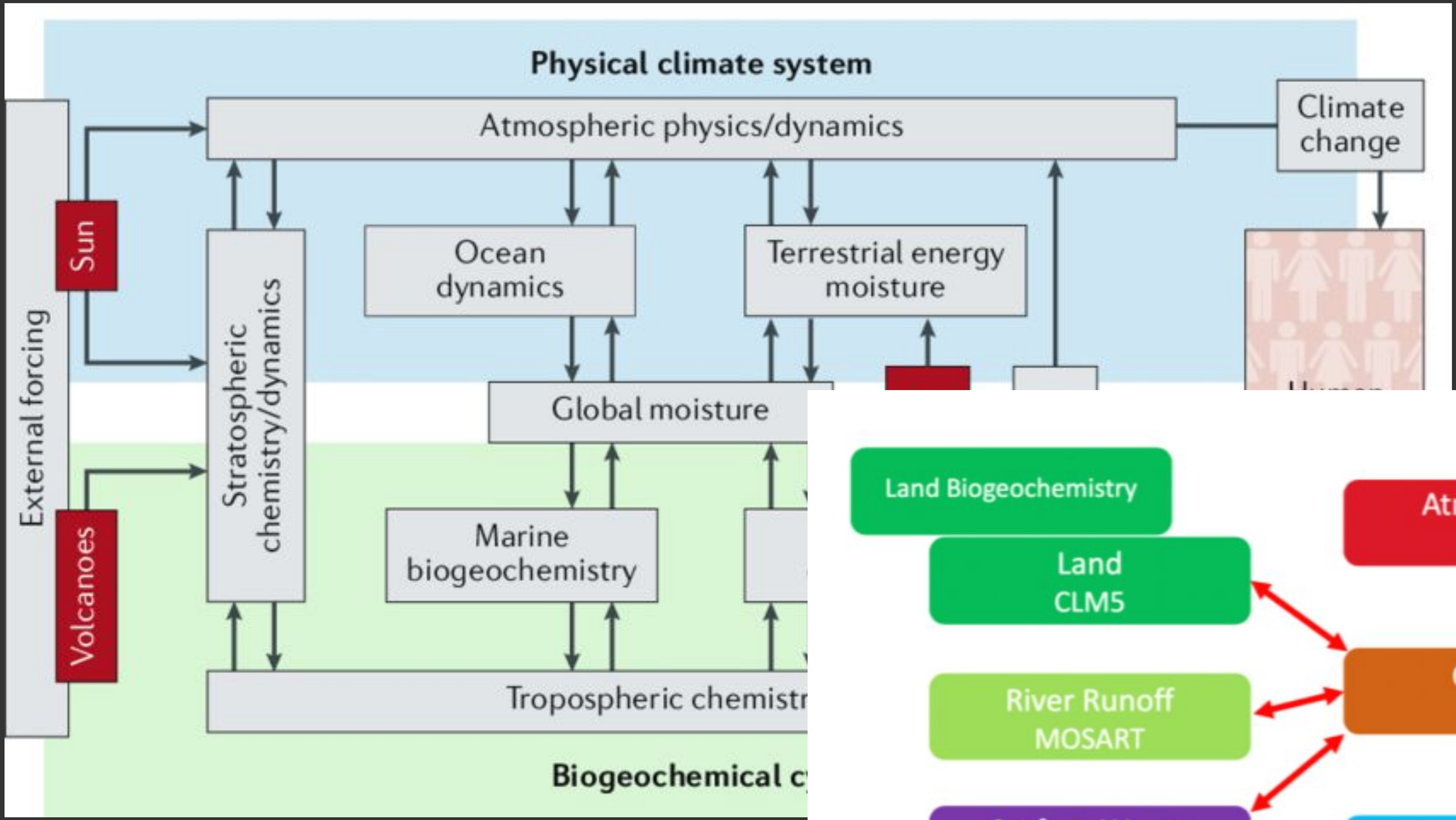
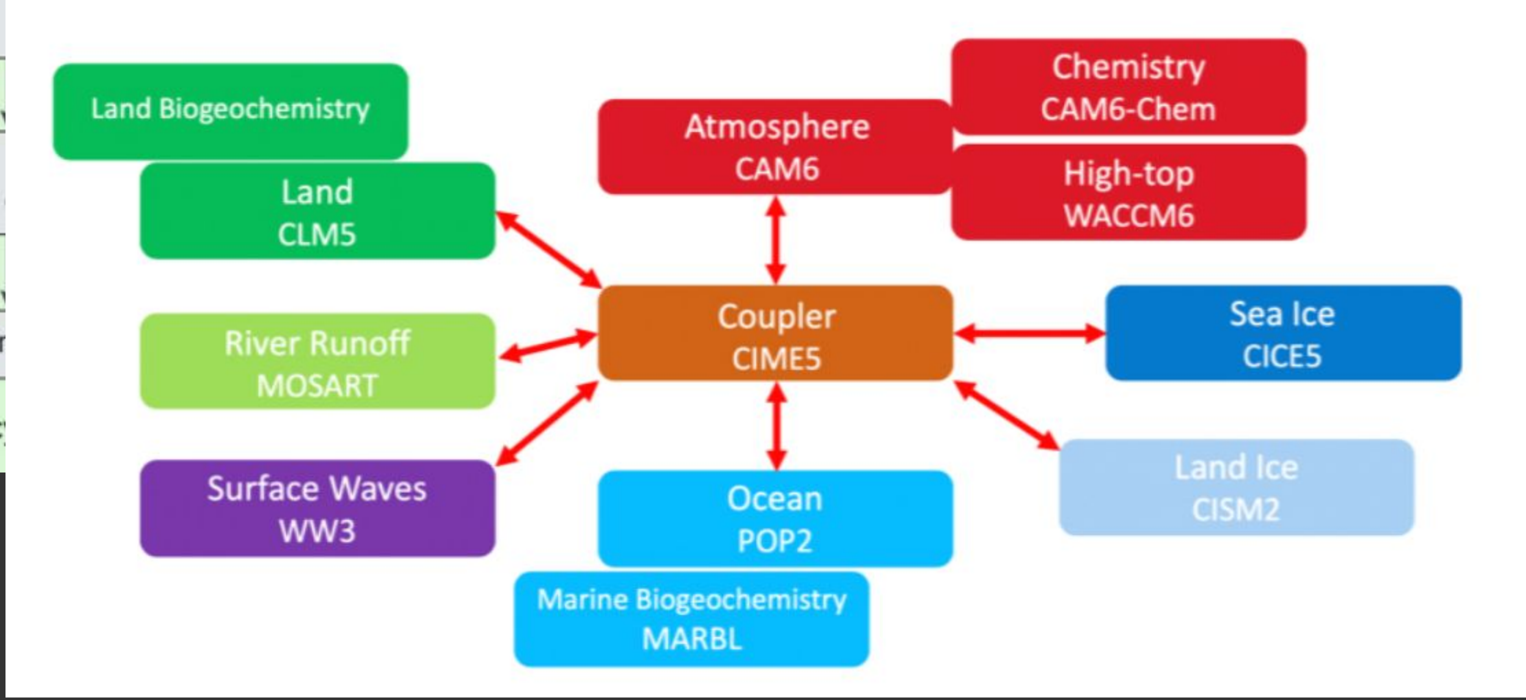
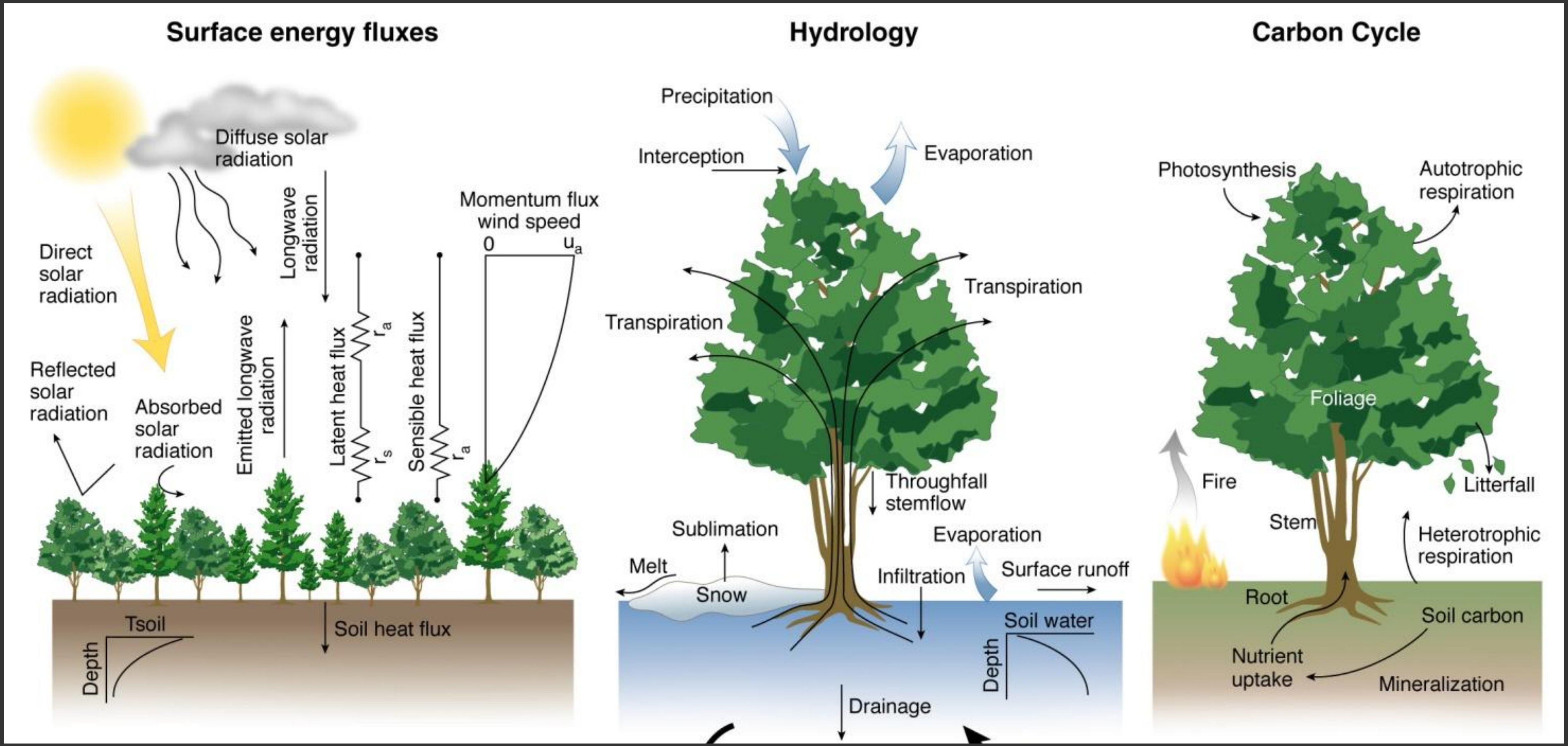
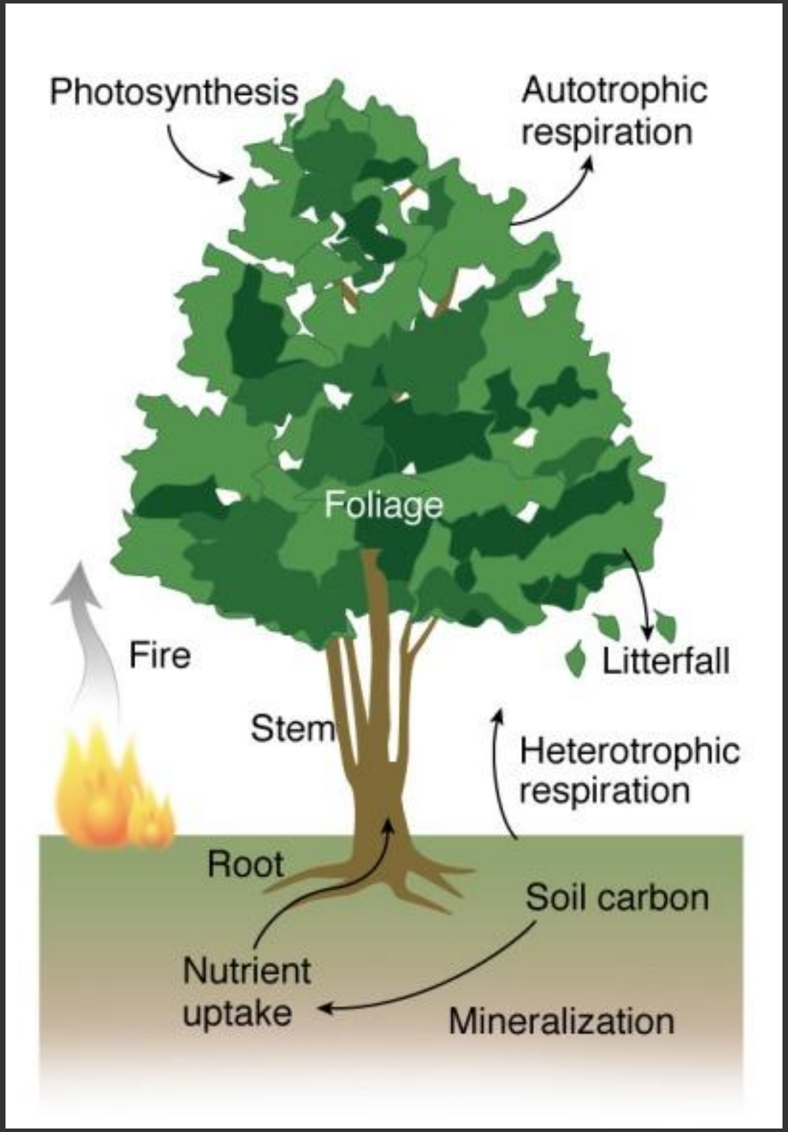




Community LAND MODEL DEVEL O N



Bonan 2008, Science



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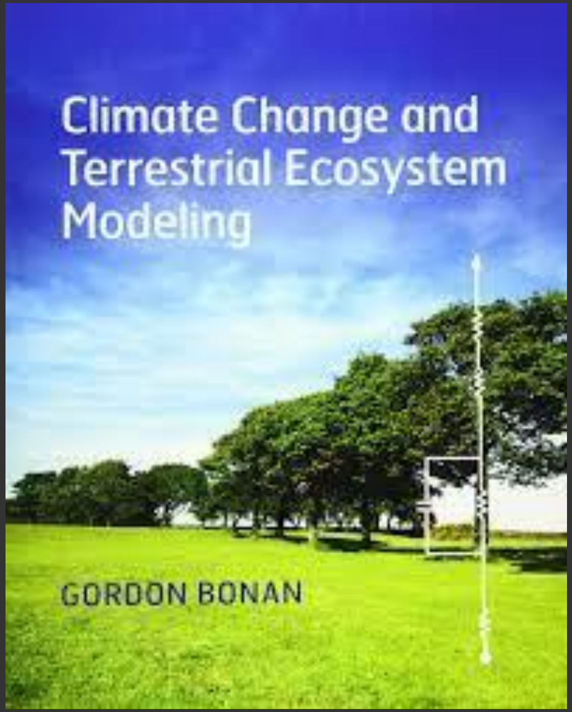
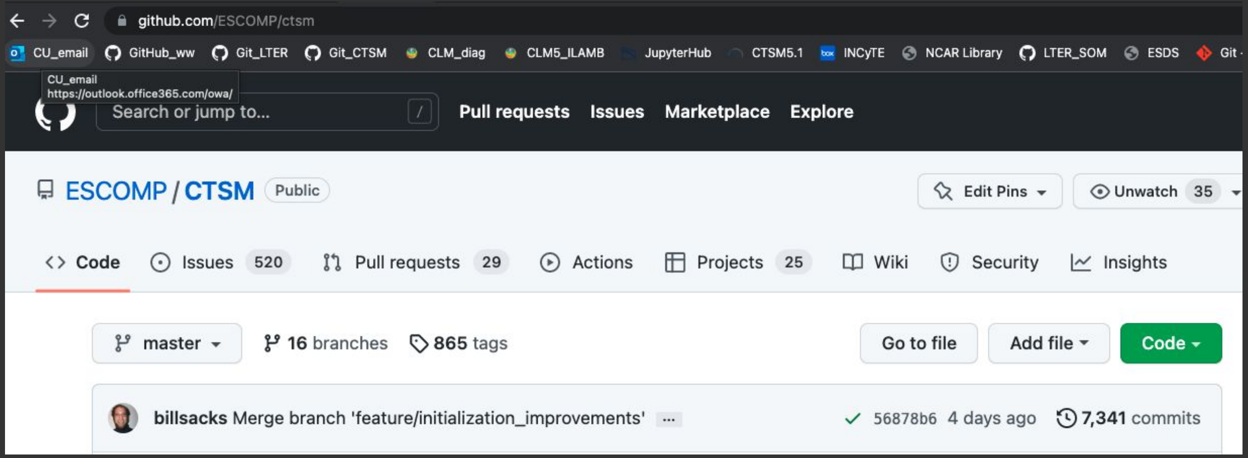
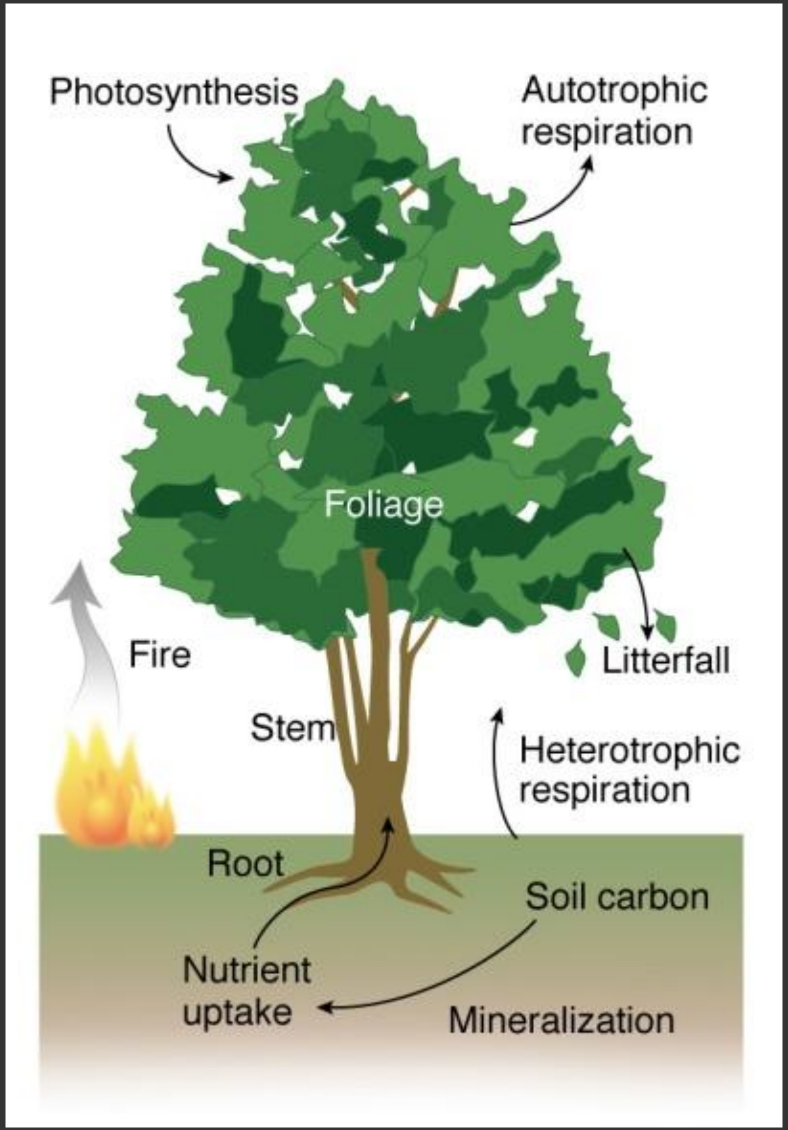




https://github.com/ESCOMP/ctsm



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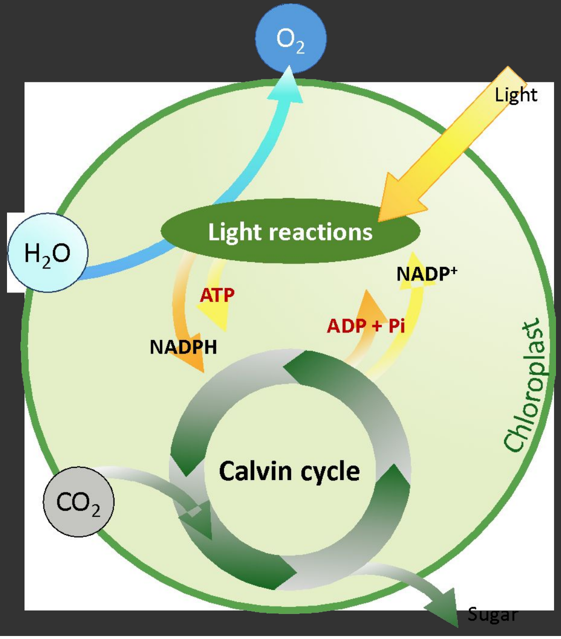
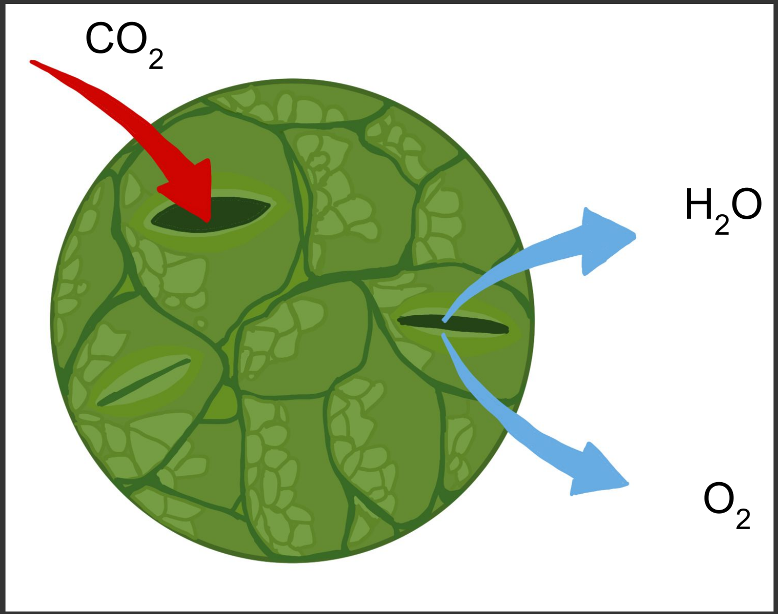
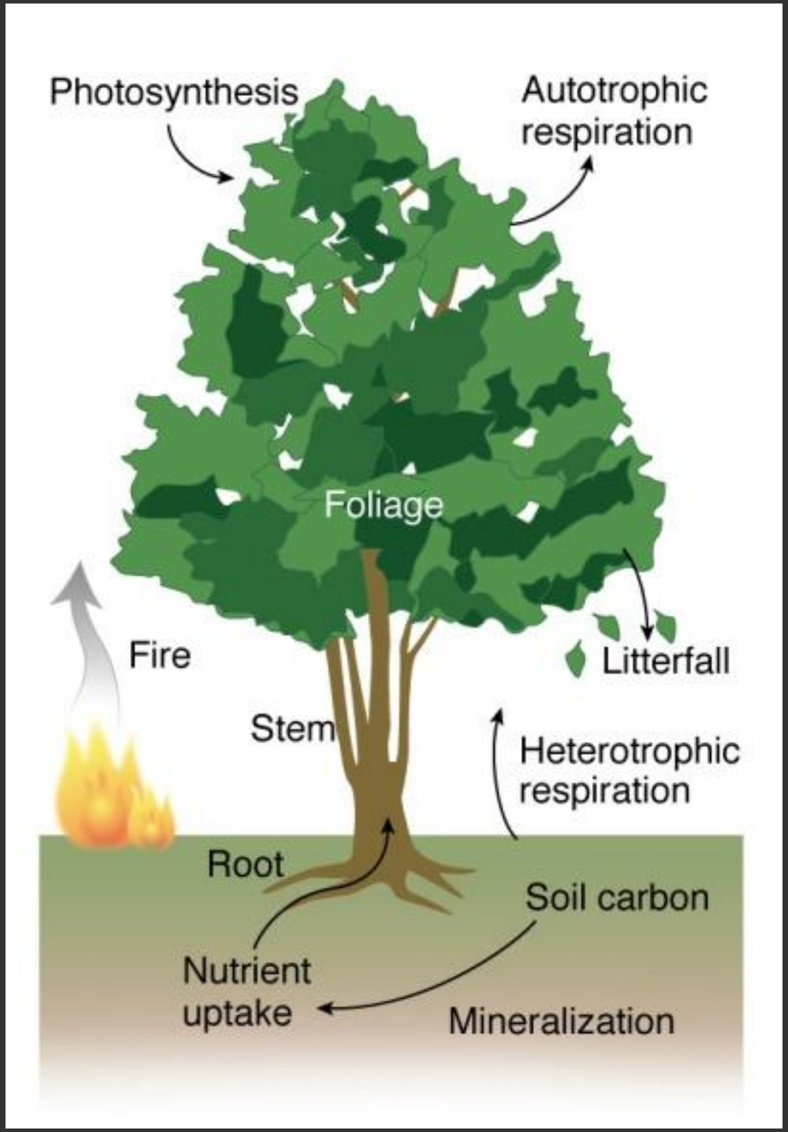
Leaves

Farquhar Photosynthesis
Medlyn Stomatal Conductance







Bonan 2008, Science

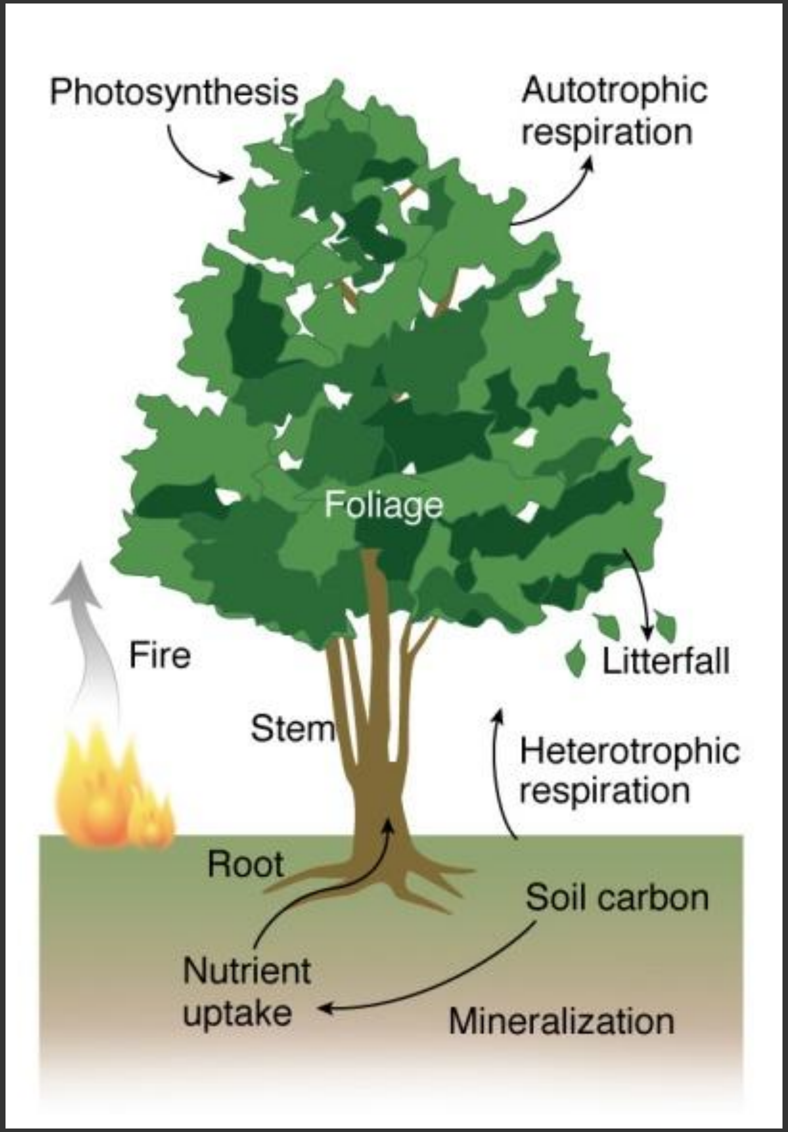
Leaves

- Farquhar Photosynthesis
- Medlyn Stomatal Conductance

Canopy

- Two stream approximation, sunlit / shaded

GPP - Gross Primary Productivity



Bonan 2008, Science

Leaves

Farquhar Photosynthesis

Medlyn Stomatal Conductance

Canopy

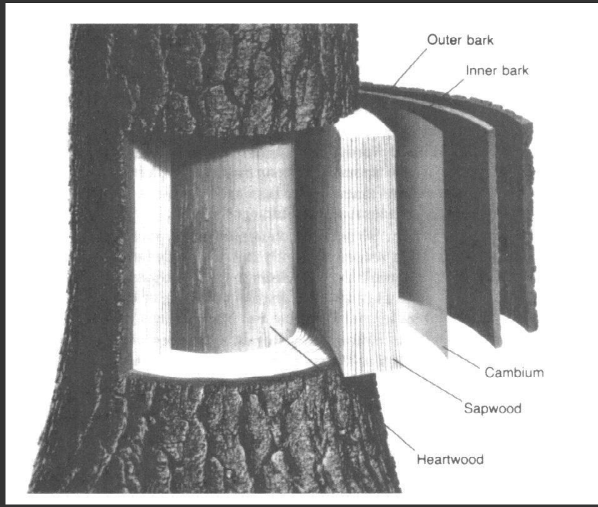
Two stream approximation, sunlit / shaded

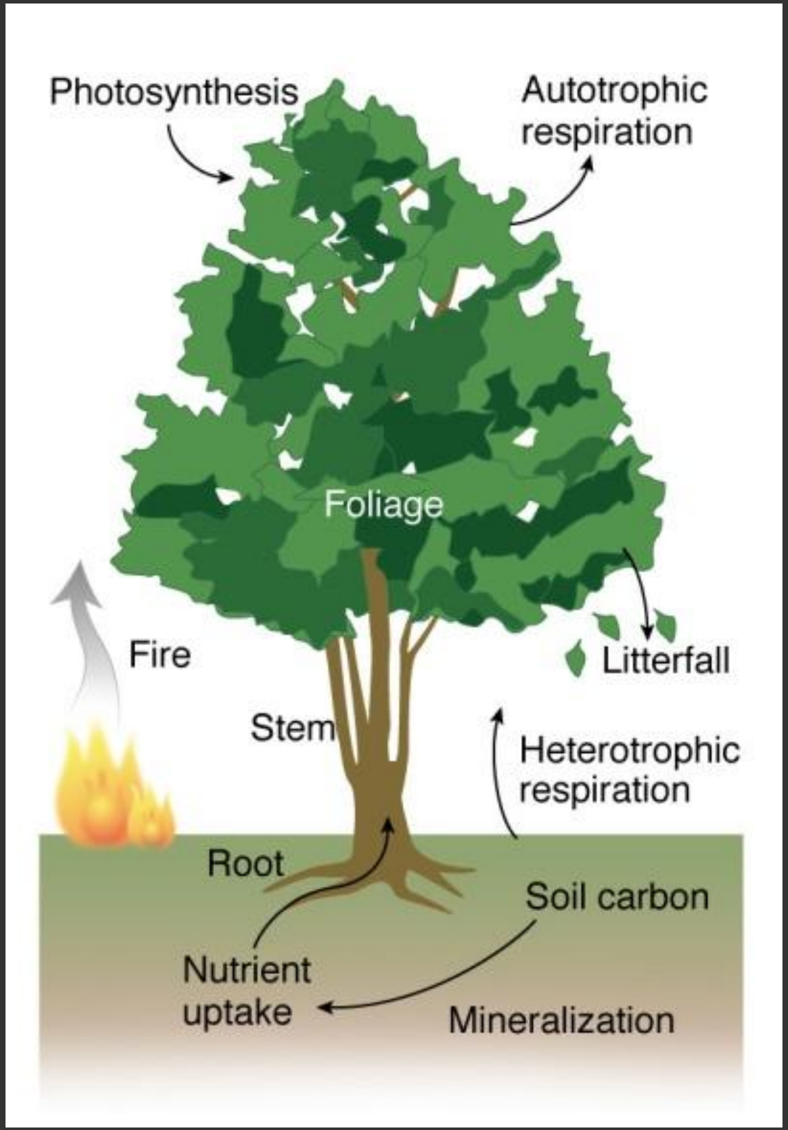
Allocation

Respiration, leaves, wood, roots

AU – Autotrophic Respiration

NPP – Net primary production = GPP - AR





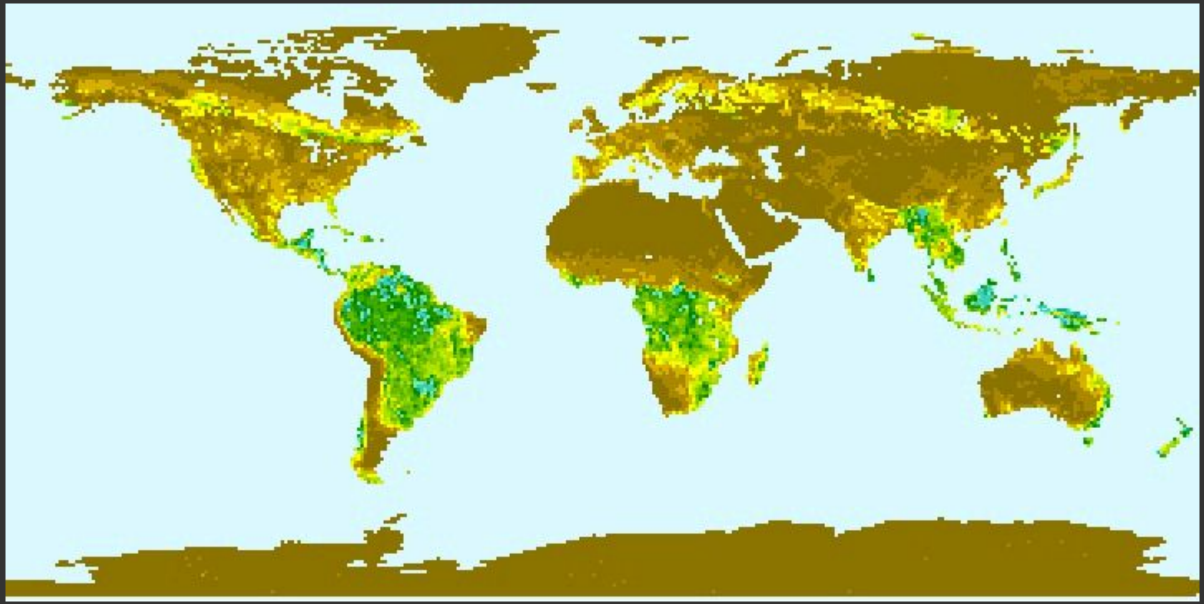
Bonan 2008, Science

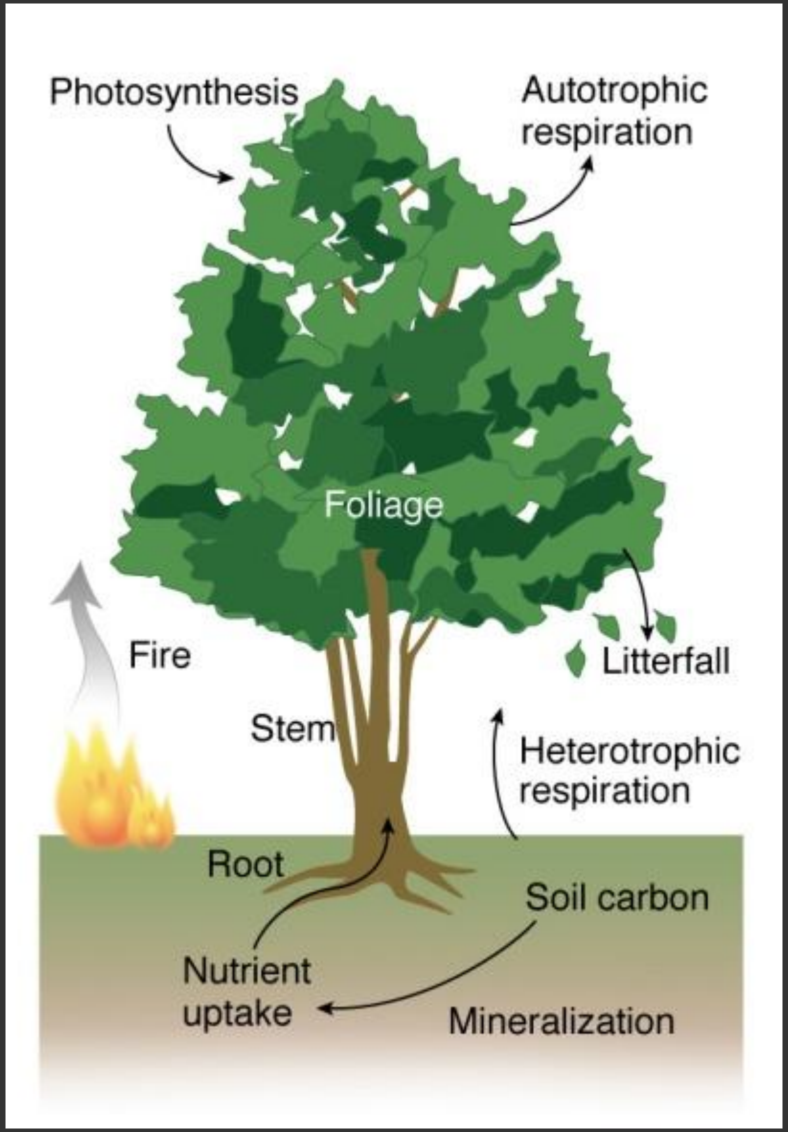
Phenology

mortality and turnover

(e.g., evergreen, drought or stress deciduous)

ELAI – Leaf Area Index





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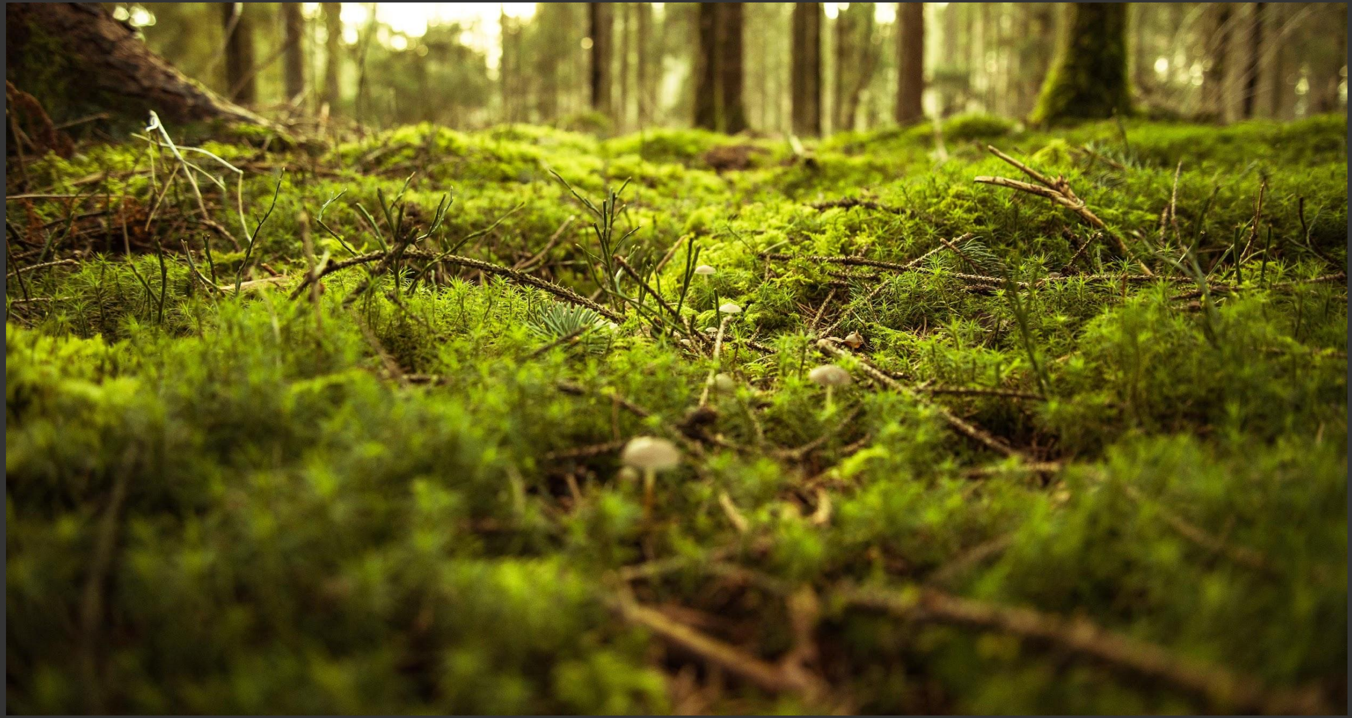
Phenology
 mortality and turnover
 (e.g., evergreen, drought or stress deciduous)

Decomposition

HR – Heterotrophic respiration



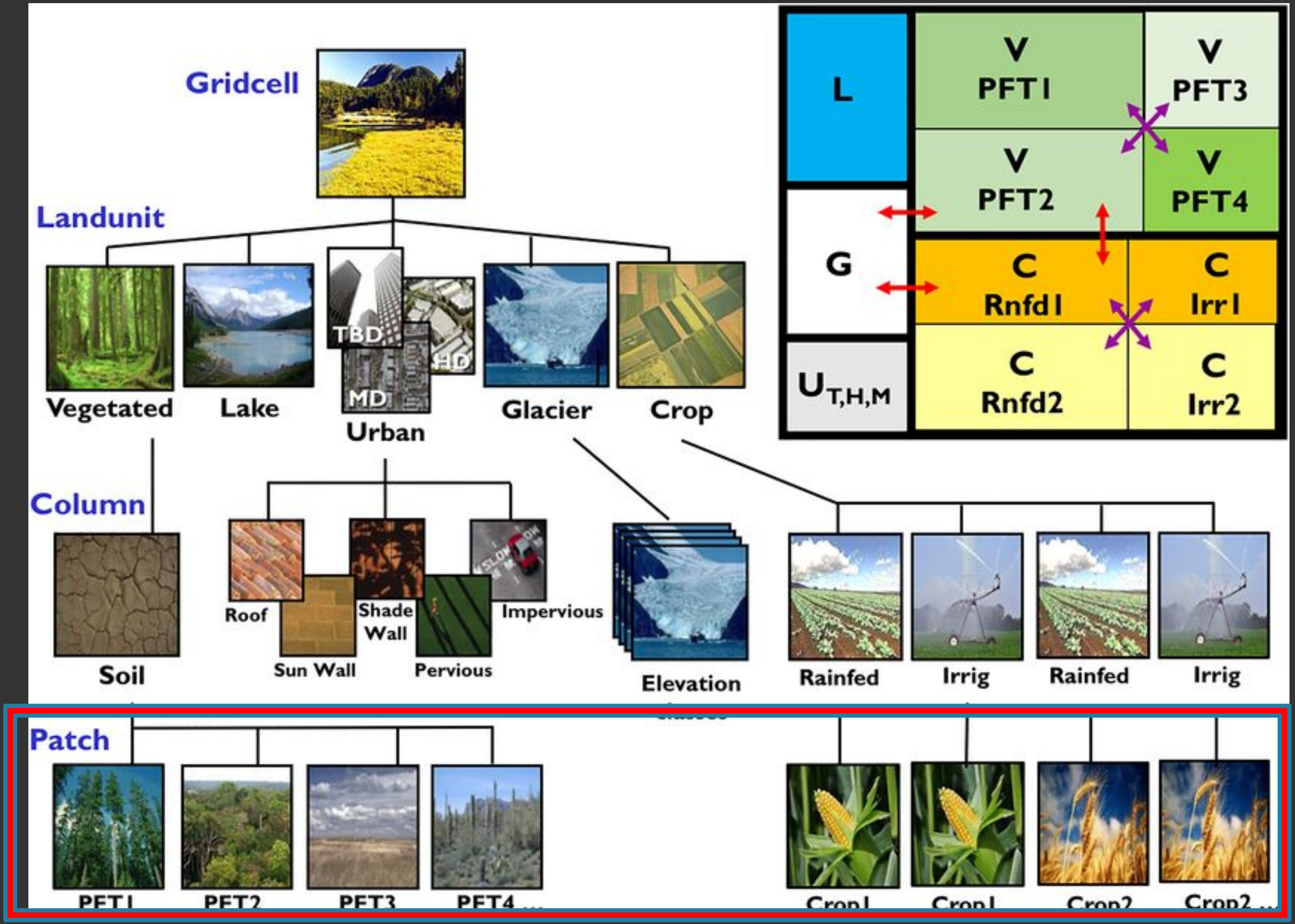
GPP - Gross Primary Productivity

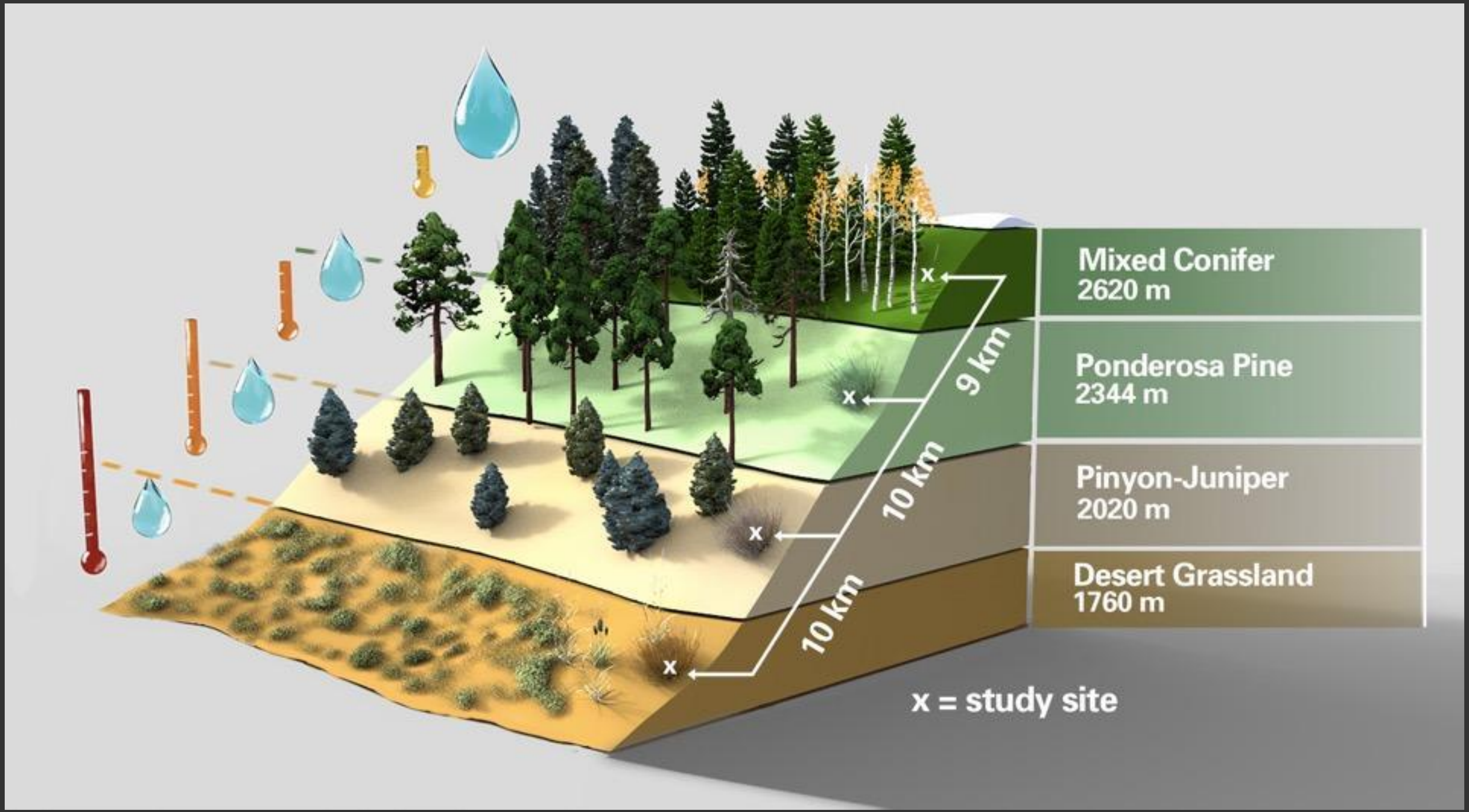
AR – Autotrophic respiration

NPP – Net primary productivity = GPP - AR
ELAI – Leaf Area Index

HR – Heterotrophic Respiration

NEP – Net Ecosystem Production = GPP – AR – HR
NEE – Net Ecosystem Exchange = NEP – Fire
NBP = NEE - Land Use - Harvest


Gridcell
Landunit
Vegetated
Lake
TBD
HD
MD
Urban
Glacier
Crop
Column
Soil
Roof
Sun Wall
Shade Wall
Pervious
Impervious
Elevation
Rainfed
Irrig
Rainfed
Irrig
Patch
PFT1
PFT2
PFT3
PFT4 ...
Crop1
Crop1
Crop2
Crop2 ...
L
V PFT1
V PFT3
V PFT2
V PFT4
G
C Rnfd1
C Irr1
C Rnfd2
C Irr2
U T,H,M



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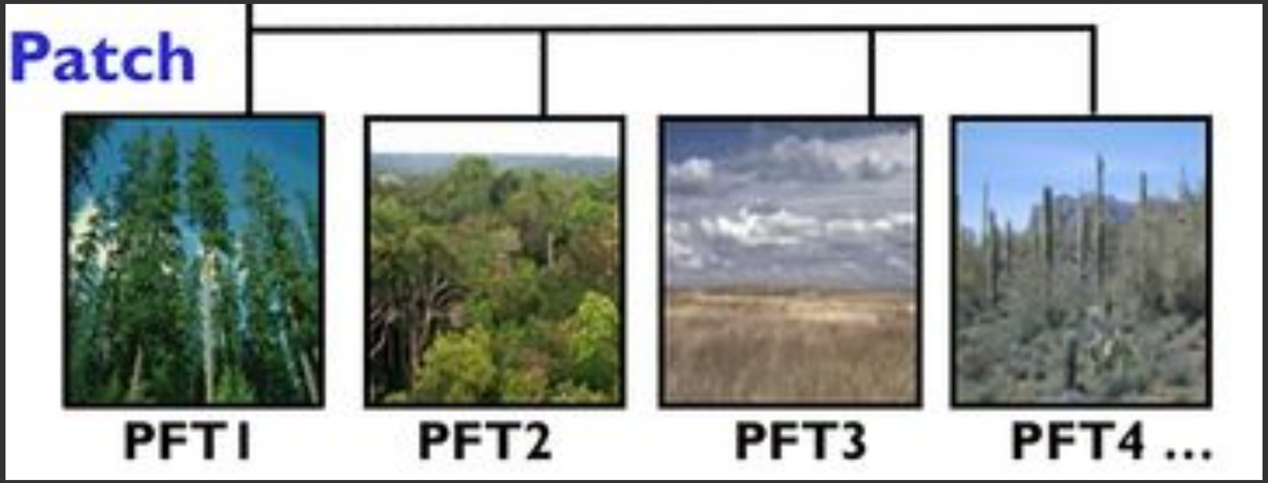
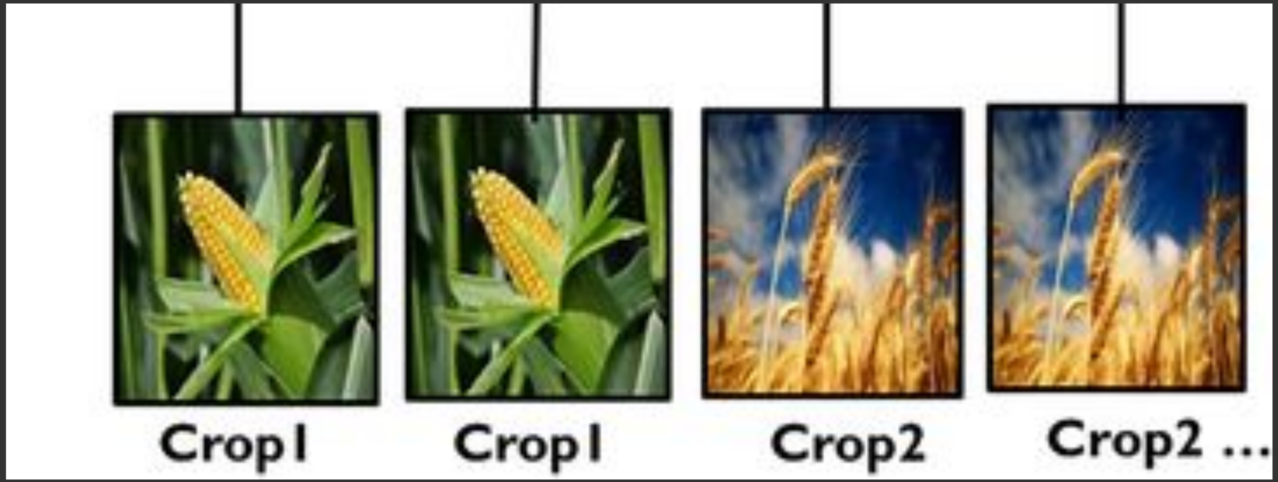
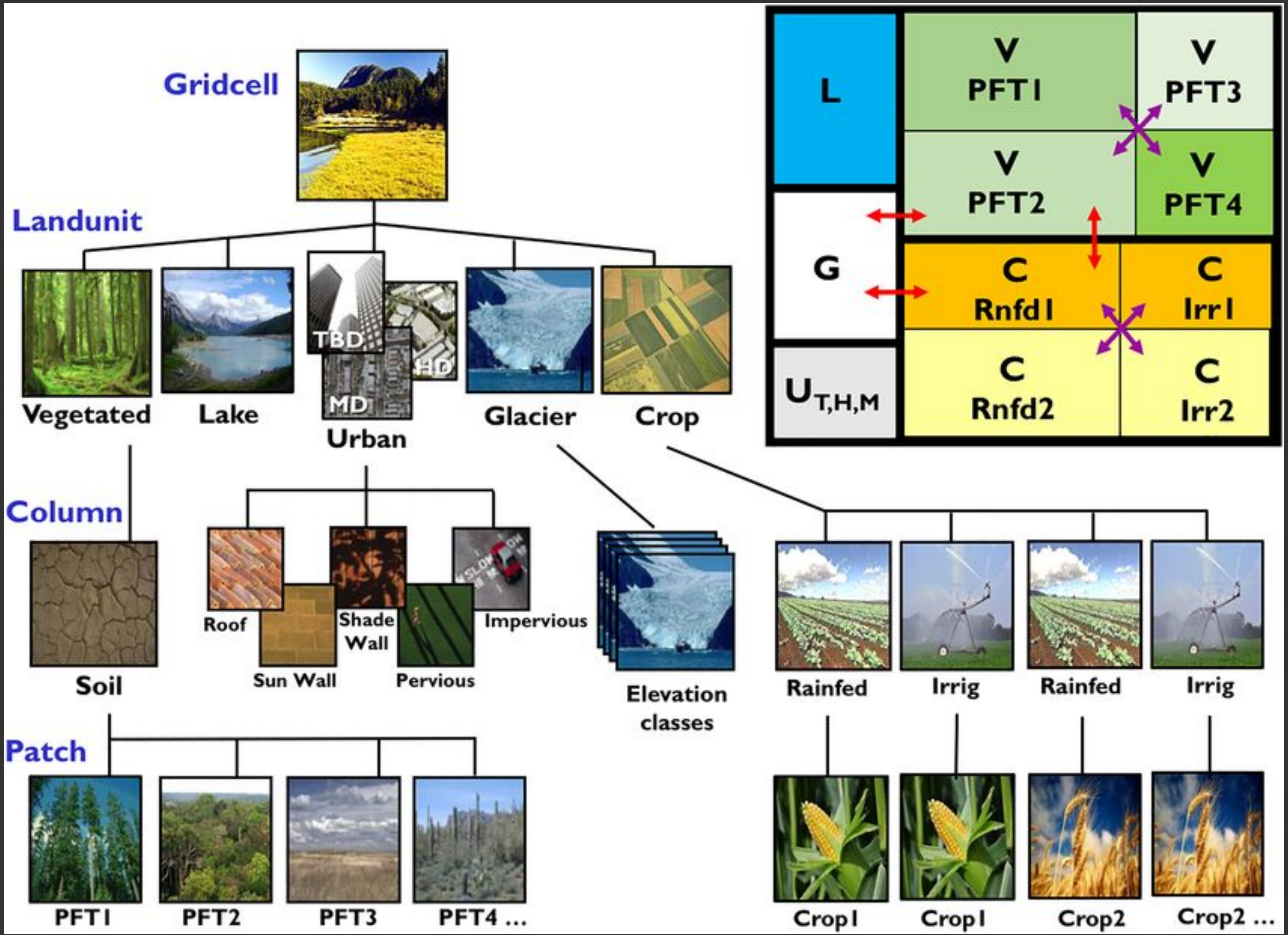

Patch
PFT1
PFT2
PFT3
PFT4 ...


Crop1
Crop1
Crop2
Crop2 ...


L
V
PFT1
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PFT2
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PFT4
G
C
Rnfd1
C
Irr1
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C
Irr2
$U_{T,H,M}$
Gridcell
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TBD
HD
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Vegetated
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Urban
Glacier
Crop
Column
Roof
Shade
Wall
Impervious
Soil
Sun Wall
Pervious
Elevation
classes
Rainfed
Irrig
Rainfed
Irrig
Patch
PFT1
PFT2
PFT3
PFT4 ...
Crop1
Crop1
Crop2
Crop2 ...

Agriculture in CLM5

Corn*

Wheat

Sugarcane

Soy*

Cotton

Rice

* Temperate and tropical varieties

Agriculture in CLM5

Fertilize

Irrigate

Transient fertilizer and irrigation (1850-2100)

1850 fertilizer assumed to be from manure only

Where do parameterizations come from?

1. **Laboratory understanding: of plant physiological processes**
   e.g., Farquhar: Photosynthesis is co-limited by: light, energy, export of sugars

2. **Empirical relationships: From as large a sample of the real world as possible**
   e.g., TRY Database (Leaf N and dark respiration)

3. **Optimality theory: plants try to optimize things like water use efficiency**
   e.g., FUN and LUNA modules

Land biogeochemistry in CESM?

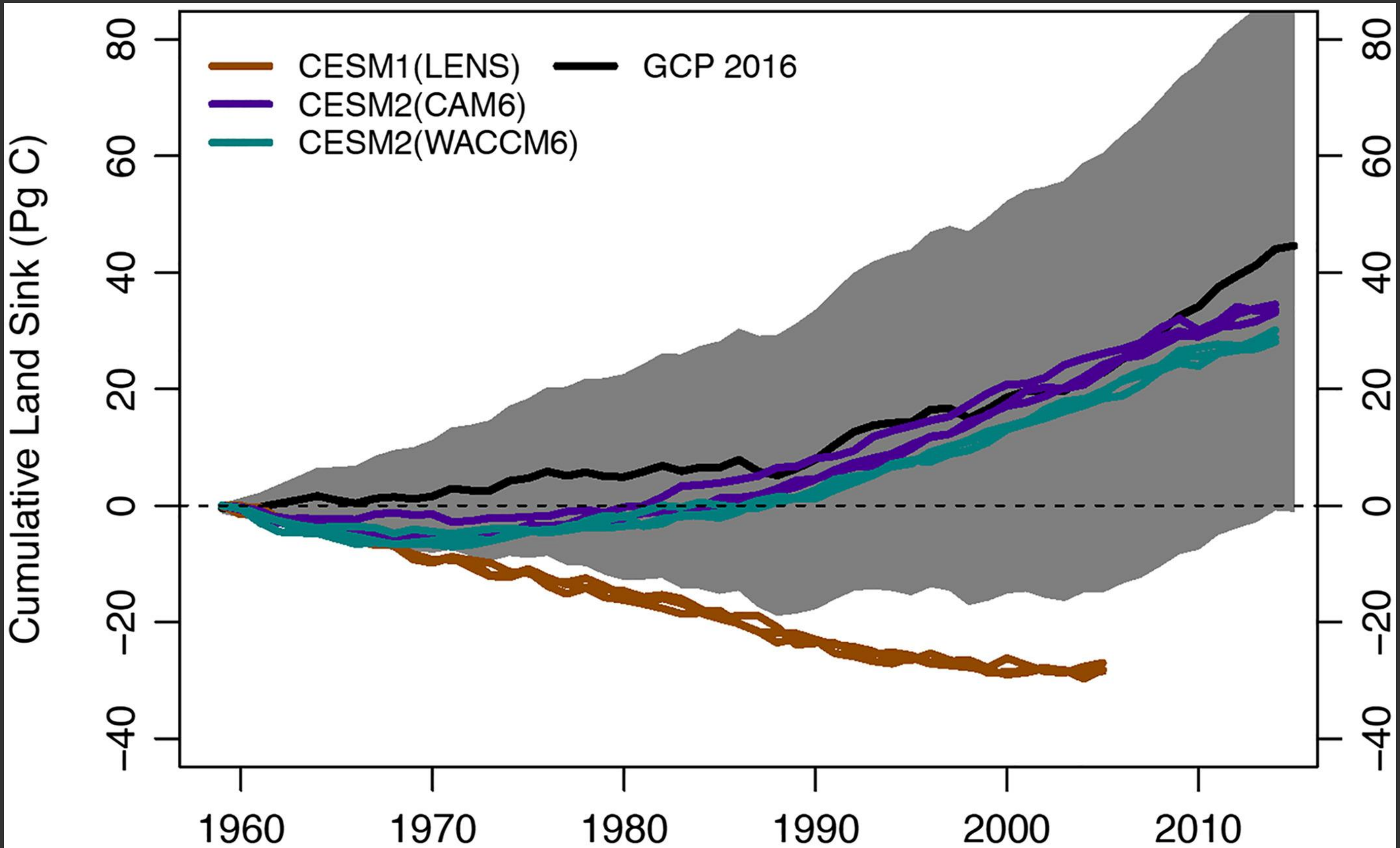
Why?

How?

Uncertainties and future directions

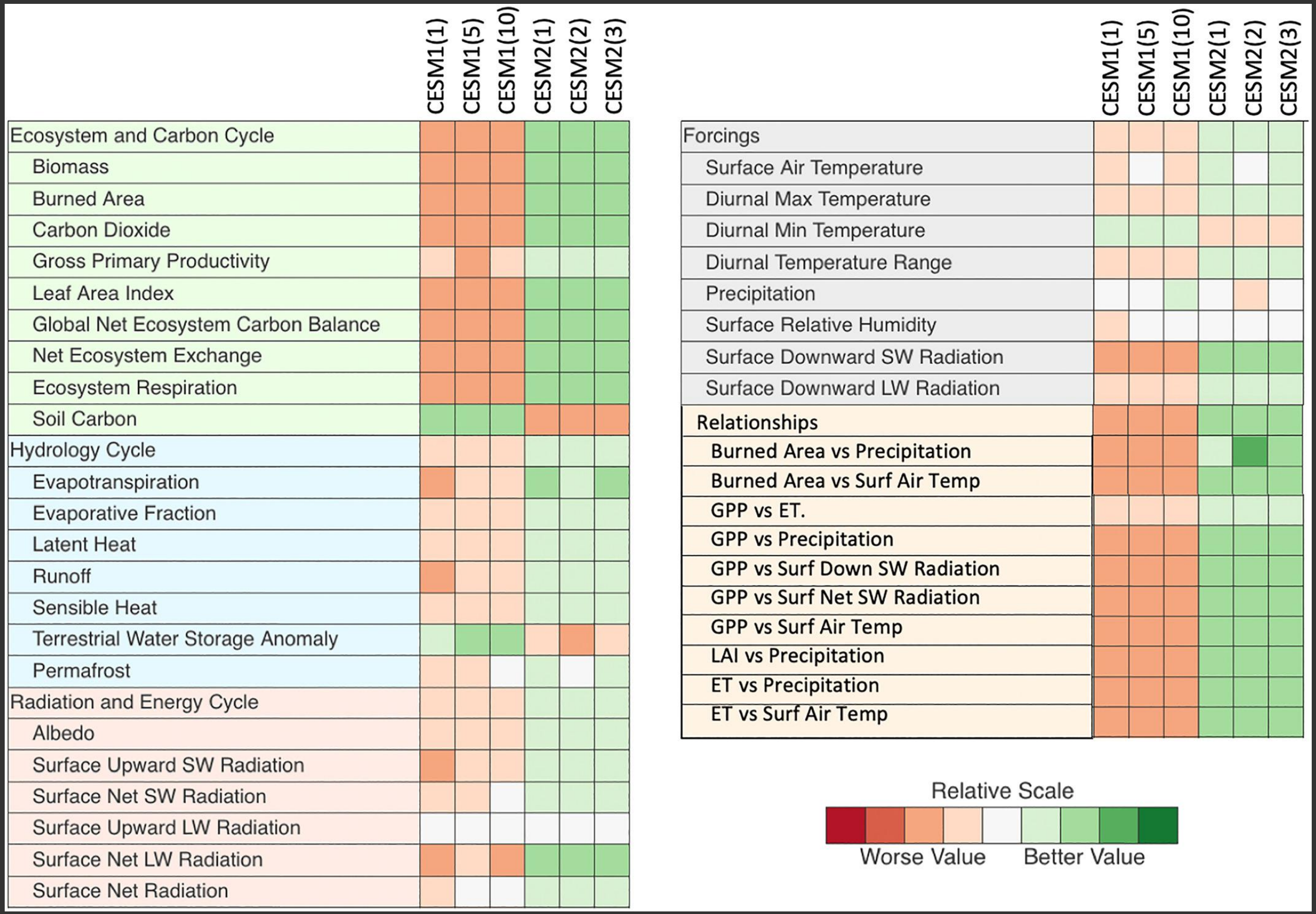
Represent land C sink!

Danabasoglu et al 2020 JAMES



Objectively 'better' carbon cycle

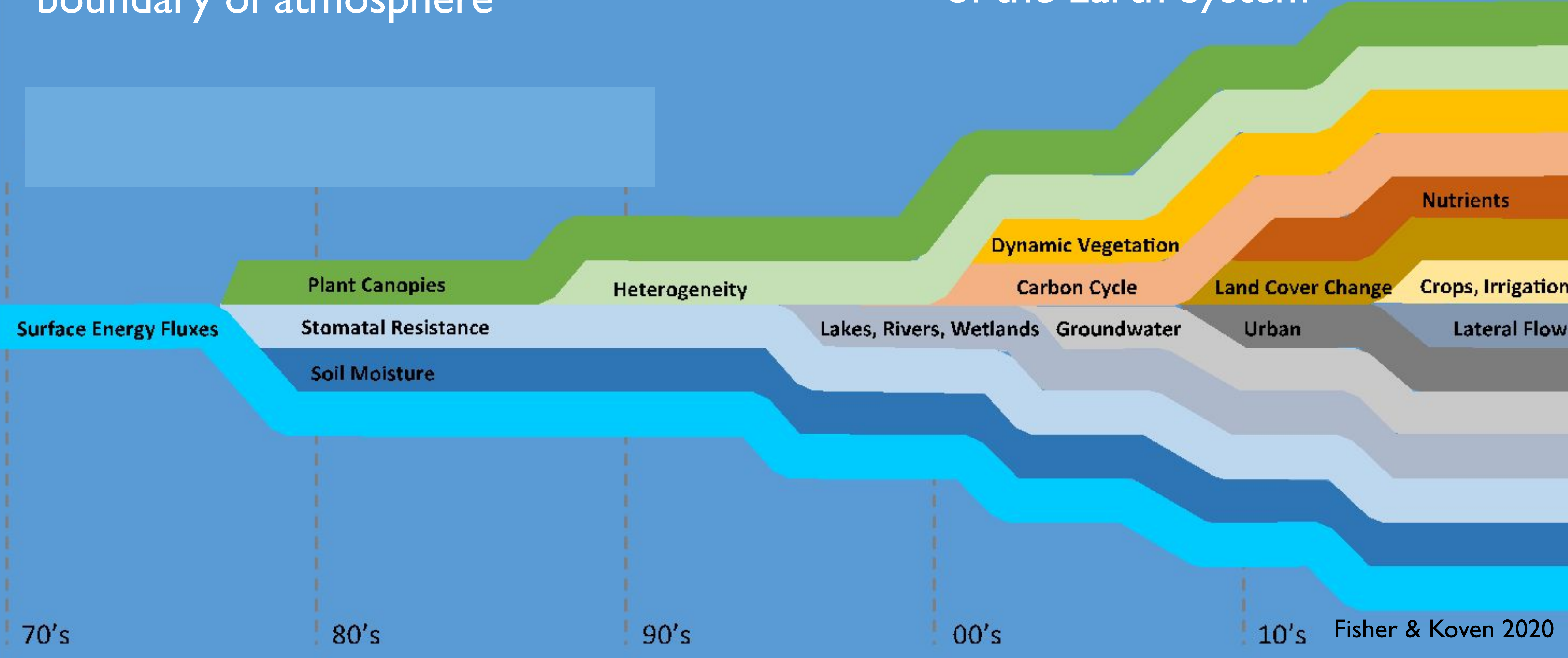
Danabasoglu et al 2020 JAMES



ILAMB – International Land Model Benchmarking package

the Evolution of land modeling

Land as lower boundary of atmosphere → Land as an integral component of the Earth System

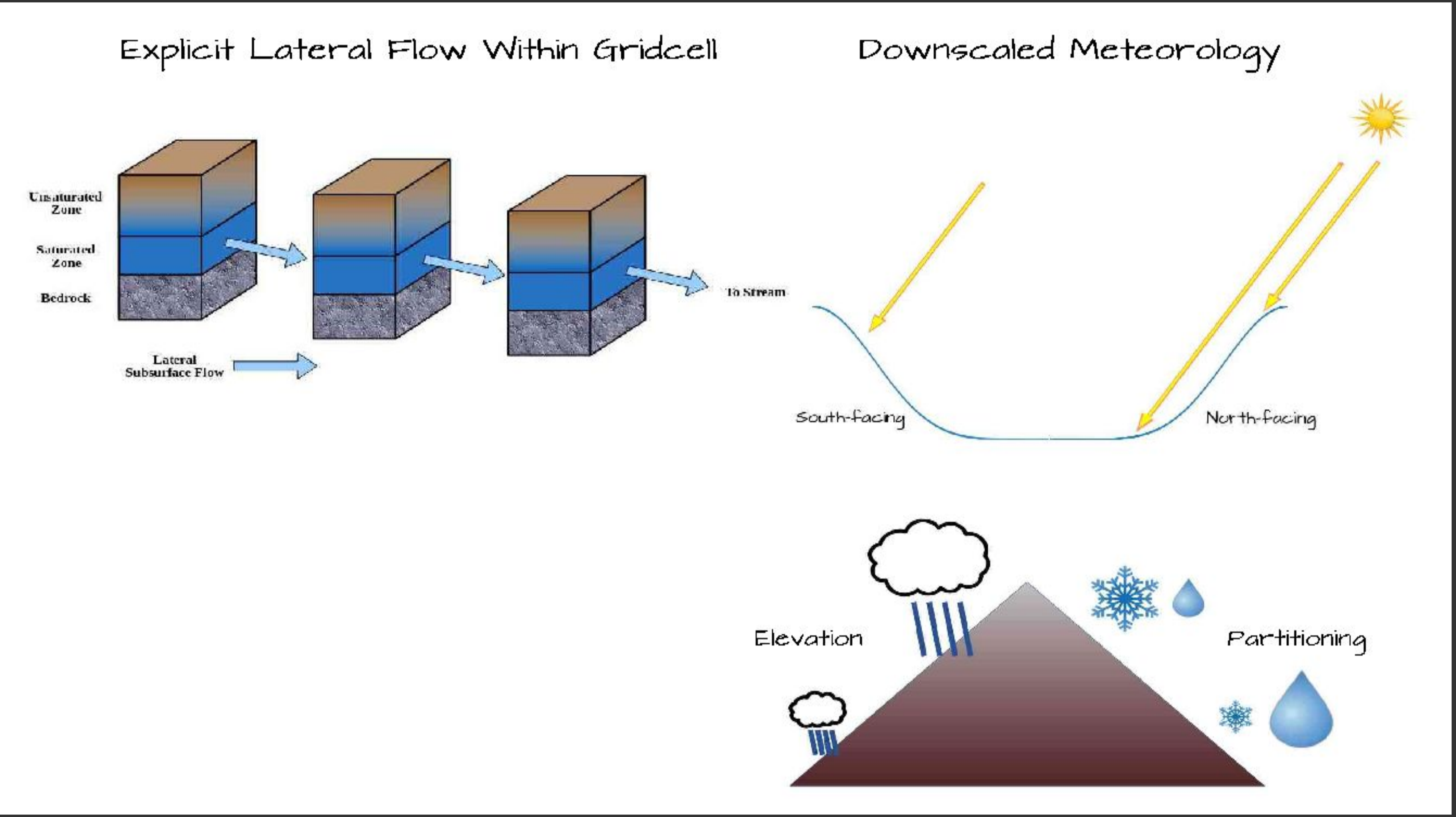


Fisher & Koven 2020

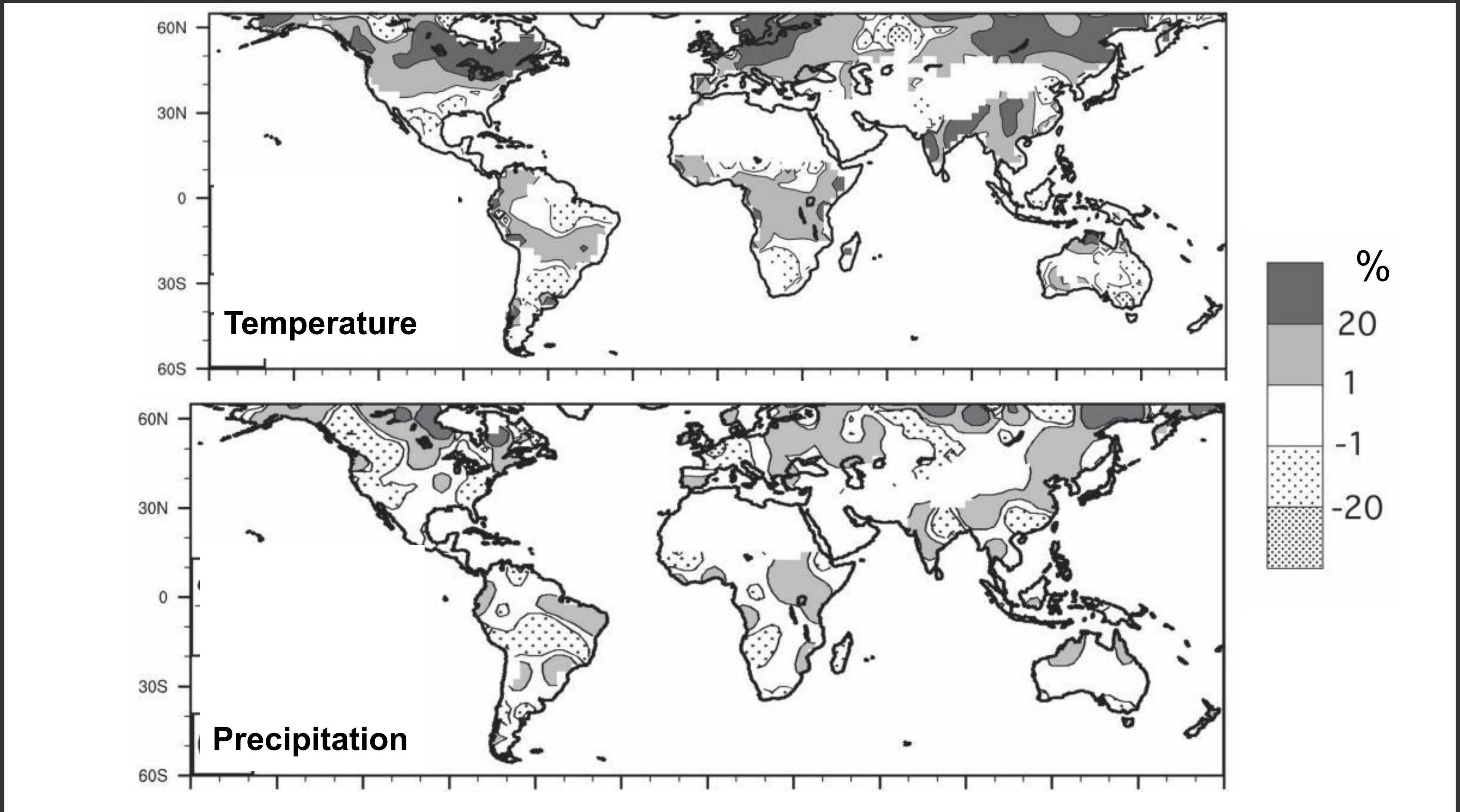
LMWG priorities for CESM3+

Representative Hillslope Model

Sean Swenson



Functionally Assembled Terrestrial Ecosystem Simulator (FATES)



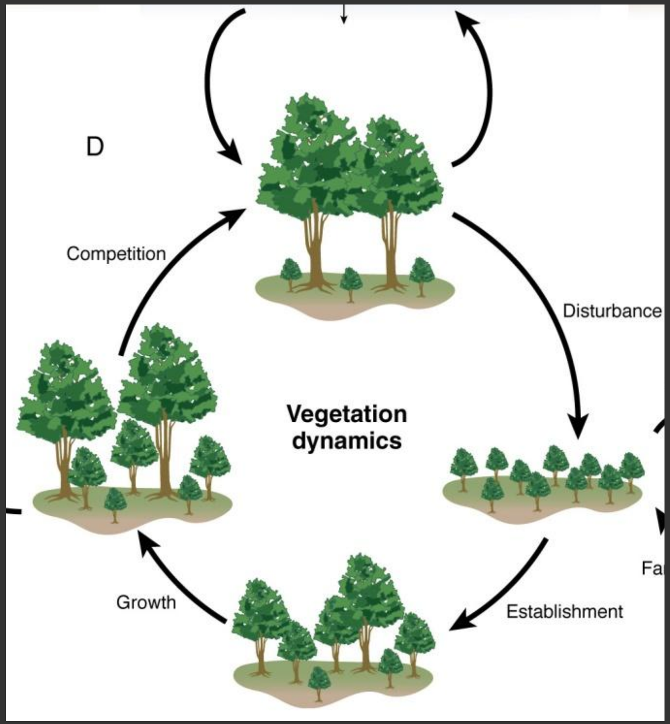
Liu et al. 2006 *Journal of Climate*

Forest height, structure, age, competition all feed back to climate!

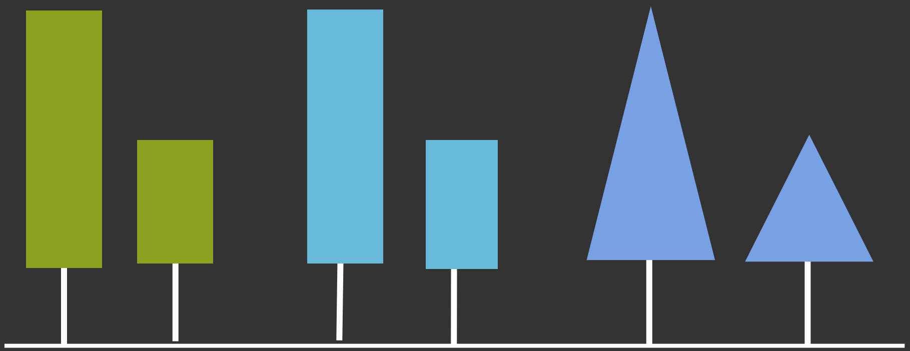
Functionally Assembled Terrestrial Ecosystem Simulator (FATES)

Forests are a mosaic of patches

Forest dynamics are the average responses of many such gaps/patches

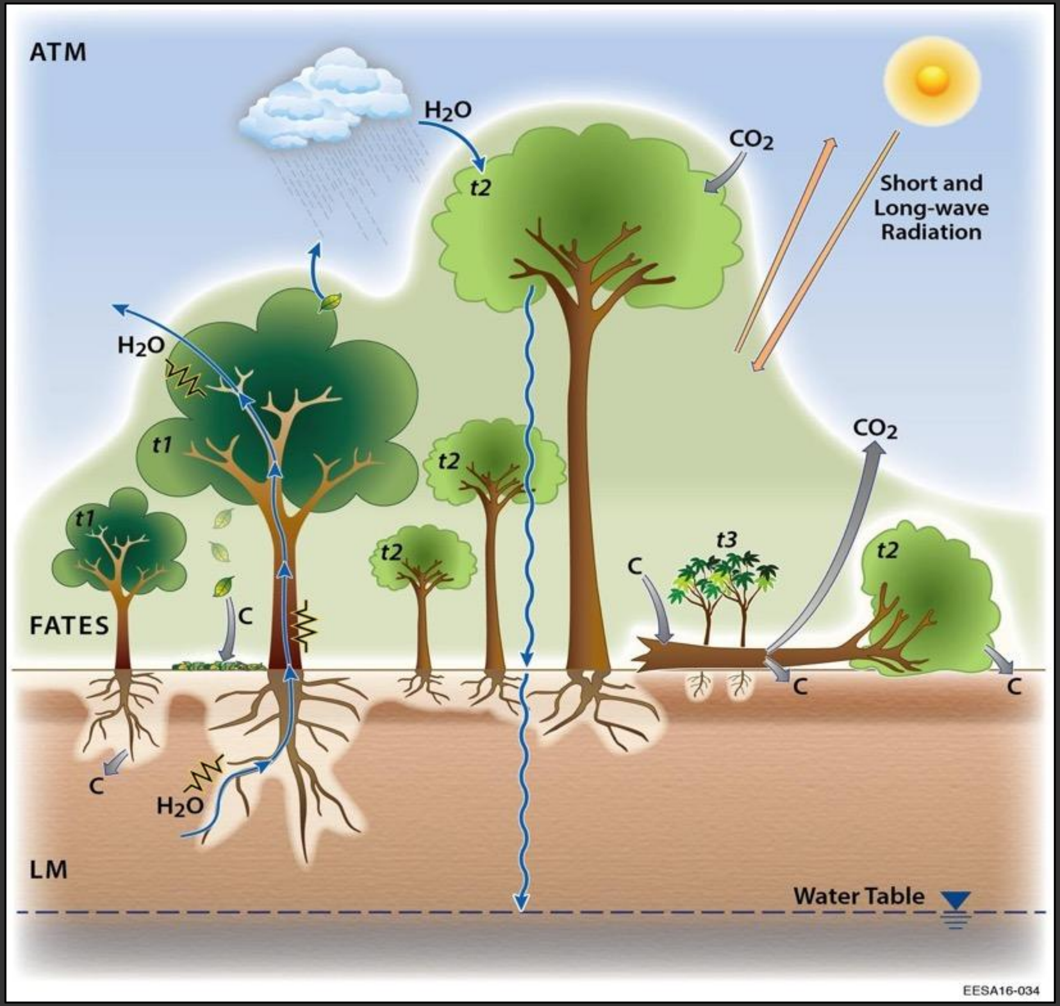


Functionally Assembled Terrestrial Ecosystem Simulator (FATES)

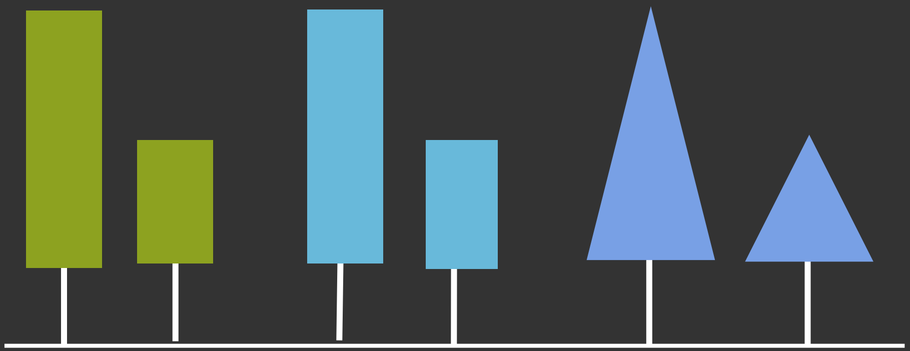


cohort-specific model

30-minute photosynthesis and fluxes



Functionally Assembled Terrestrial Ecosystem Simulator (FATES)



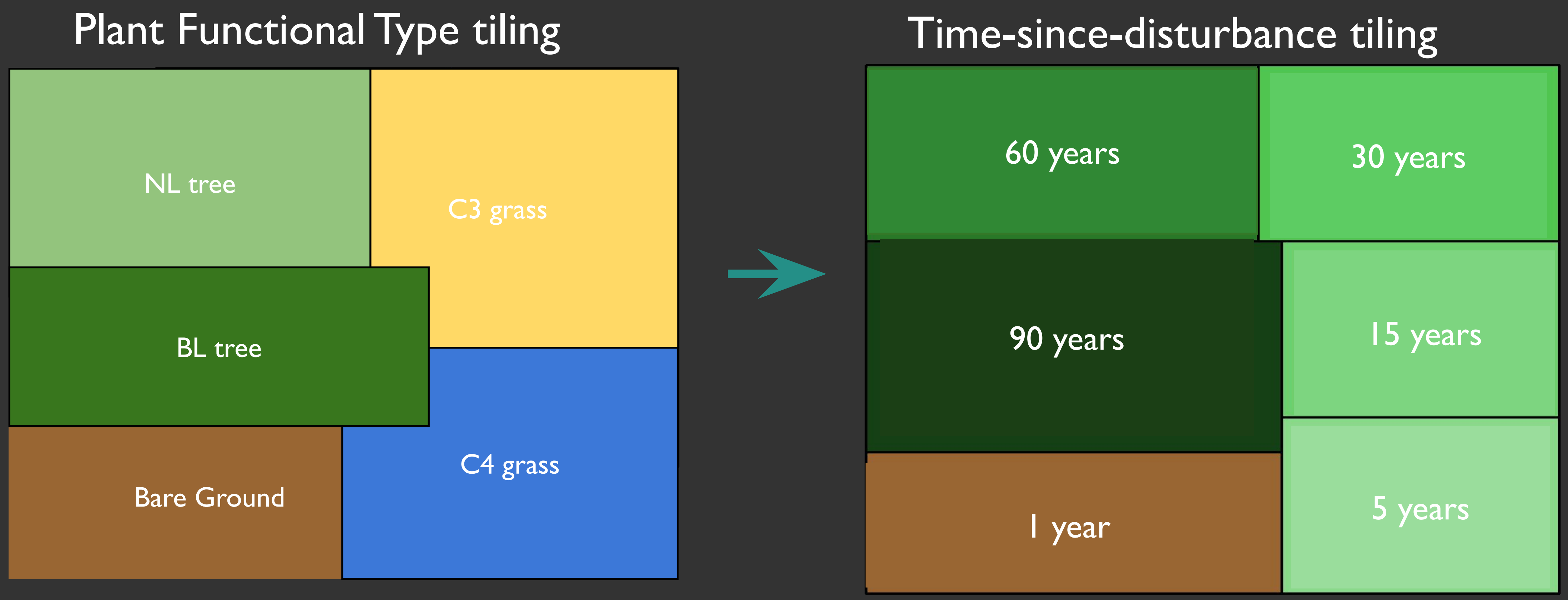
cohort-specific model

30-minute photosynthesis and fluxes

daily growth and allocation

dynamic vegetation!

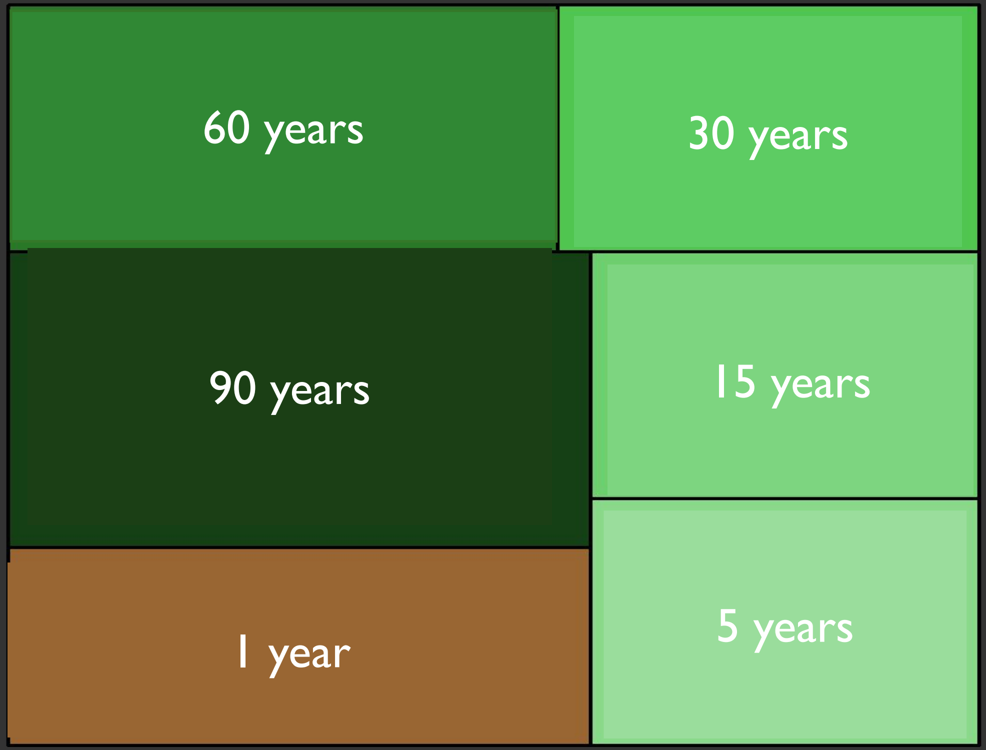
Functionally Assembled Terrestrial Ecosystem Simulator (FATES)



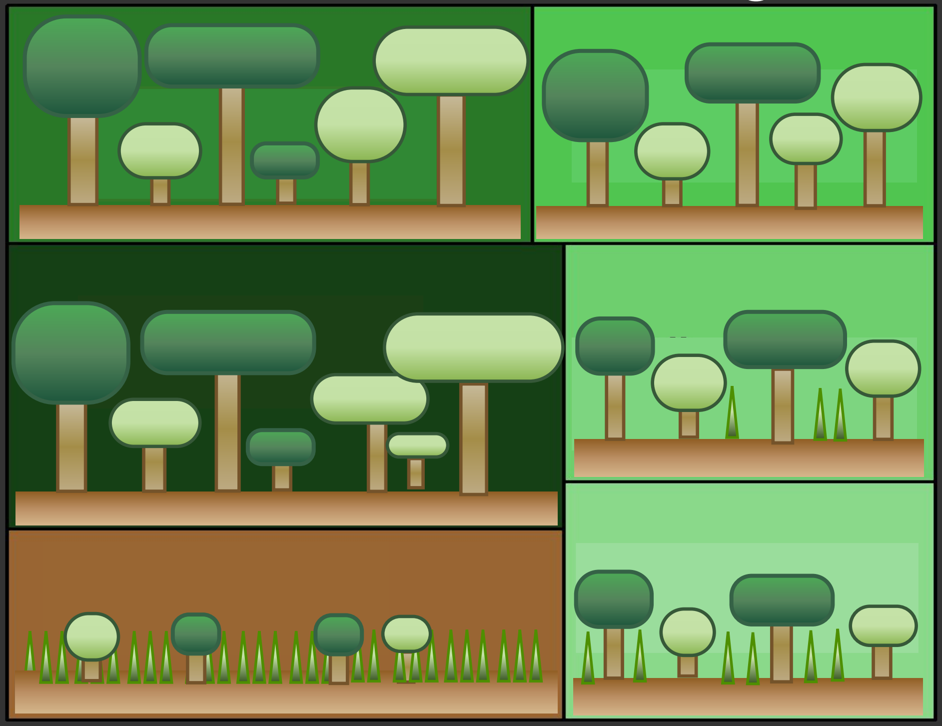
Functionally Assembled Terrestrial Ecosystem Simulator (FATES)

Each time-since-disturbance tile contains cohorts of plants, defined by PFT and size.

Time-since-disturbance tiling

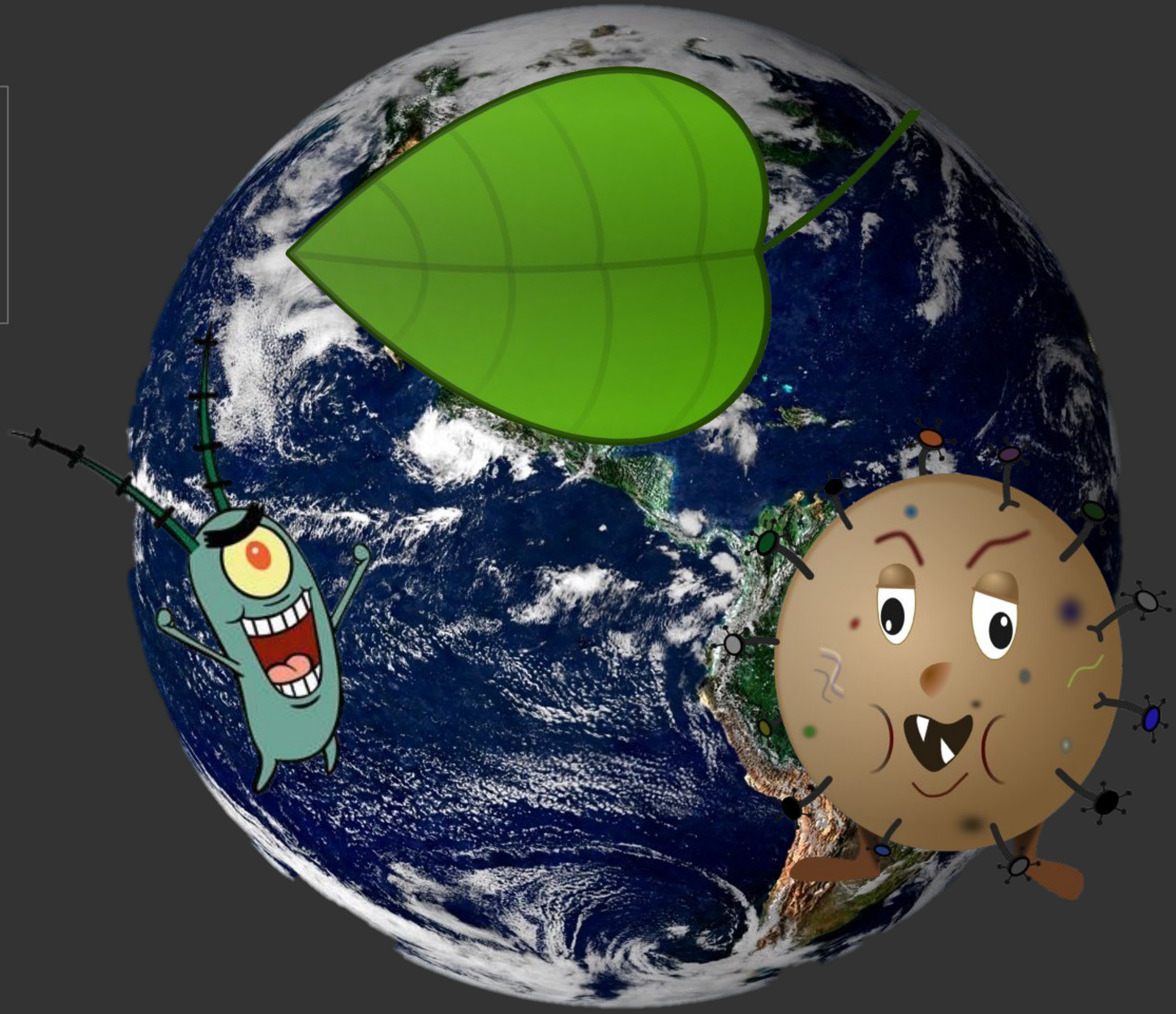


Time-since-disturbance tiling



Functional traits and the global C cycle

We consider biology above ground and at sea, what about in the world beneath our feet?



How do ecosystem function and vulnerabilities transform under climate change?

- **Community Terrestrial Systems Model**: Land model used for climate change and weather predictions that can be run at single points (~ 1 ha) to global scale.
- **Hillslope Hydrology**: Considers effects of aspect, elevation, and hydrologic connectivity on water availability (feature within CTSM).
- **FATES:** Represents vegetation demographics, traits, and recovery from disturbance (feature within CTSM).
- **MIMICS**: Soil biogeochemistry model (explicitly represent microbial activity and physiological diversity).