# Land Modeling II

## Biogeochemistry and Ecosystems

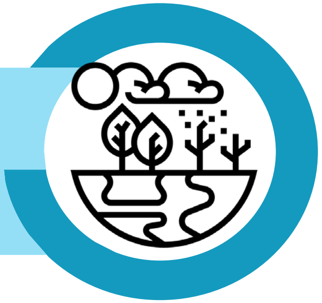
*Adrianna Foster*
*Project Scientist II, NCAR CGD Terrestrial Sciences Section*

Community Earth System Model (CESM) Tutorial
Tuesday, July 8

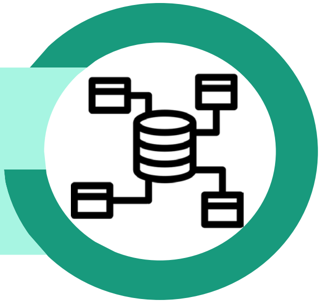
This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

# Land biogeochemistry in CESM

**Why?**



**How?**



**Future directions**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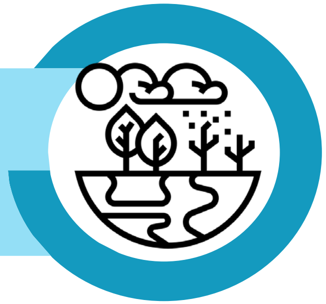
# Land biogeochemistry in CESM

**Why?**

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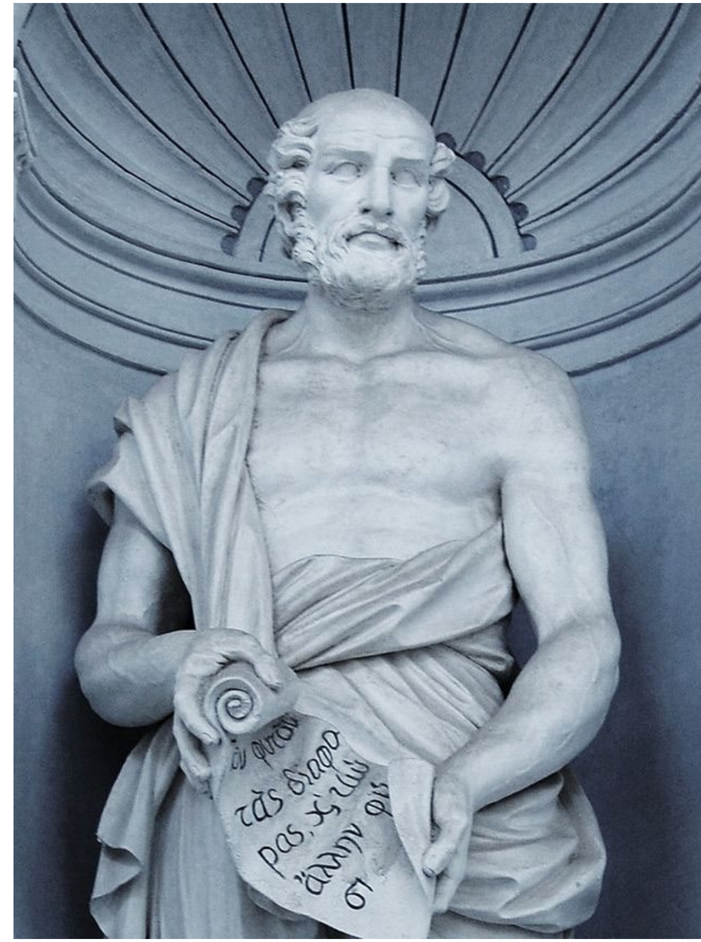
# How do ecosystems change when climate changes?

# Climate -ecosystem question


*Enquiry into Plants*, c. 350 BC



Theophrastus, *Palermo Botanical Garden*

Transplanted species outside natural range
Changes in phenology with climate
Relationship between altitude/latitude and climate/vegetation

# Climate -ecosystem question

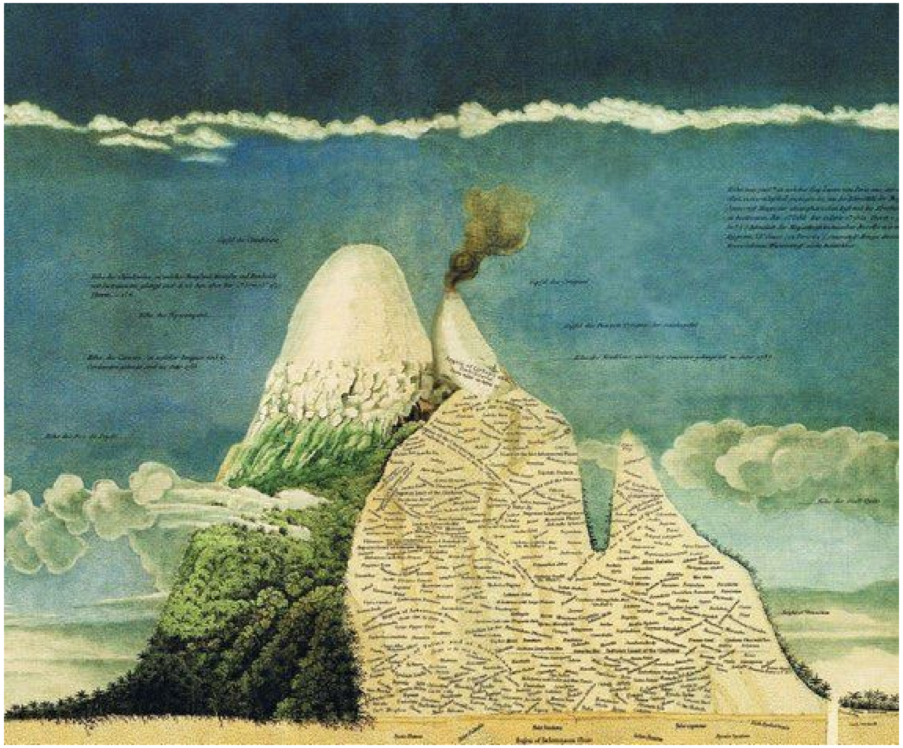
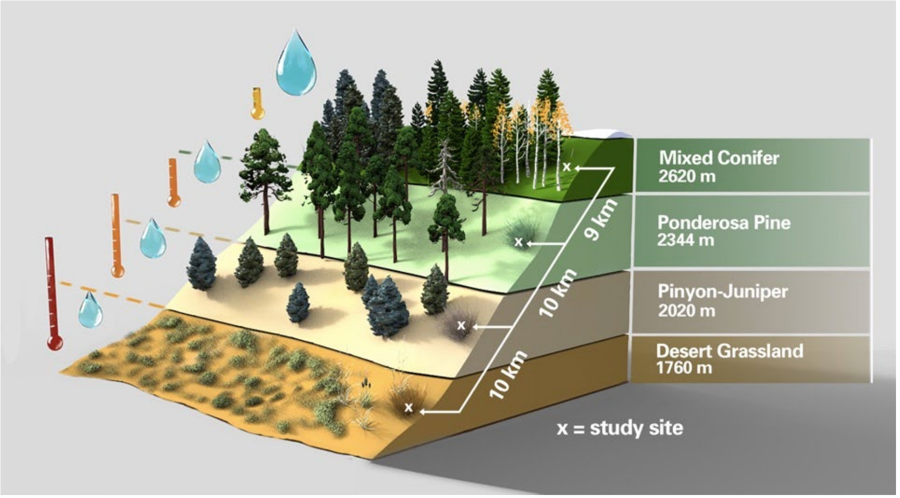


*Tableau des Régions é*quinoxiales from Humboldt (1807)




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



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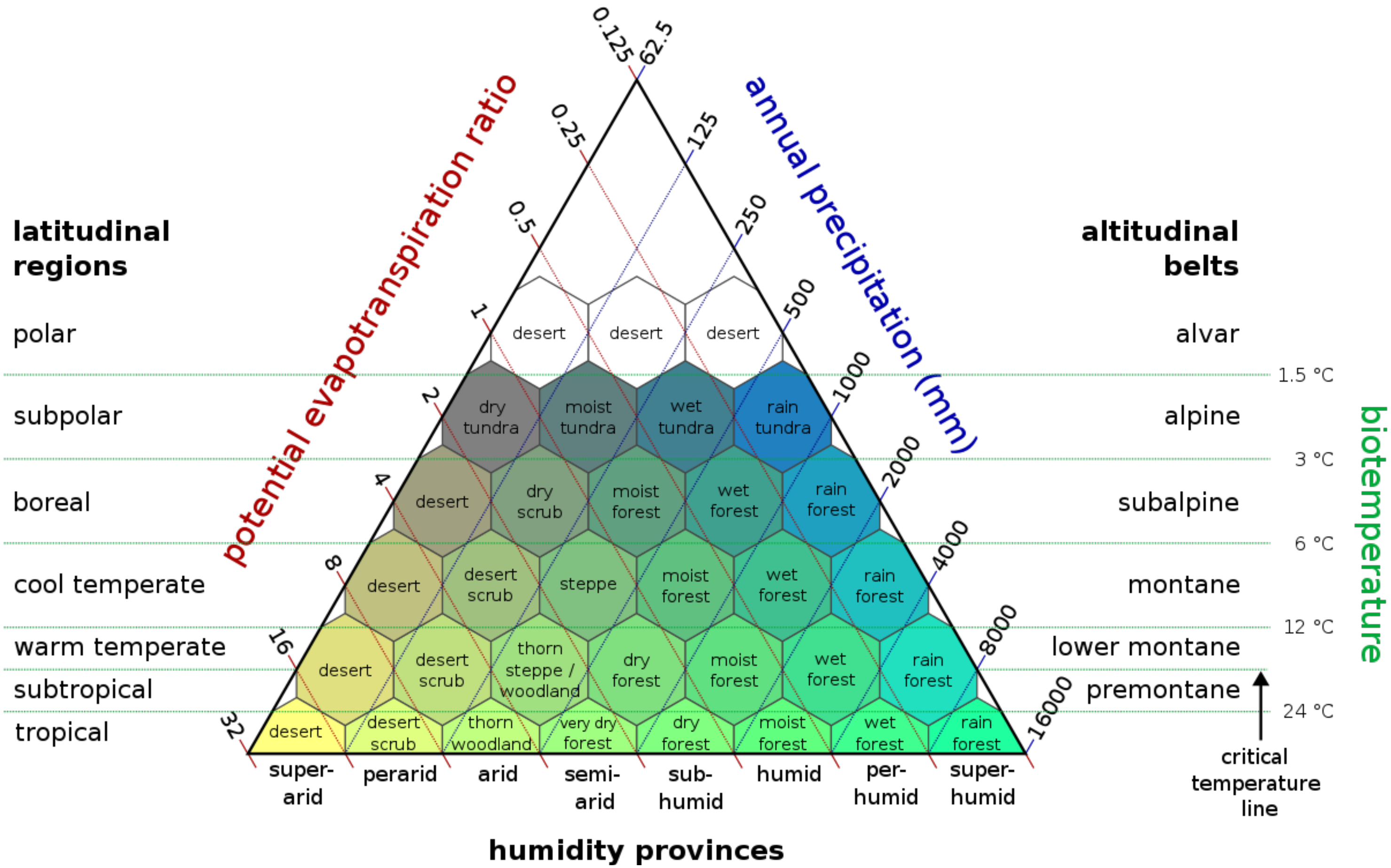
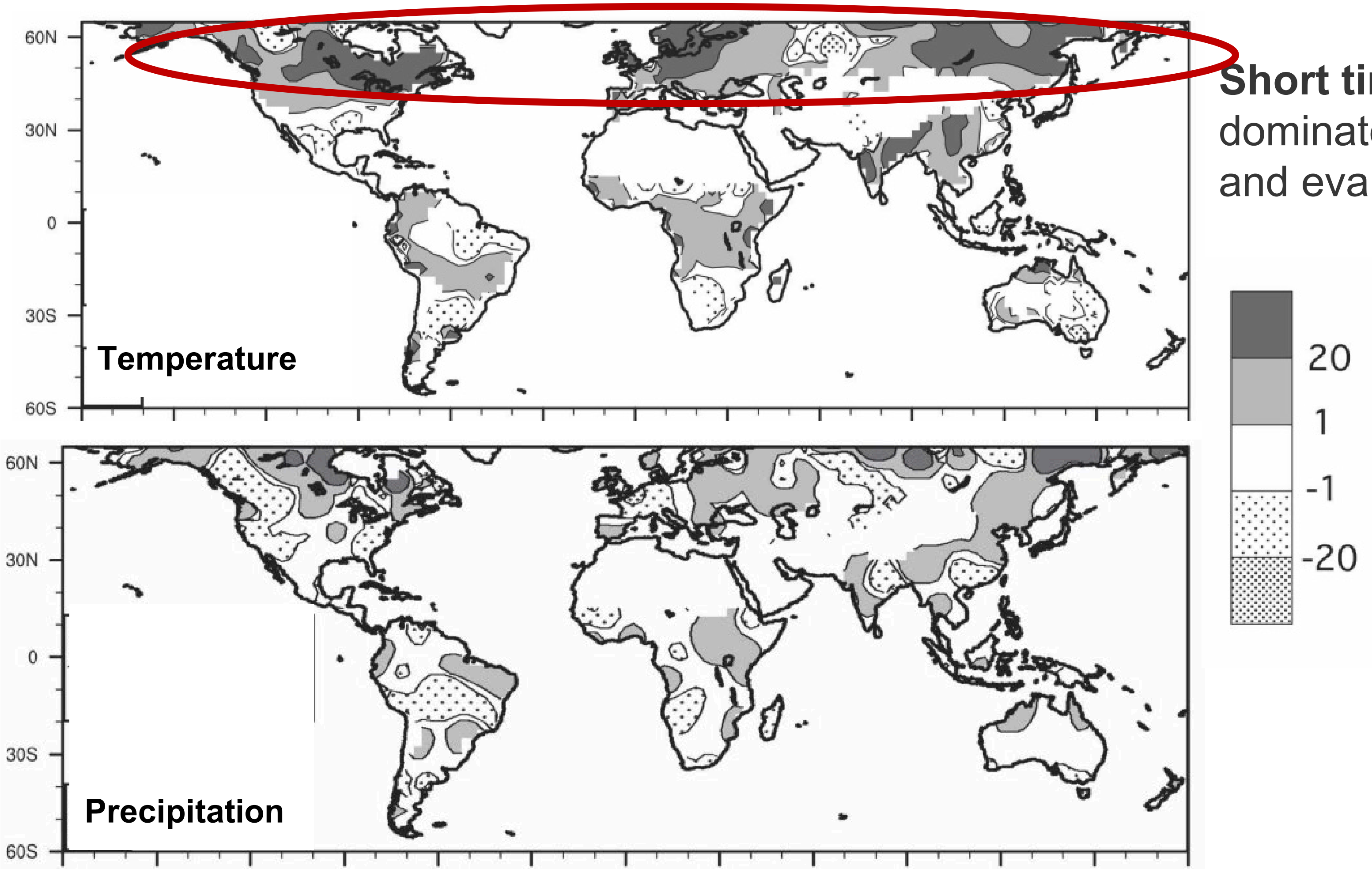
# Climate -ecosystem question




Holdridge life zones

# Vegetation impacts climate

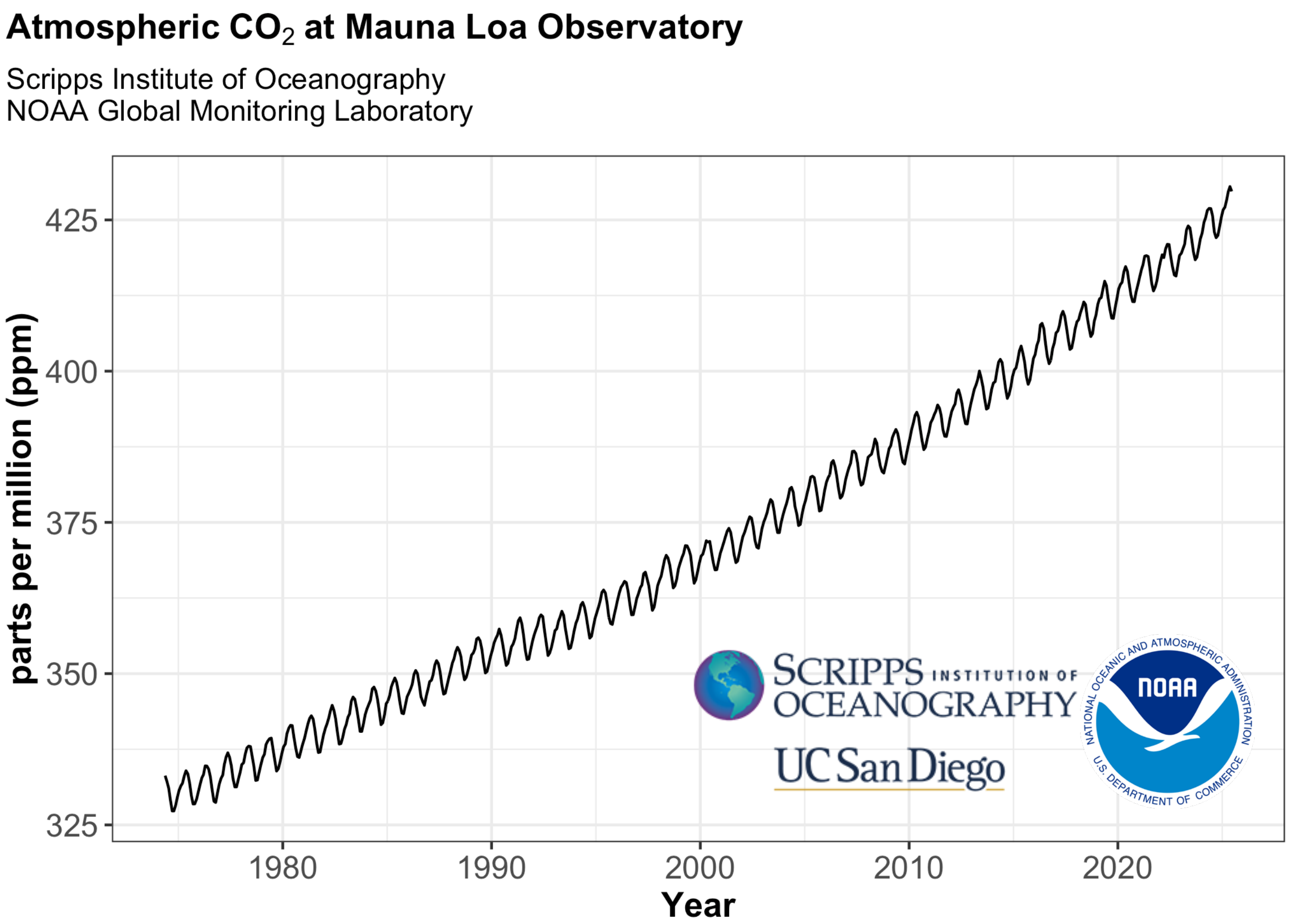



**Short time scales –** dominated by albedo and evapotranspiration

Liu et al. 2006 *Journal of Climate*

# Vegetation impacts climate

**Longer time scales -**
fate of carbon




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

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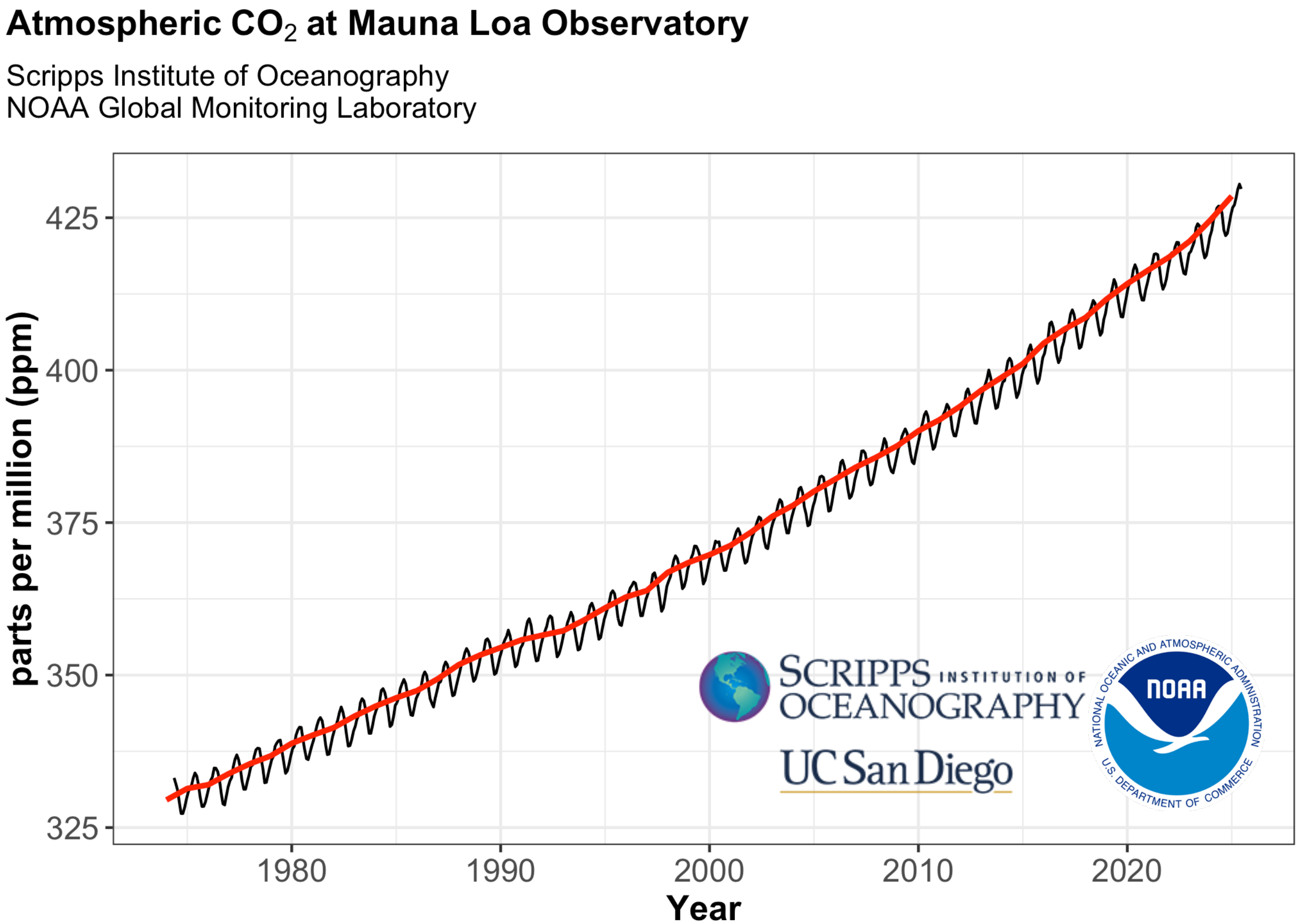


**Longer time scales -** fate of carbon

**Upward trend due to human activities**

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**Longer time scales -**
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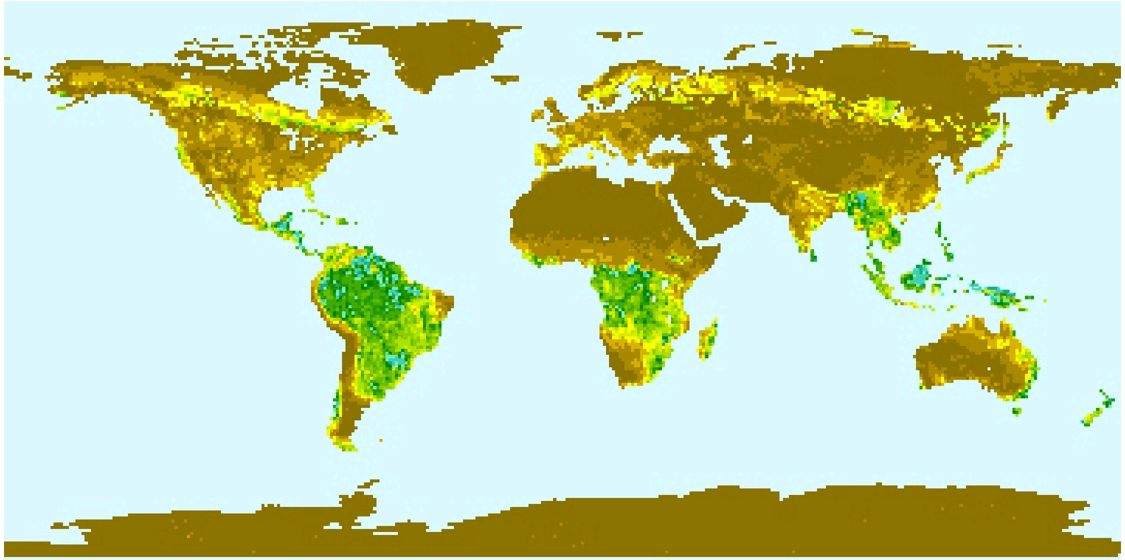
**Upward trend due to human activities**



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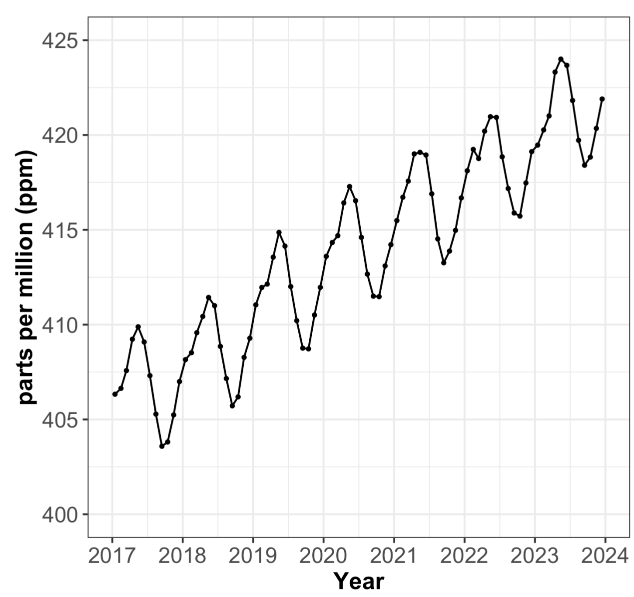


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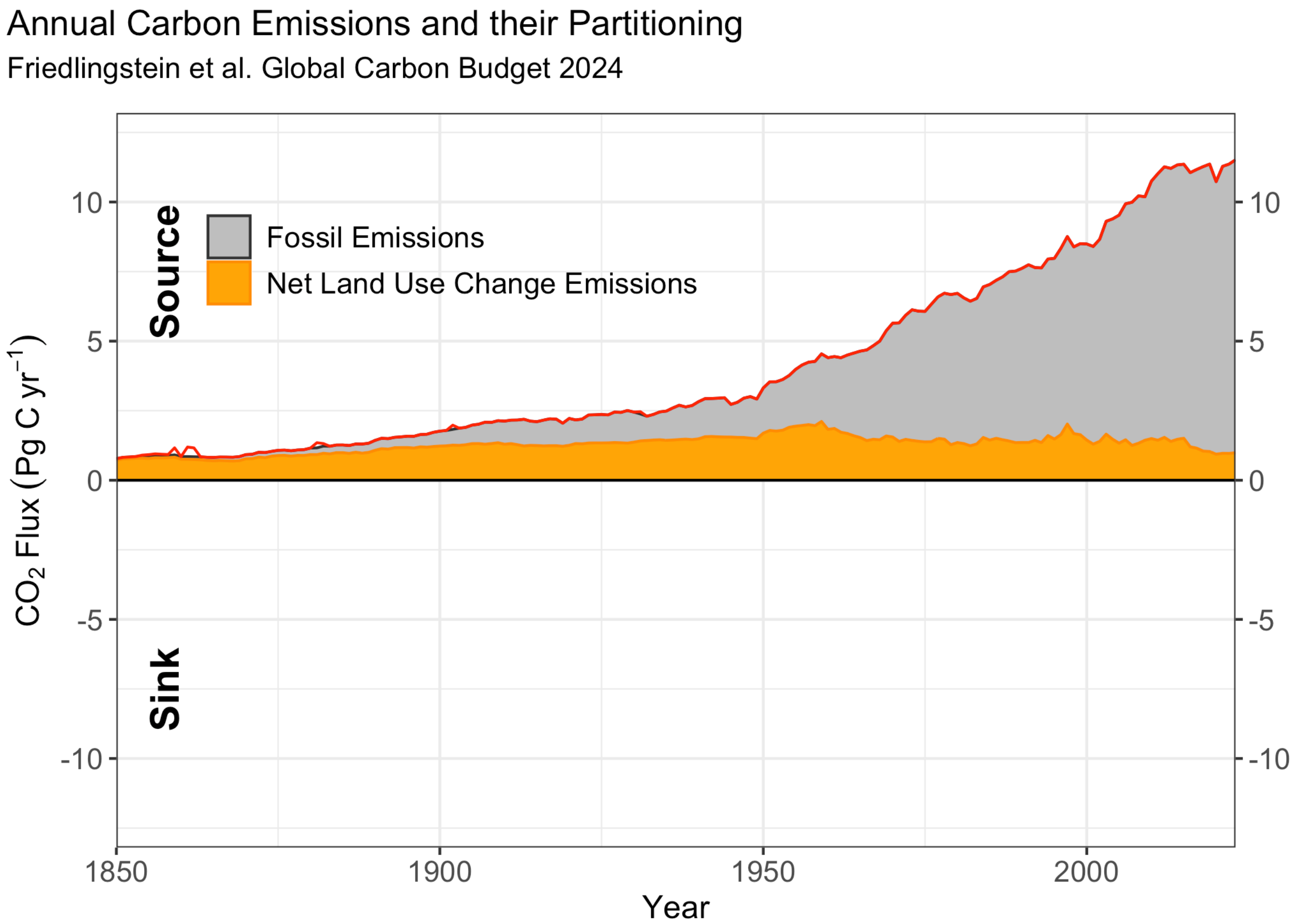
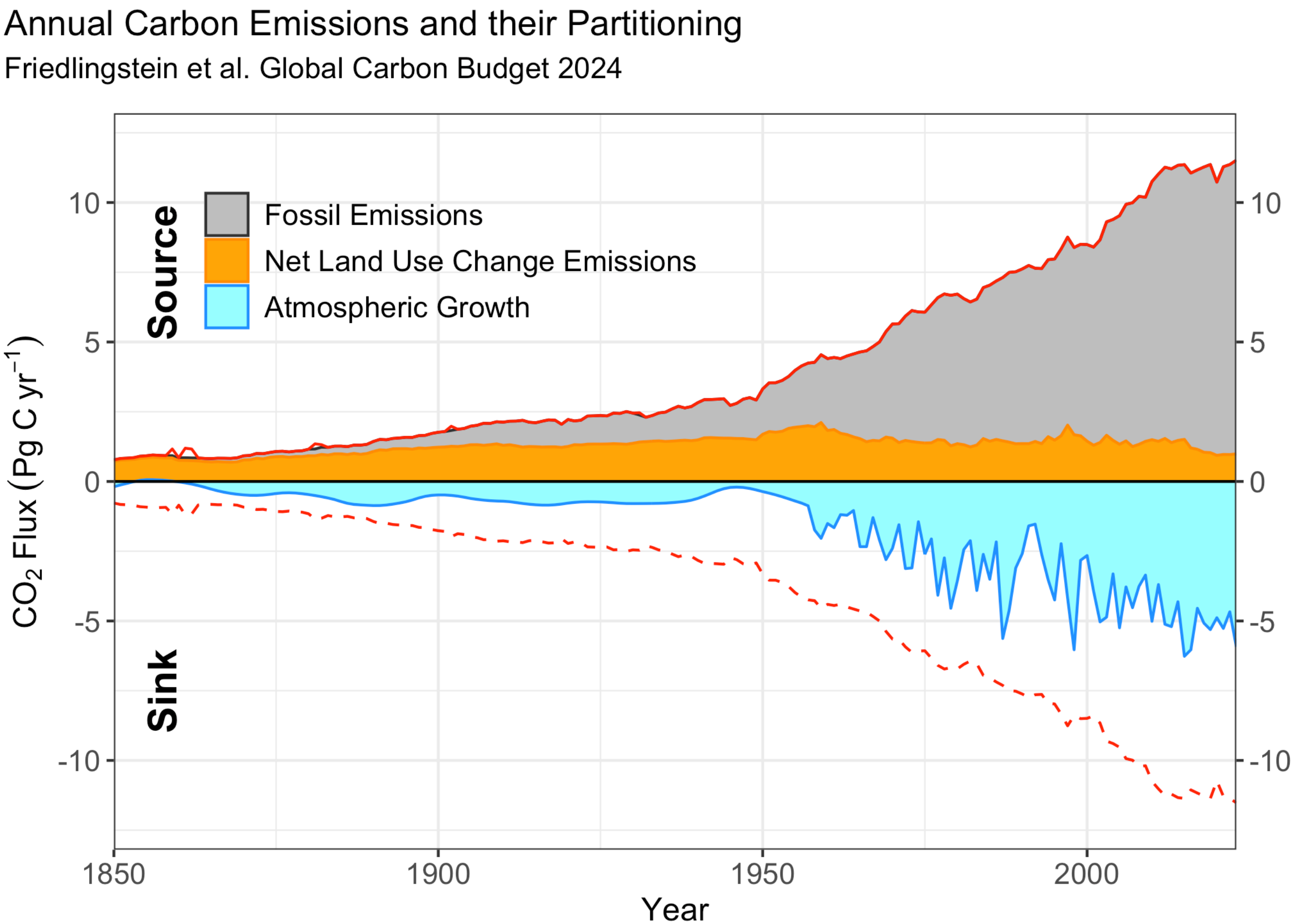
# Annual C emissions




Energy statistics and cement production data

Land use and land use change data

# Annual C emissions

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Atm $CO_2$ - observations



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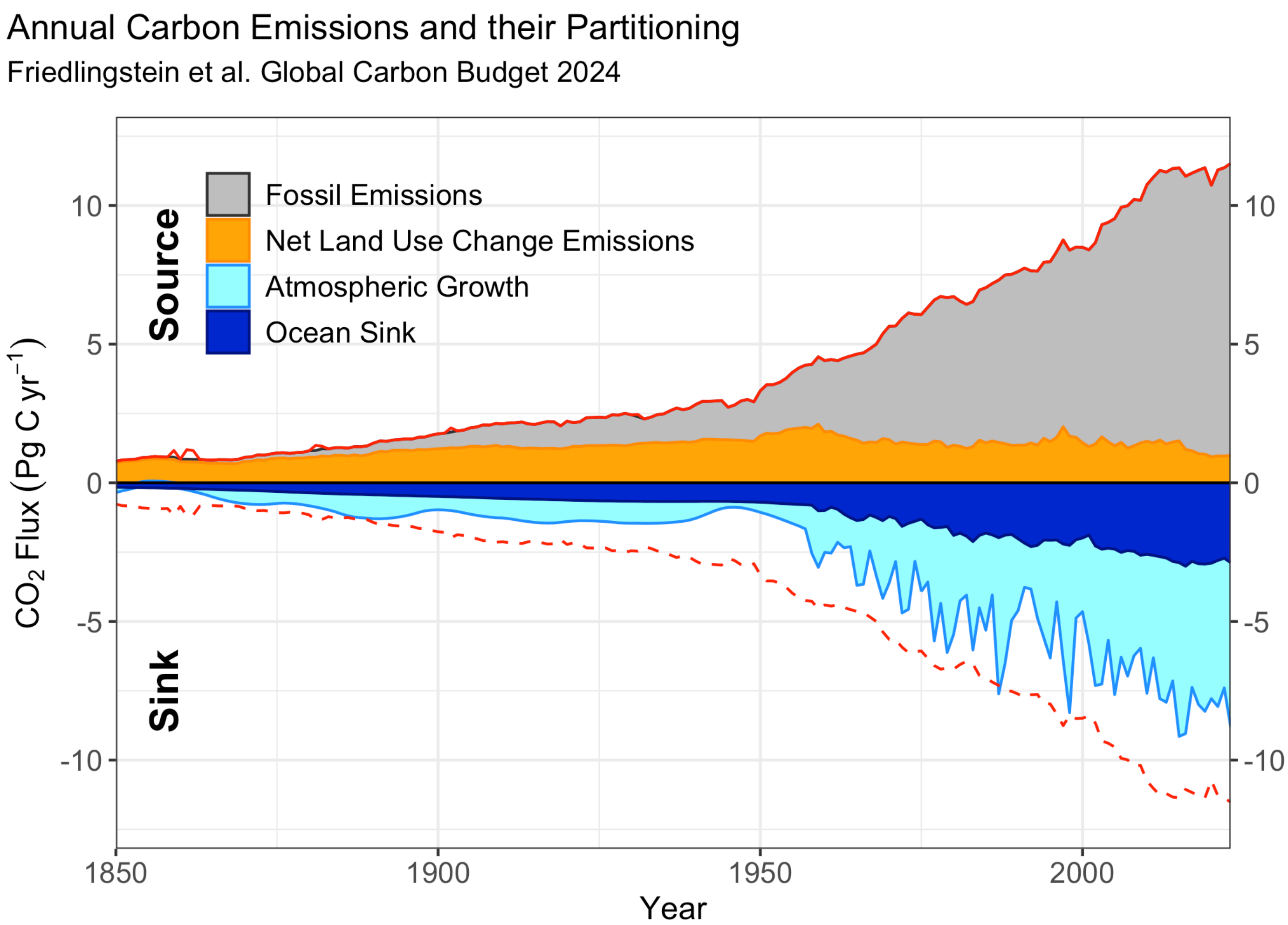


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Ocean – biogeochemistry models, data products



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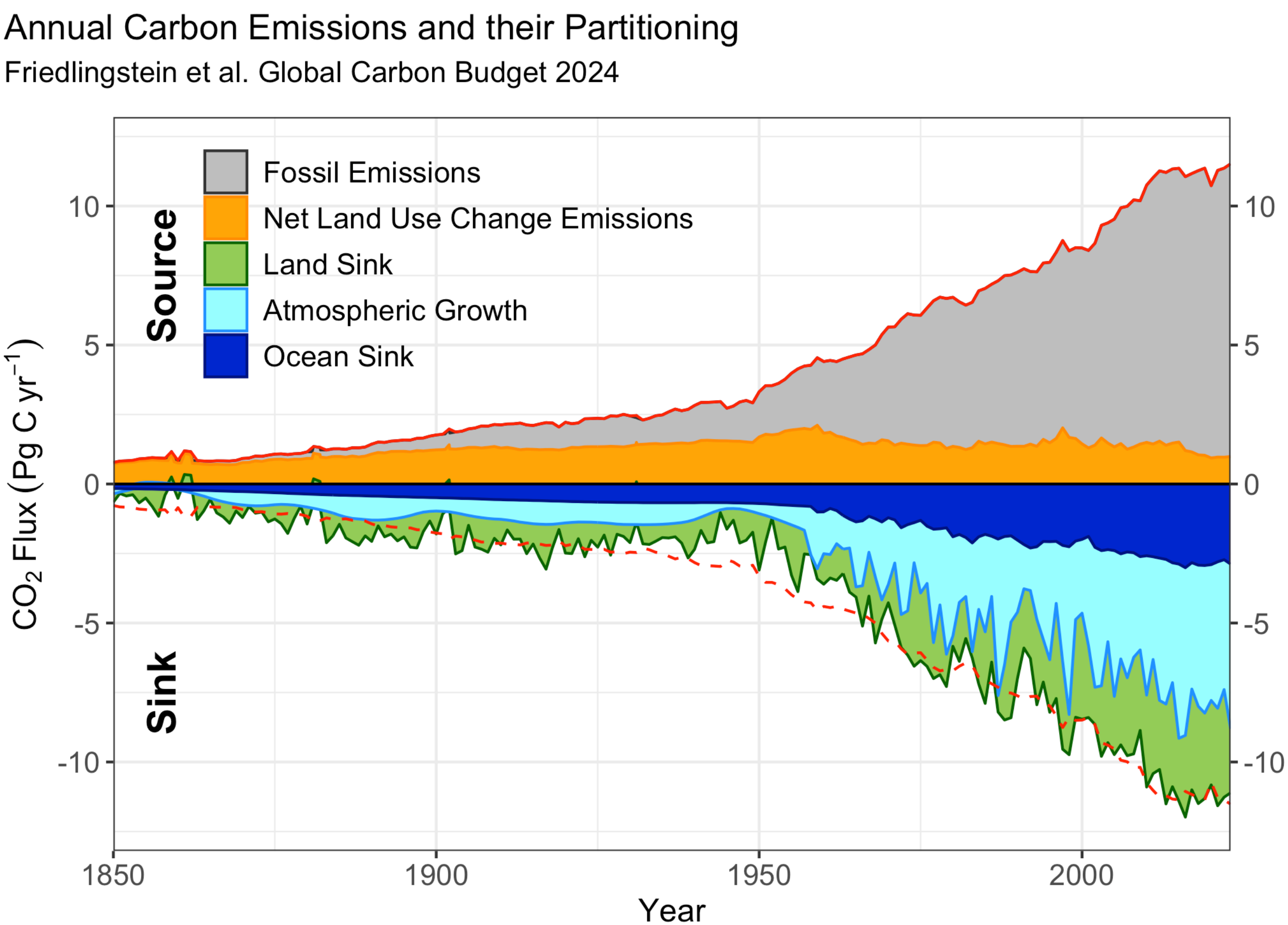


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Land – global vegetation models



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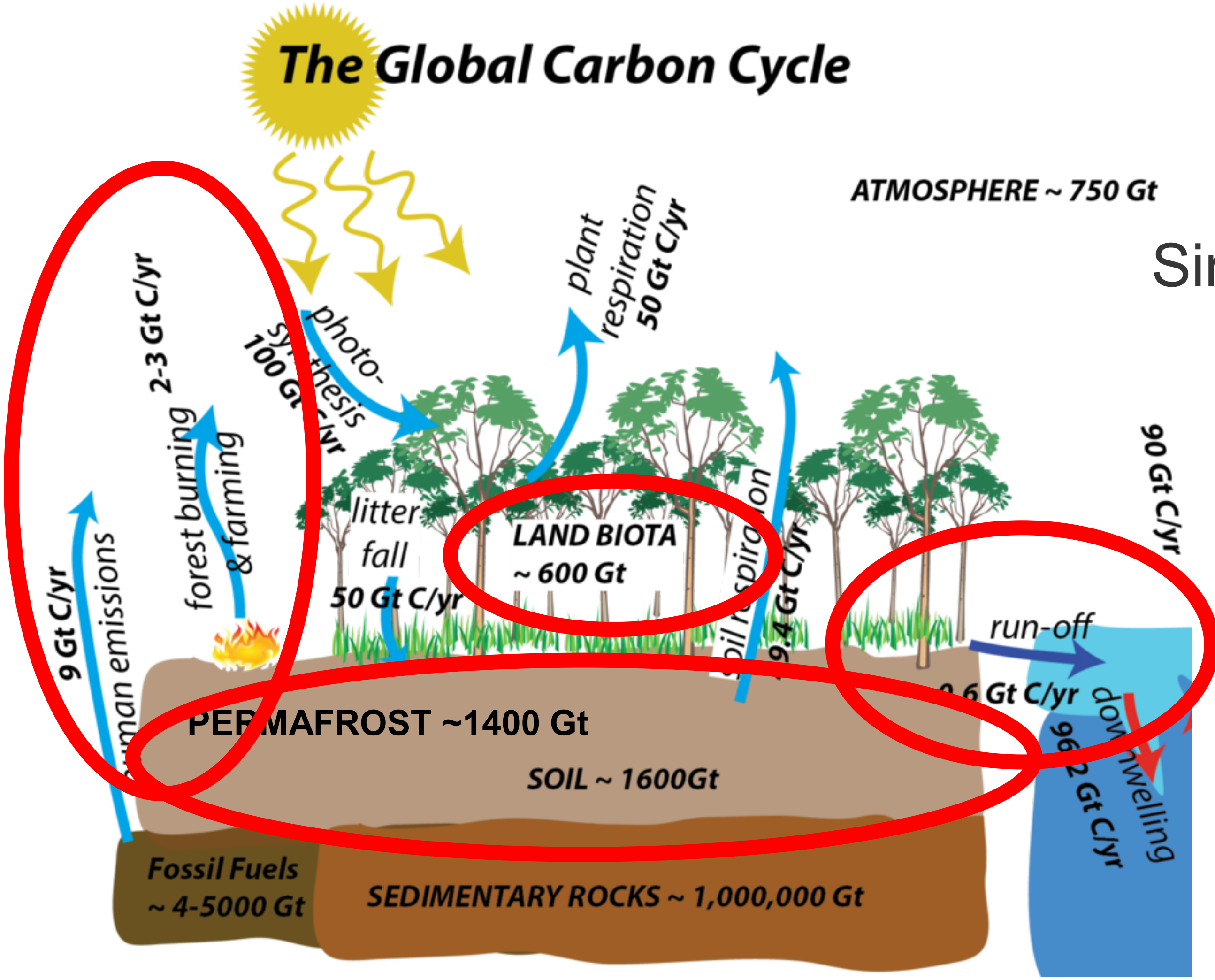
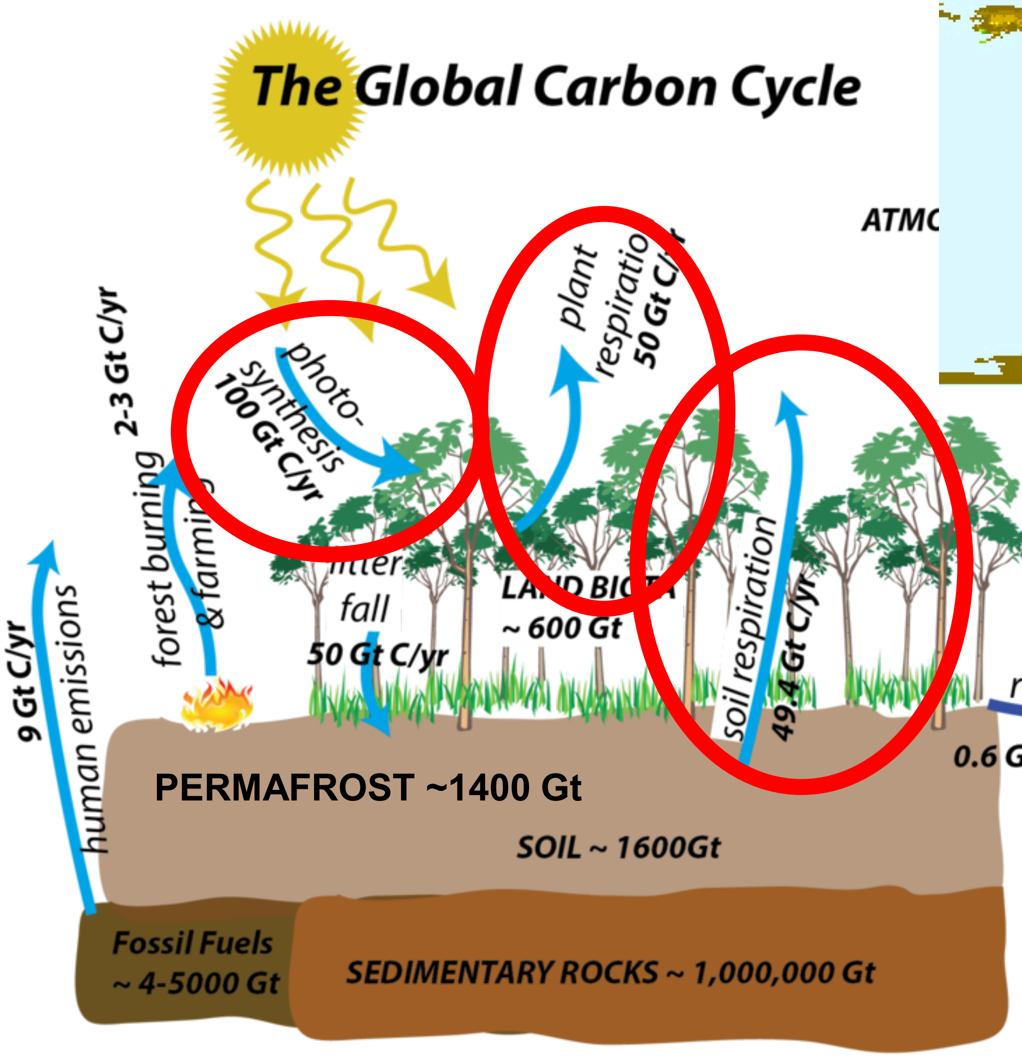


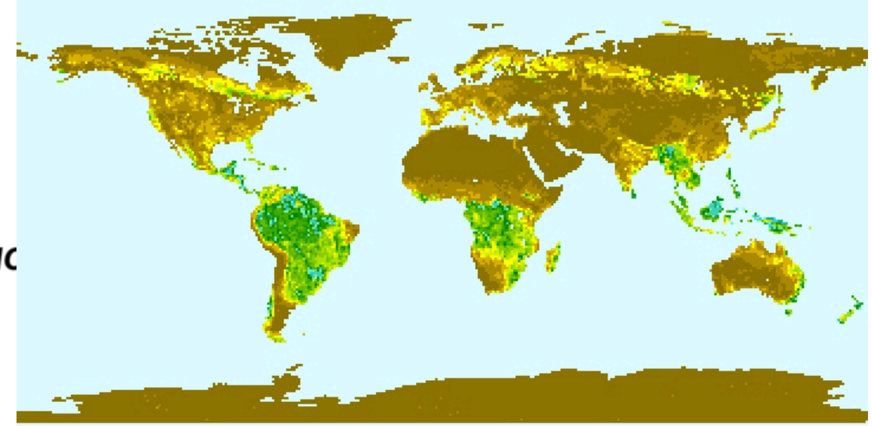

Huge pools

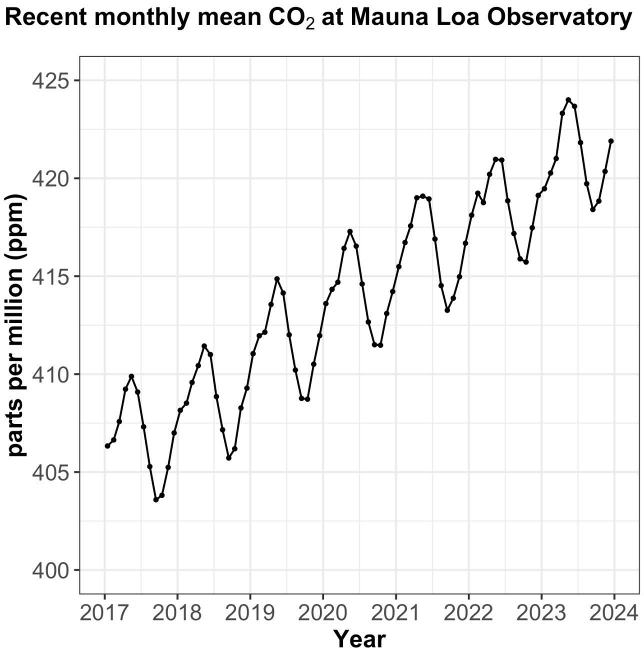
Large fluxes

Sink = small residual

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



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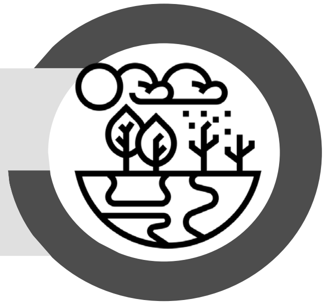

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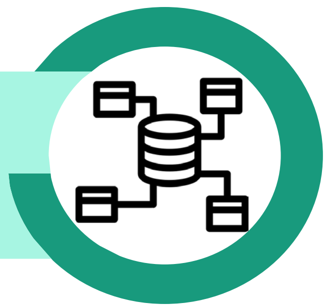


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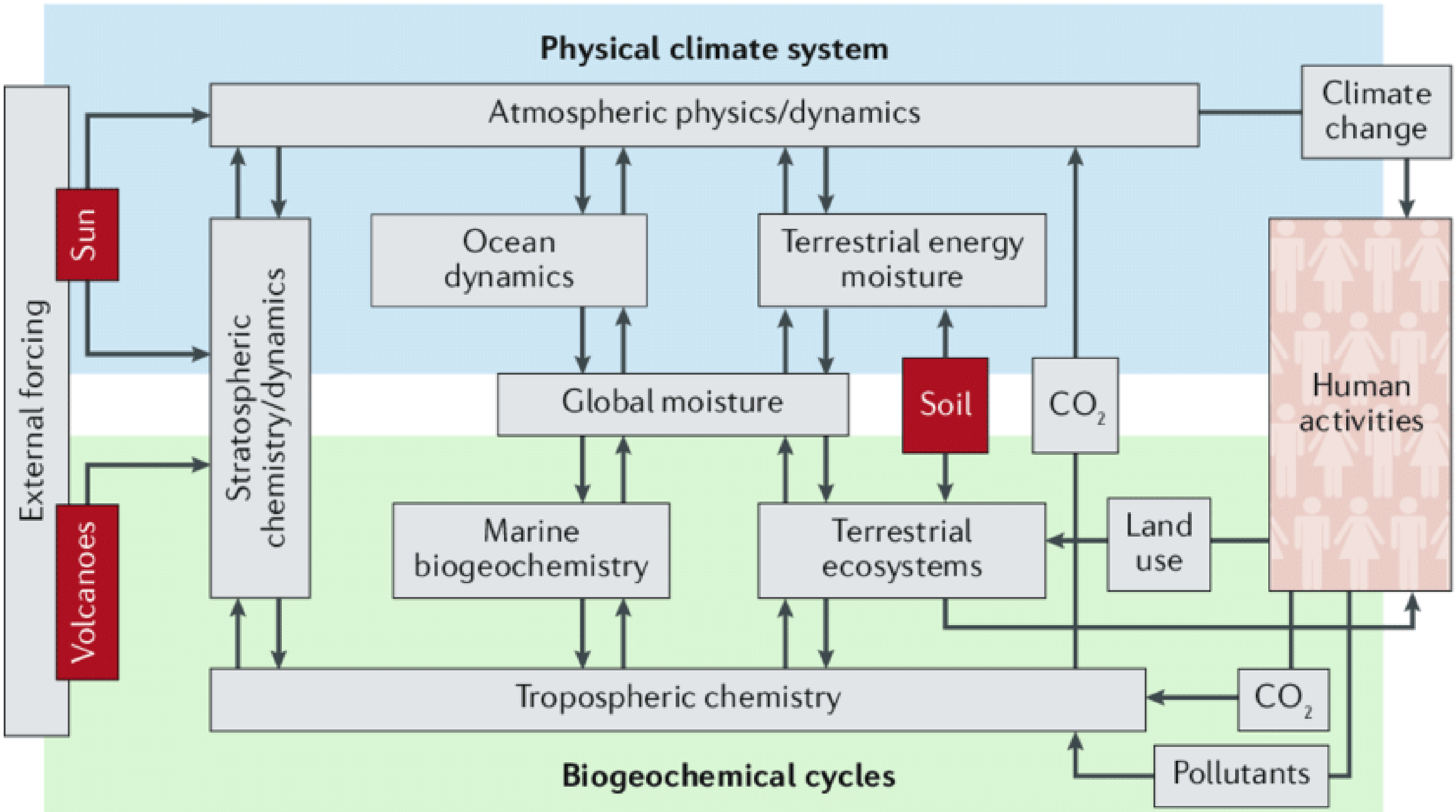



"Bretherton diagram" showing the concept of an Earth System Model

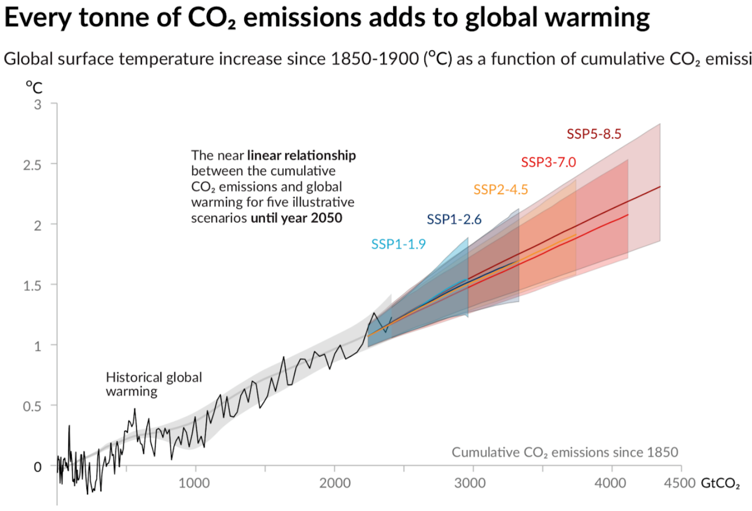
# Full-Form Earth System Models: Coupled Carbon-Climate Interaction Experiment (the "Flying Leap")

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

IGBP Newsletter, May 2000. The flying leap proposal was to make atmospheric $CO_2$ a prognostic variable in climate models

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

A. Swann, BGCWG



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+ Coupled C-N biogeochemistry - CESM1

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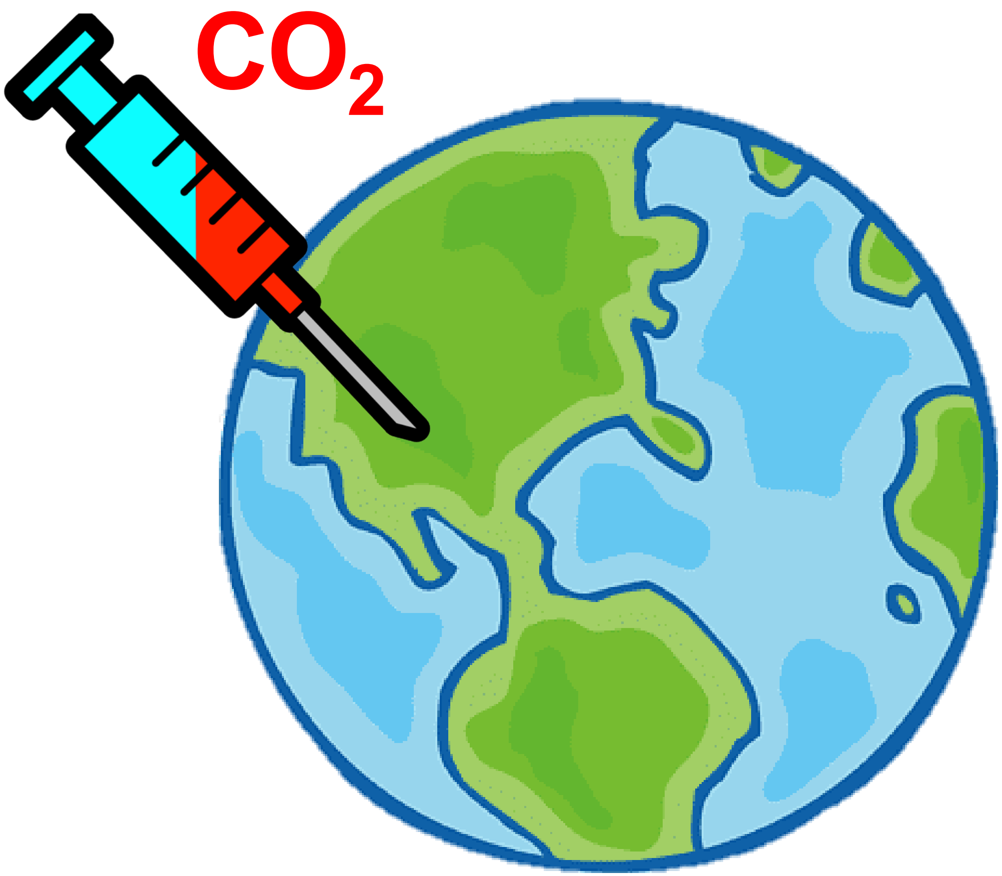
+ Coupled C-N biogeochemistry - CESM1
+ Explicit crop management - CESM2

# Idealized experiments



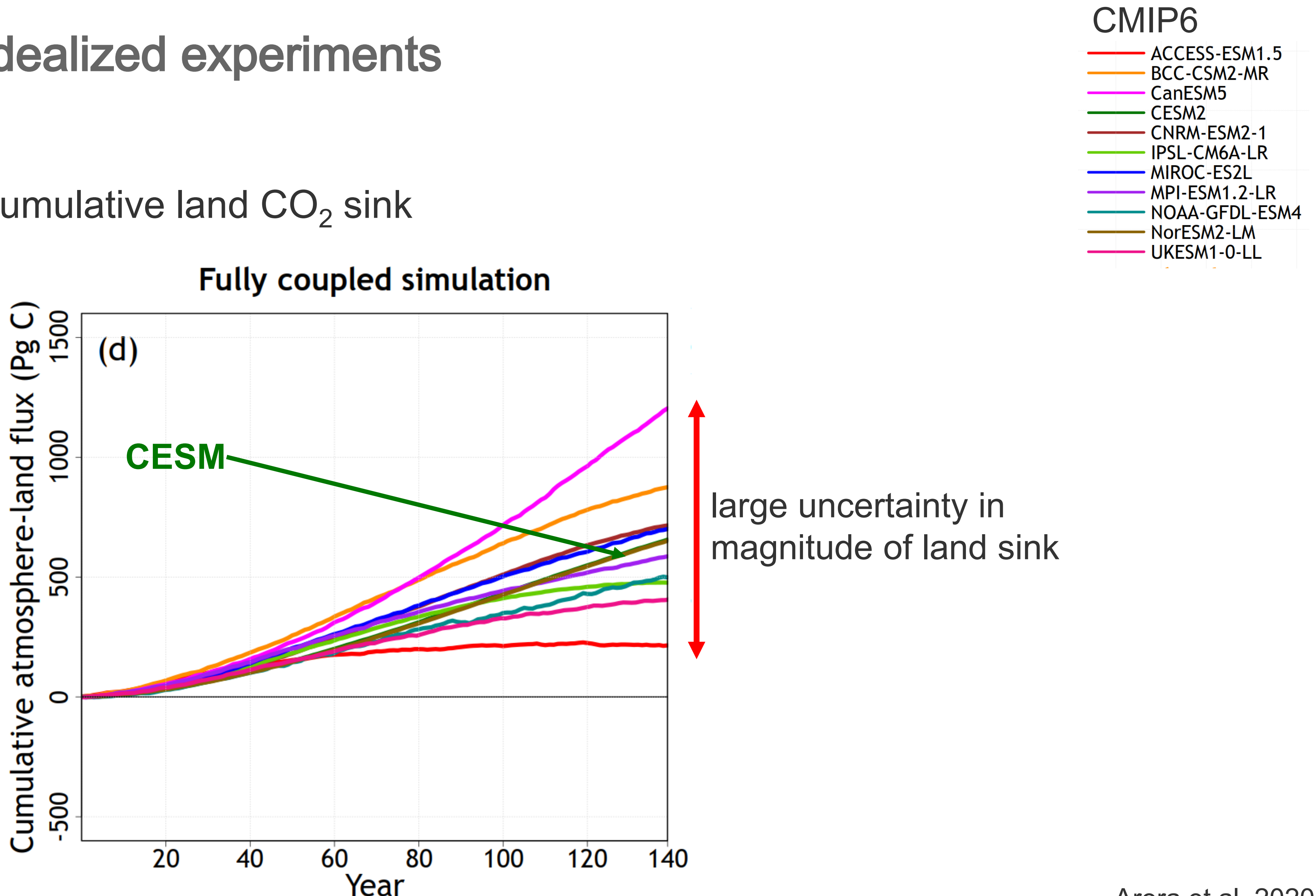

**1% CO2 / year**
**Land & Ocean uptake**
**Temperature change**

**Three experiments:**

1. Fully coupled
2. Biogeochemically coupled
3. Radiatively coupled

# Idealized experiments

Cumulative land $CO_2$ sink




large uncertainty in magnitude of land sink

Arora et al. 2020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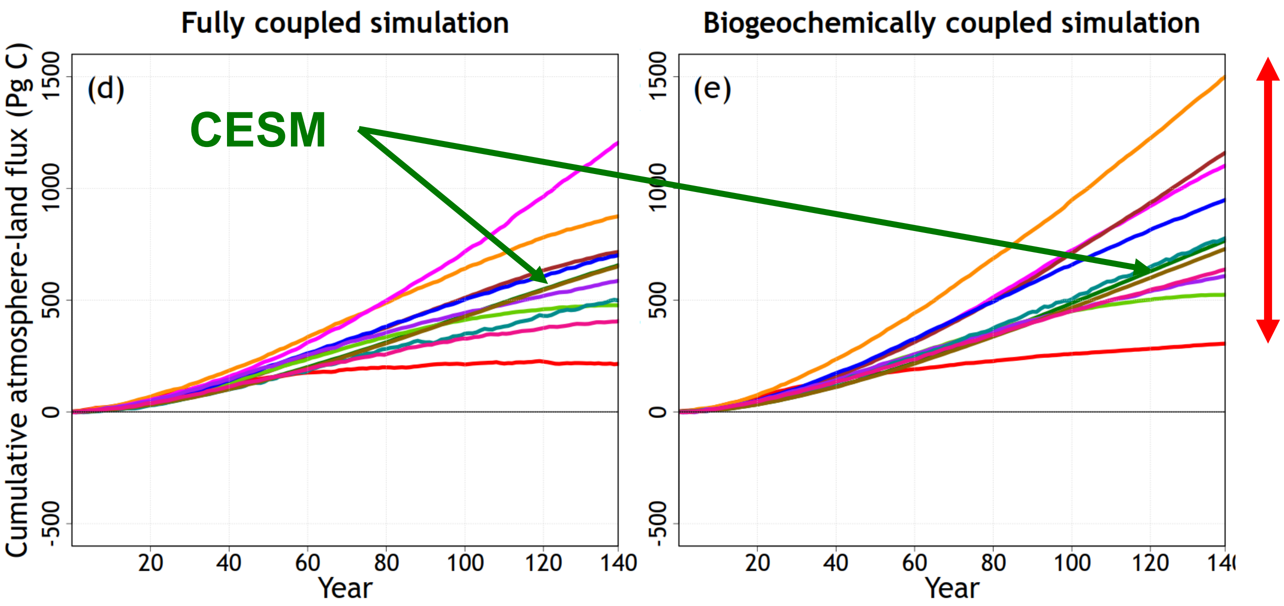
# Idealized experiments

Cumulative land $CO_2$ sink

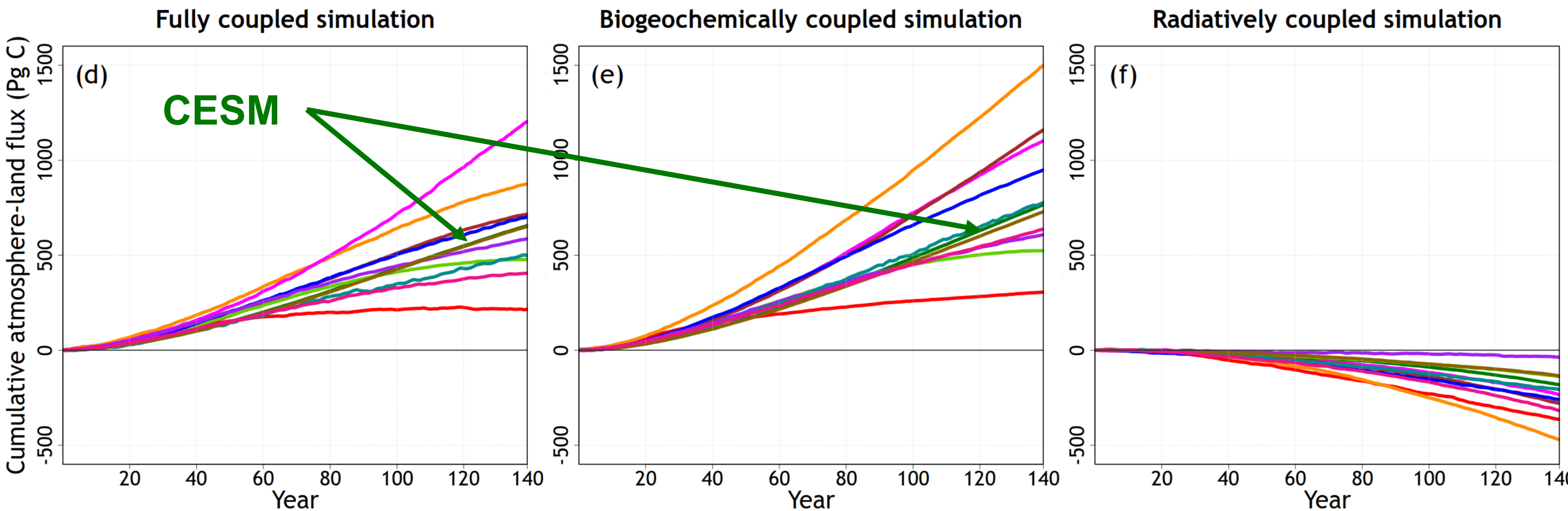



still large uncertainty in magnitude of land sink

Arora et al. 2020

# Idealized experiments

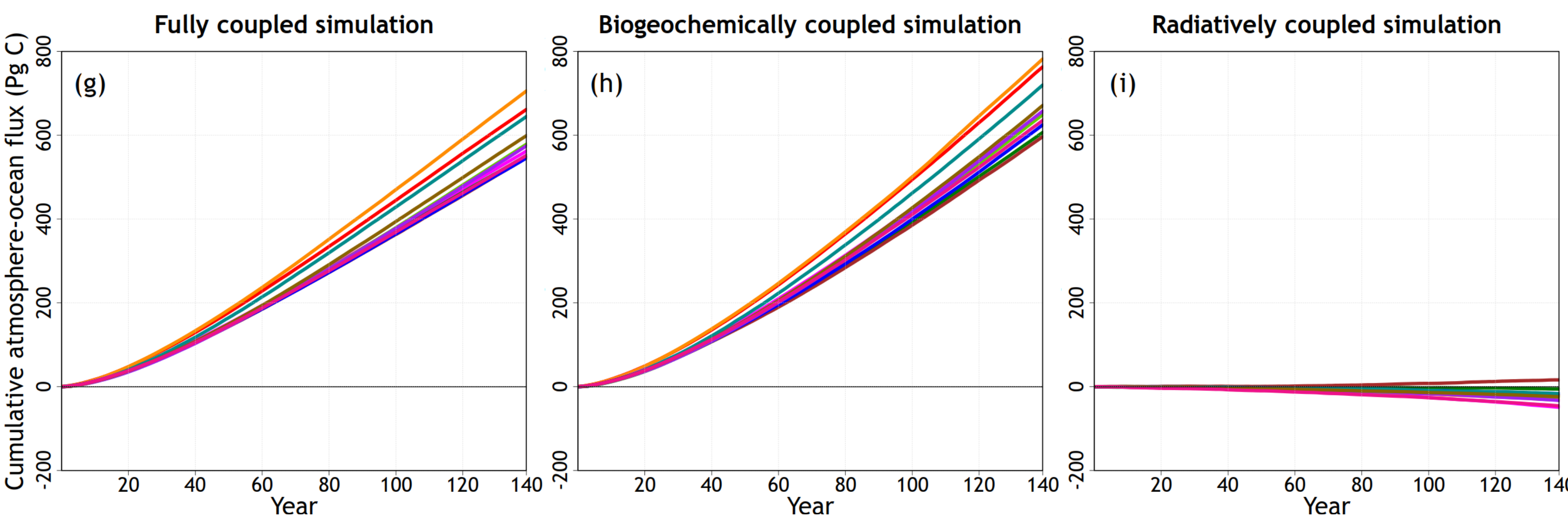
## Cumulative land $CO_2$ sink




Arora et al. 2020

# Idealized experiments

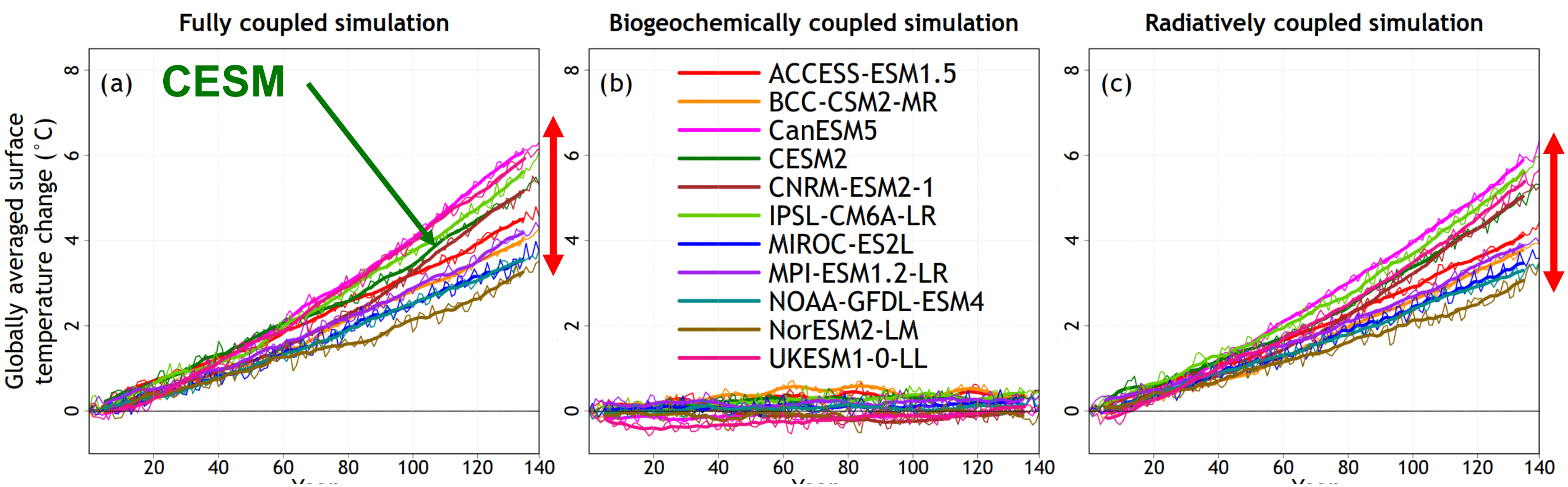
Cumulative ocean $CO_2$ sink




Arora et al. 2020

# Idealized experiments

Global average surface temperature change (ºC)

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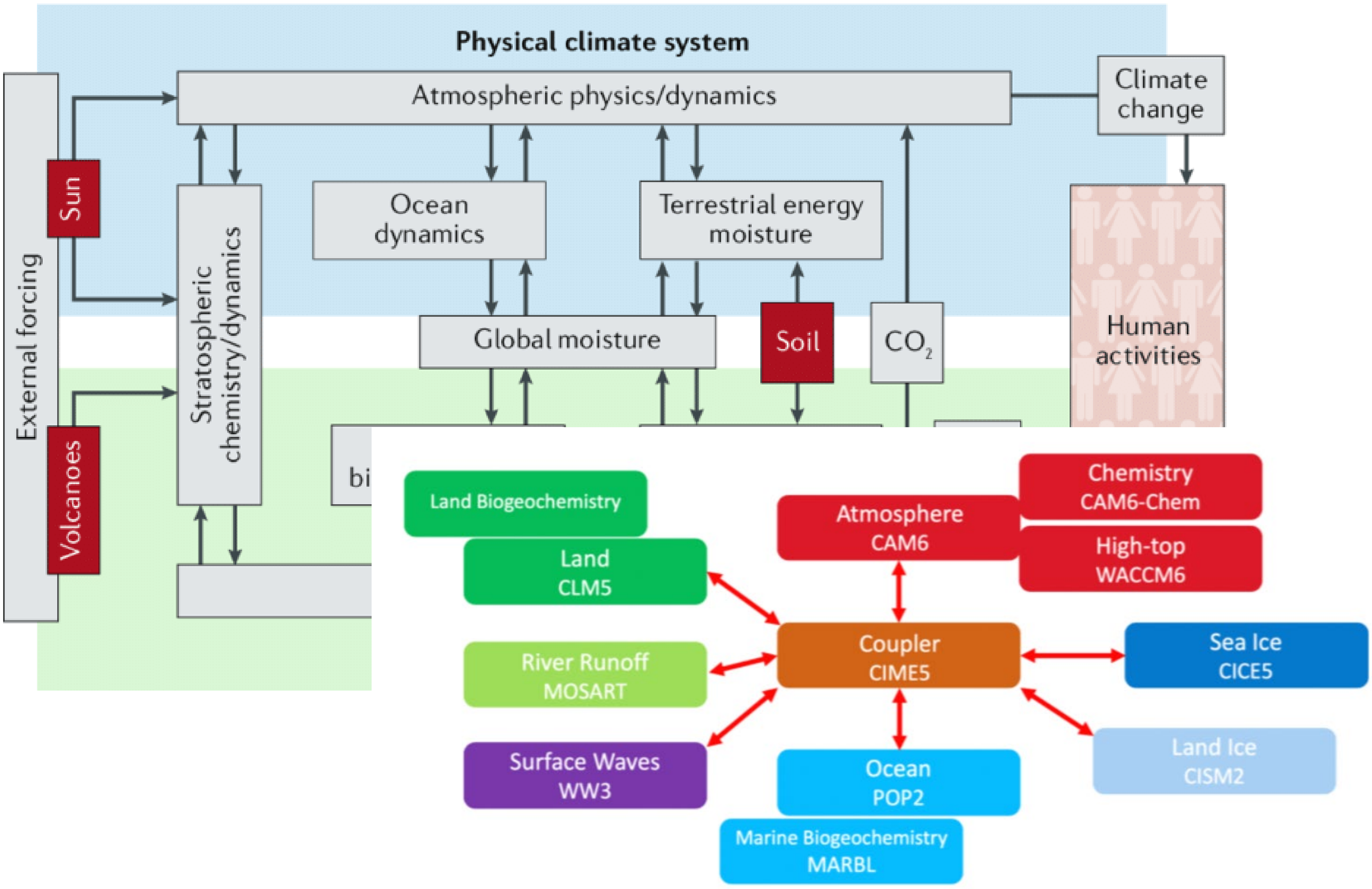



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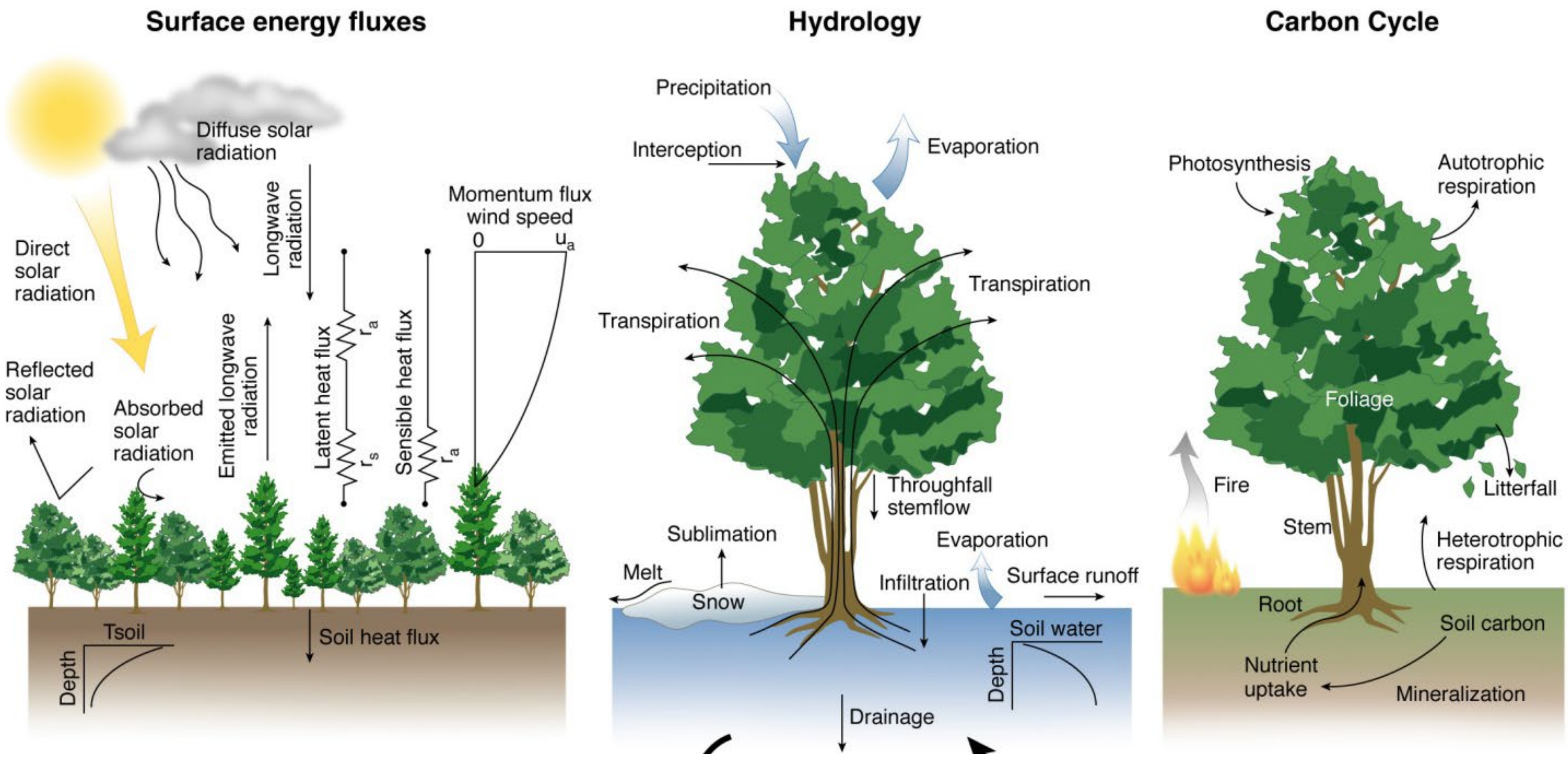
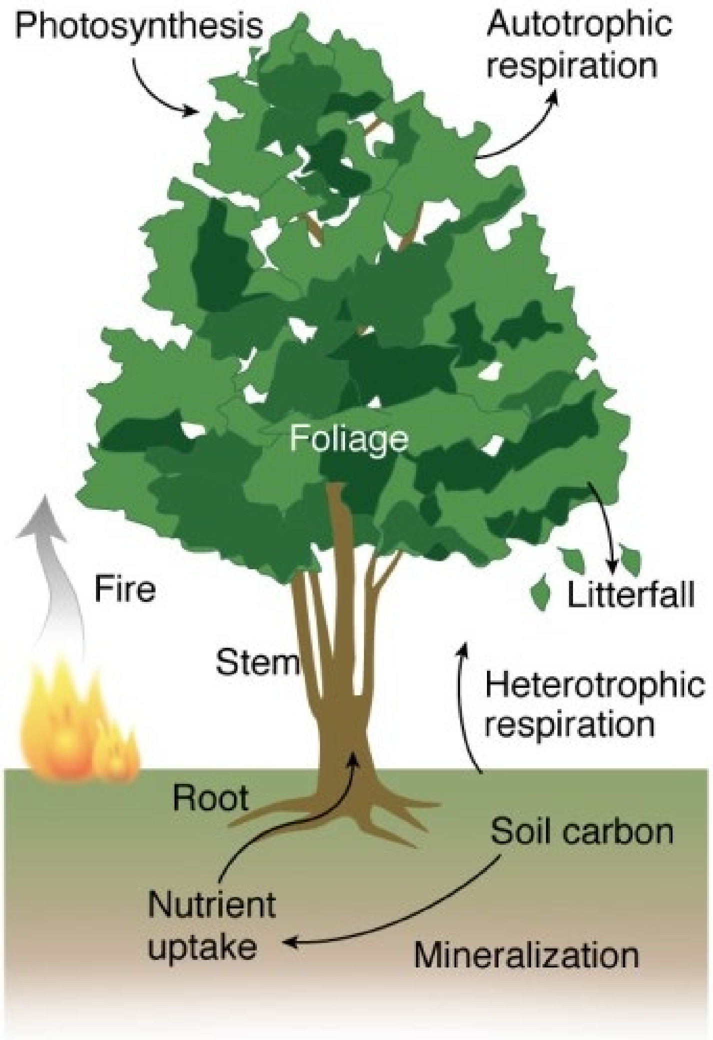
Community LAND MODEL DEVELO




Bonan 2008, Science

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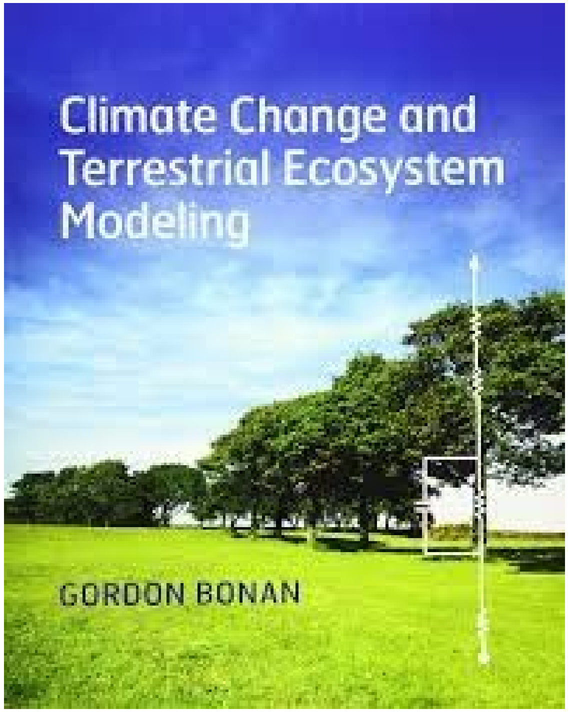
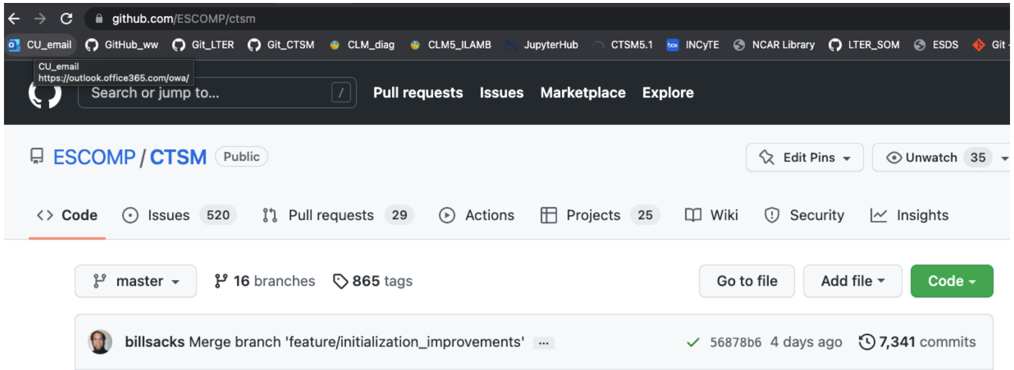


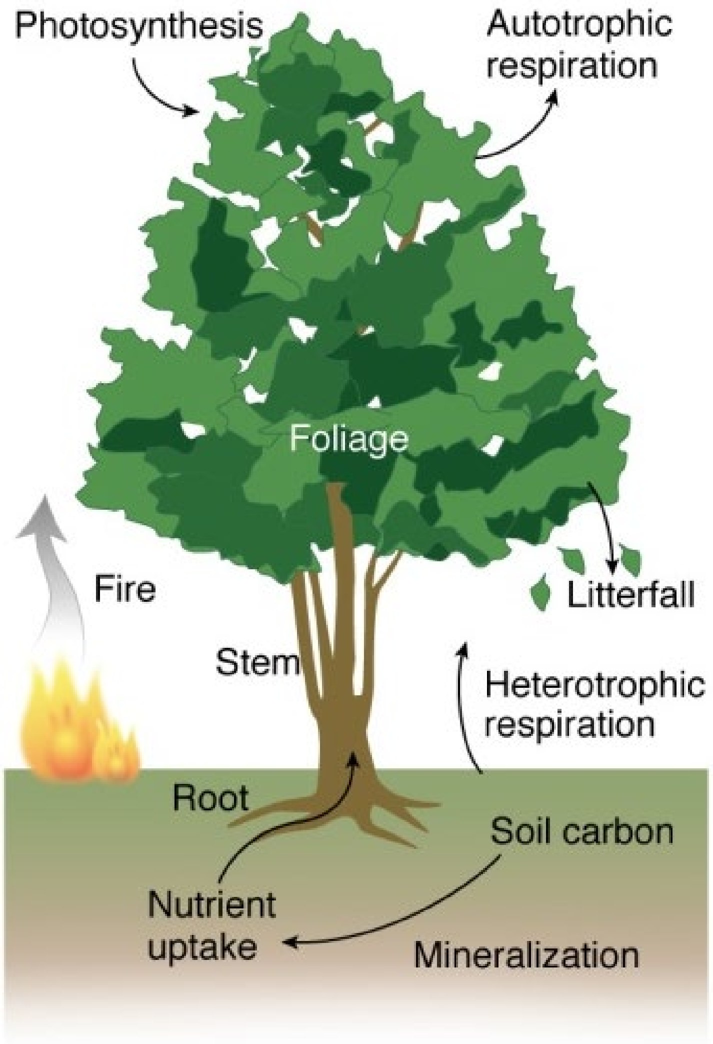




https://github.com/ESCOMP/ctsm

## Leaves

Photosynthesis

Stomatal Conductance

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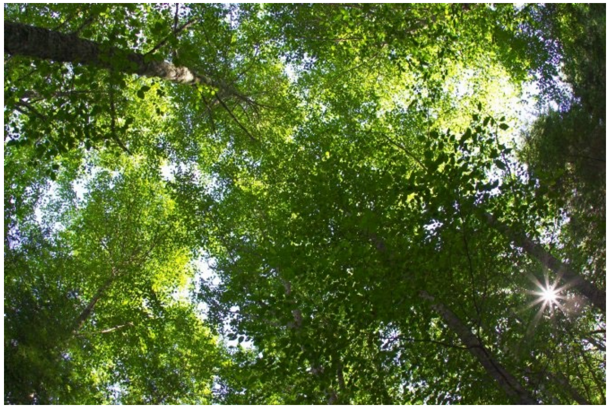

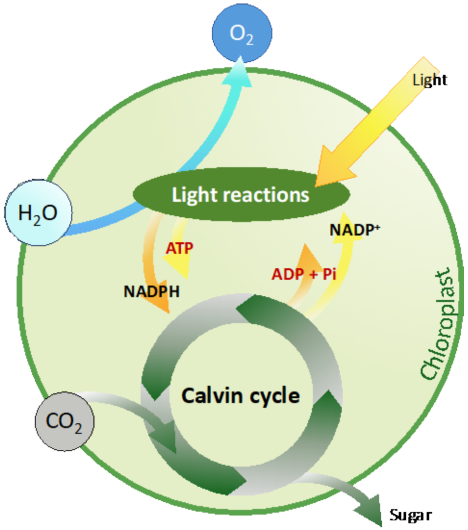


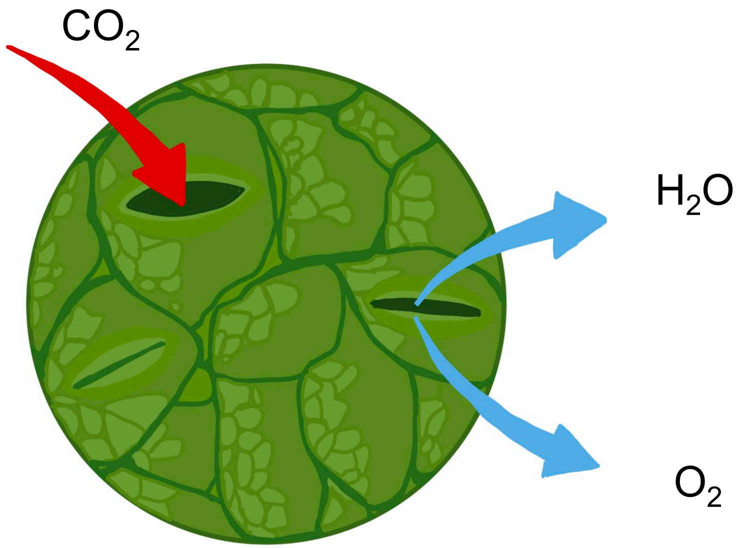




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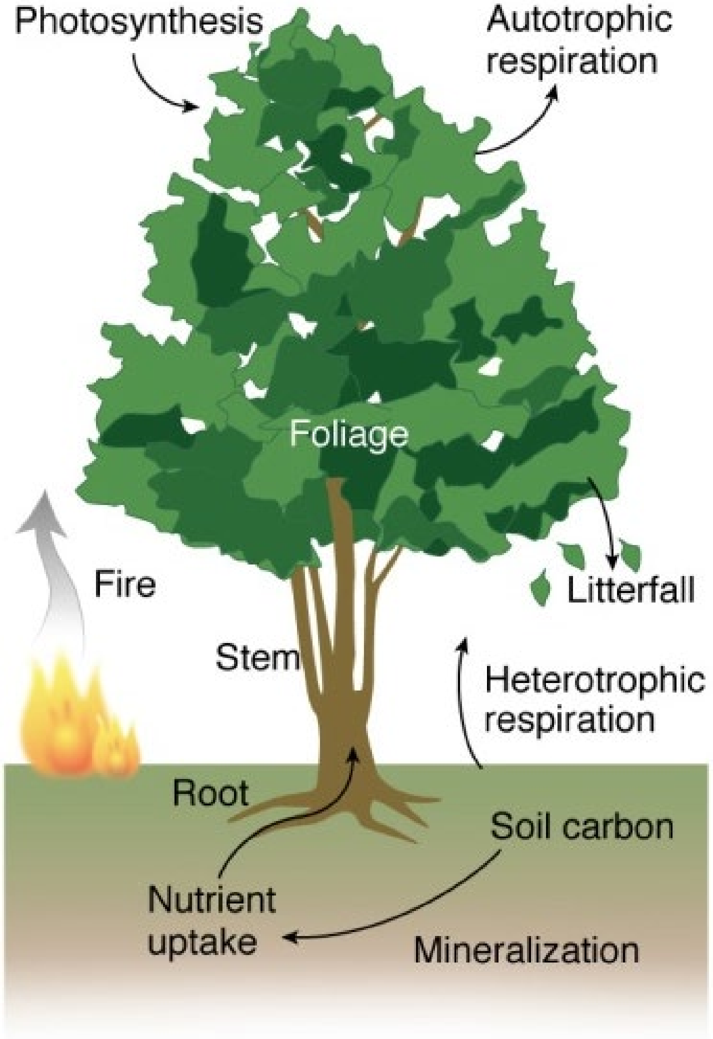



Bonan 2008, Science

**Leaves**

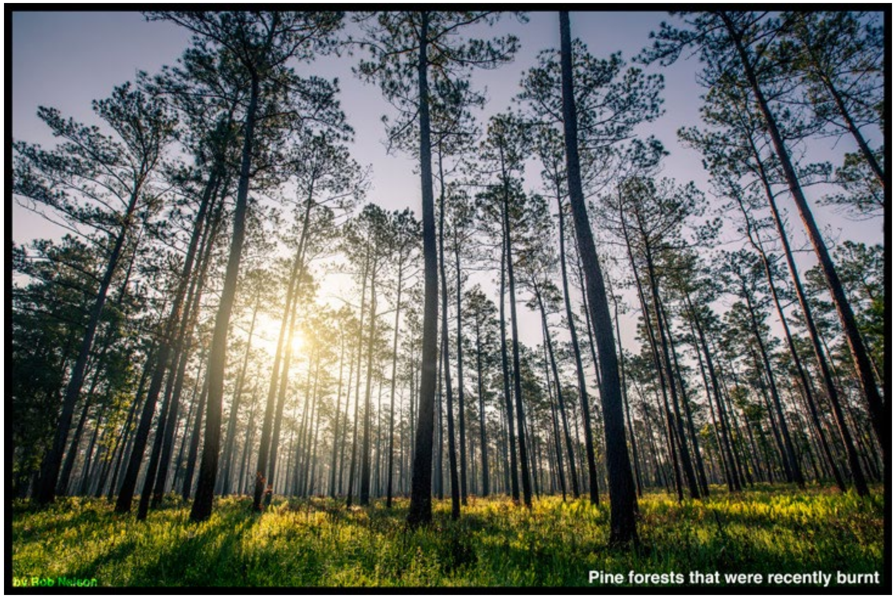
Photosynthesis

Stomatal Conductance

**Canopy & Light**

Two-stream radiation approximation, sunlit/shaded leaf

## GPP: Gross Primary Productivity



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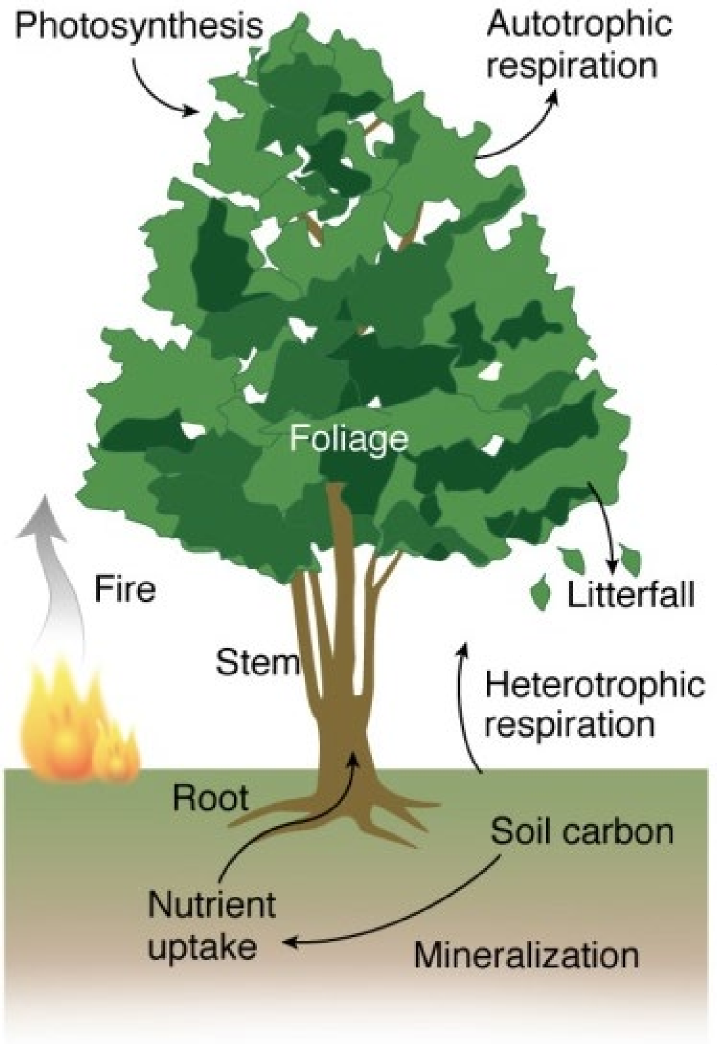


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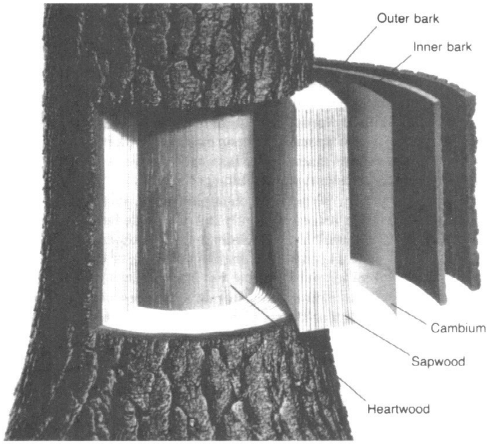
**Leaves**
- Photosynthesis
- Stomatal Conductance

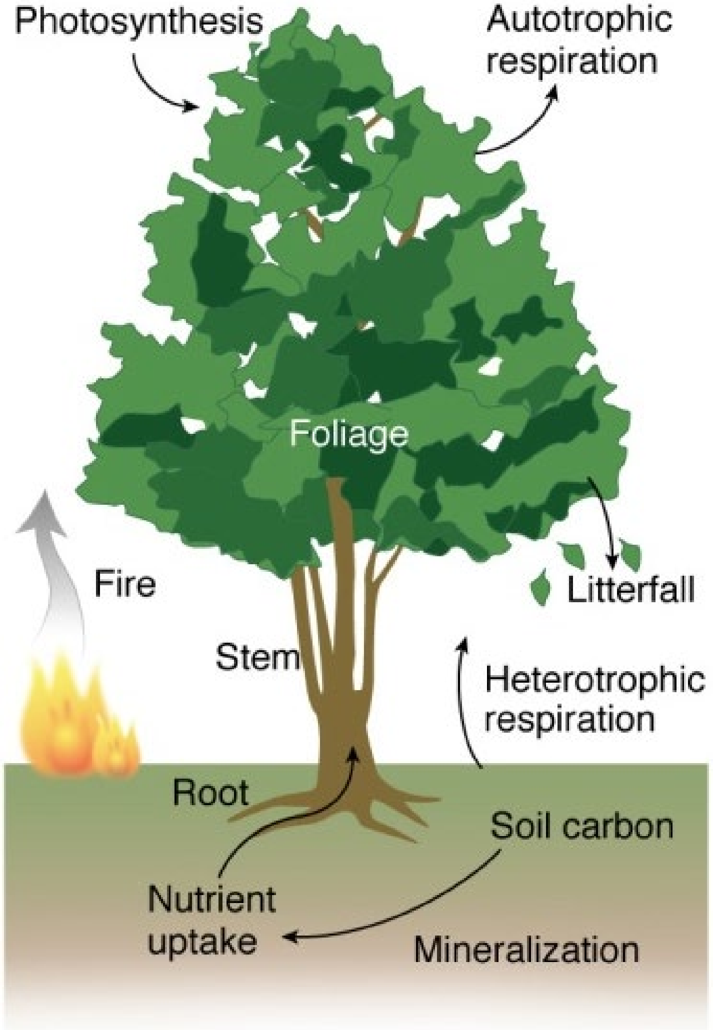
**Canopy & Light**
- Two-stream radiation approximation, sunlit/shaded leaf

**Allocation & Respiration**
- leaves, woods, roots

**AR: Autotrophic respiration**

**NPP:**
**Net Primary Productivity =**
**GPP - AR**



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**Leaves**

Photosynthesis

Stomatal Conductance

**Canopy & Light**

Two-stream radiation approximation, sunlit/shaded leaf

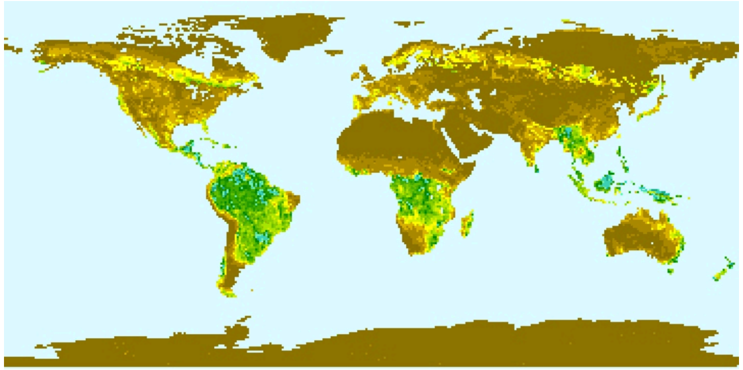
**Allocation & Respiration**

leaves, woods, roots

**Phenology & Turnover**

mortality, litter, etc.

## LAI: leaf area index

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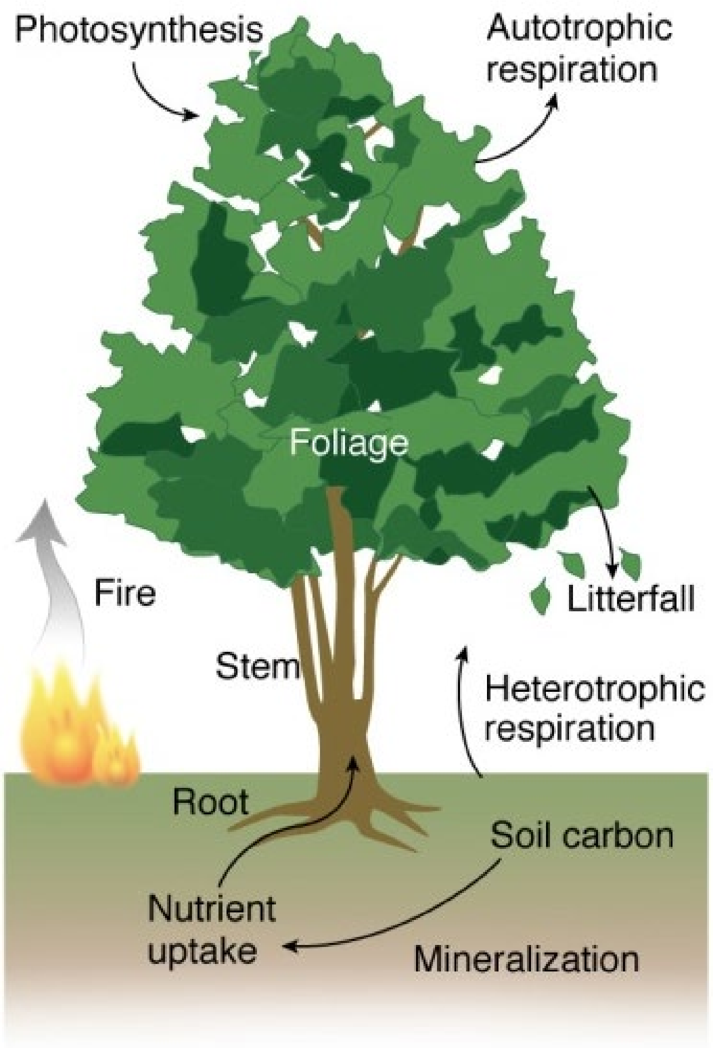


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Photosynthesis

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Two-stream radiation approximation, sunlit/shaded leaf

**Allocation & Respiration**

leaves, woods, roots

**Phenology & Turnover**

mortality, litter, etc.

**Decomposition**

**HR: heterotrophic respiration**


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GPP: Gross Primary Productivity

AR: Autotrophic respiration

NPP: Net Primary Productivity = GPP - AR

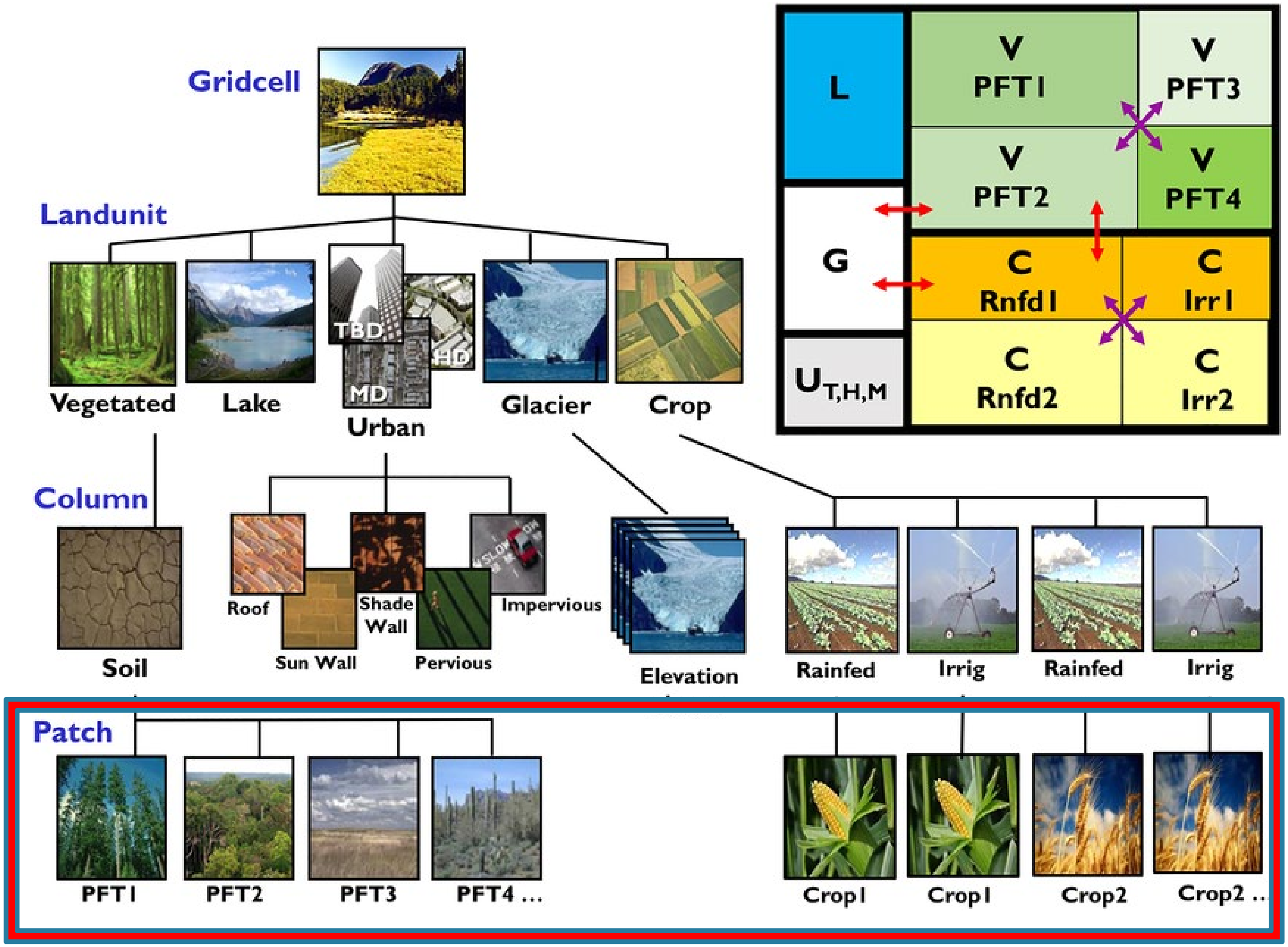
LAI: leaf area index

HR: heterotrophic respiration

NEP: Net Ecosystem Production = GPP – AR – HR

NEE: Net Ecosystem Exchange = NEP - fire loss

NBP: Net Biome Production = NEE – land use - harvest

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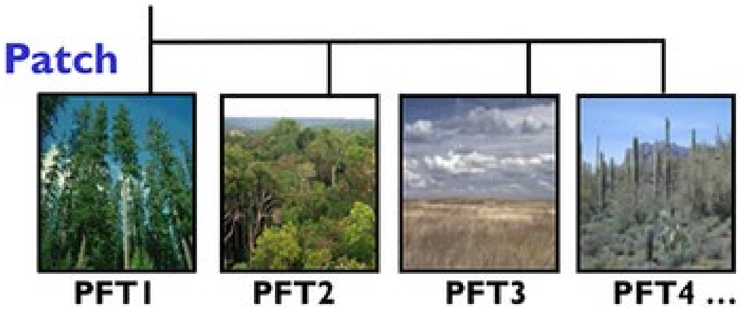
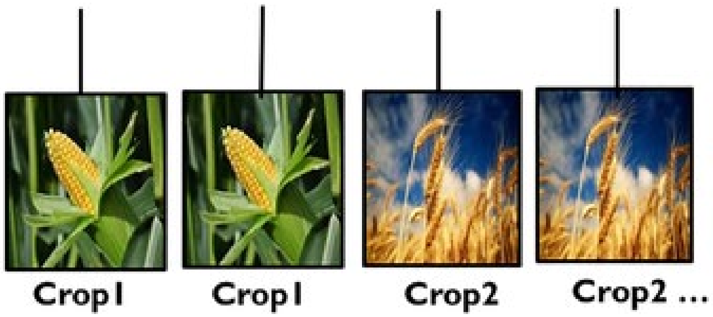
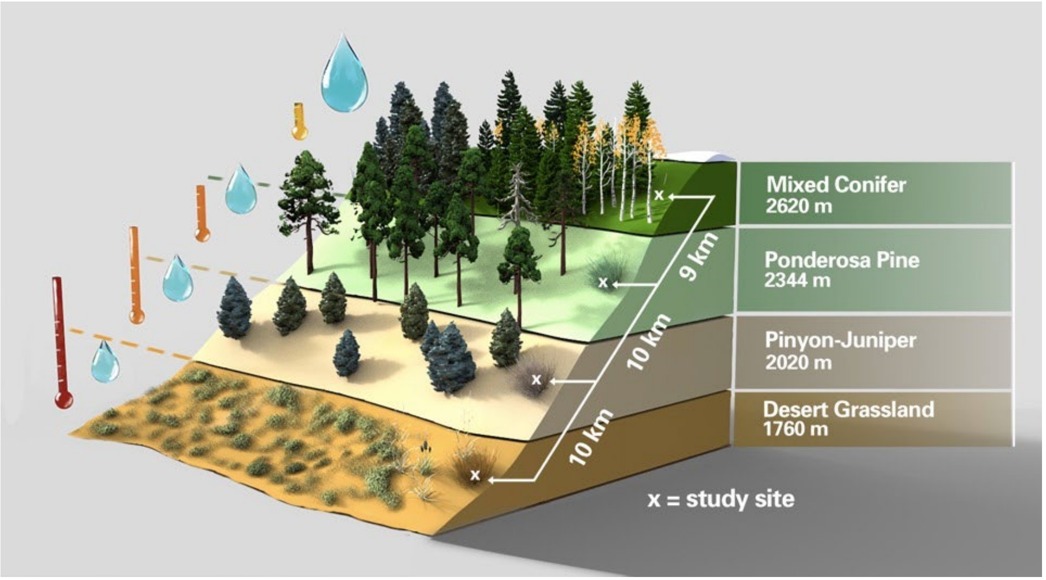



classes

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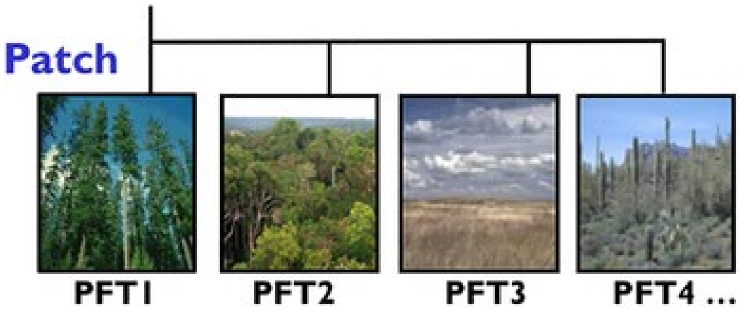


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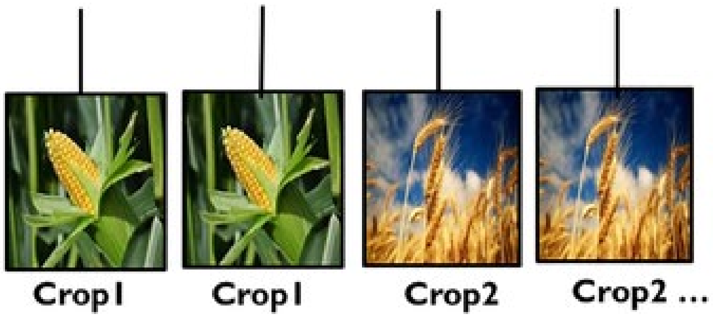


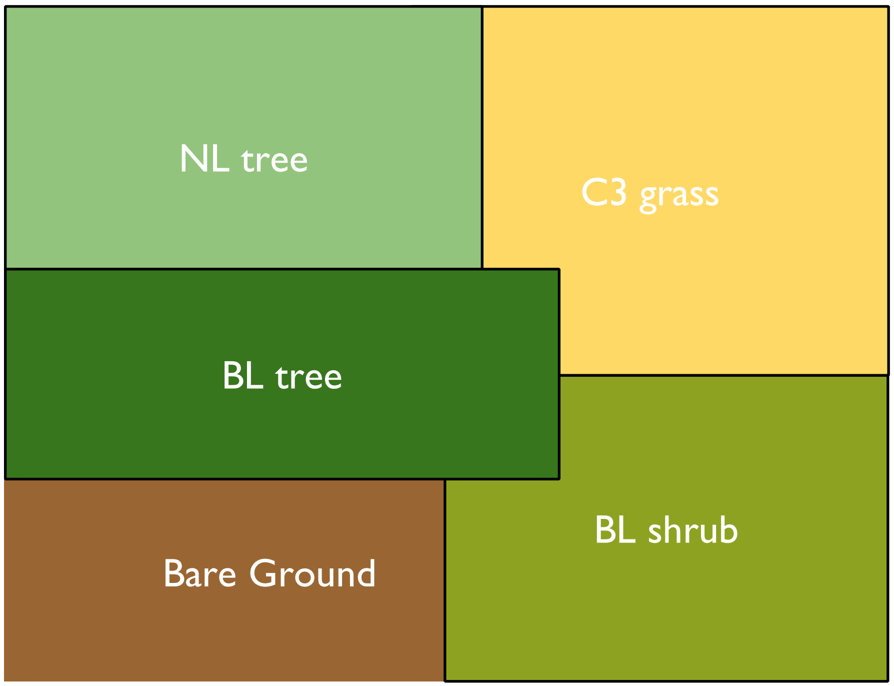


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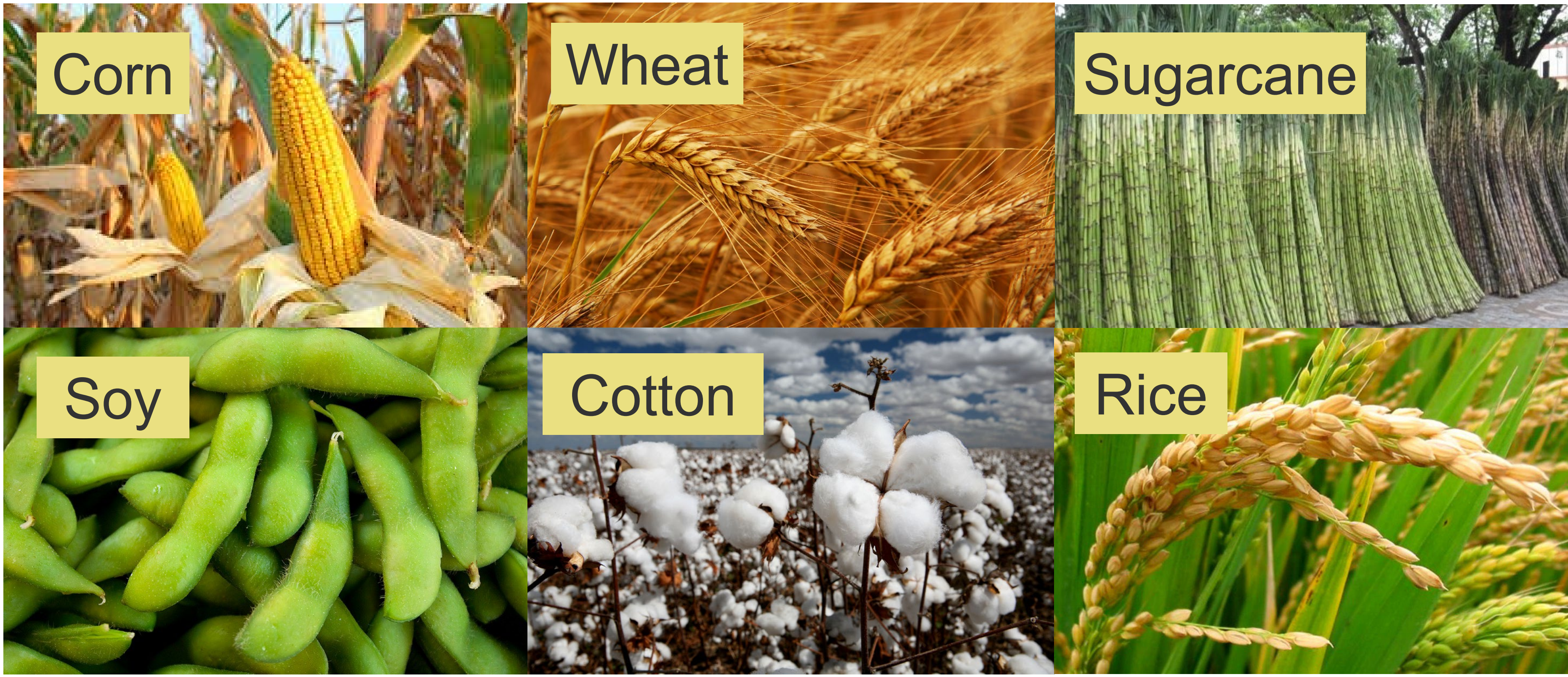
# Agriculture in CLM



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# Agriculture in CLM

Fertilize

Irrigate

Transient fertilizer and irrigation (1850 – 2100)

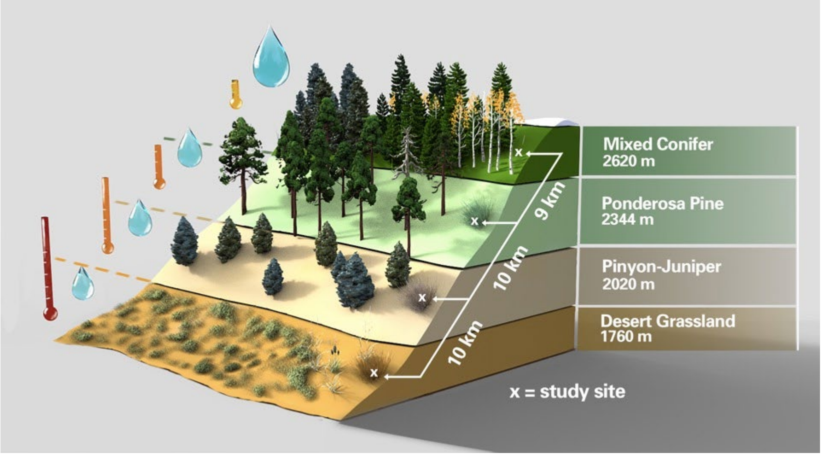
# Where do parameter values come from?

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

**Trait databases**
*e.g., TRY Database (Leaf N and dark respiration)*

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

**Calibration!**




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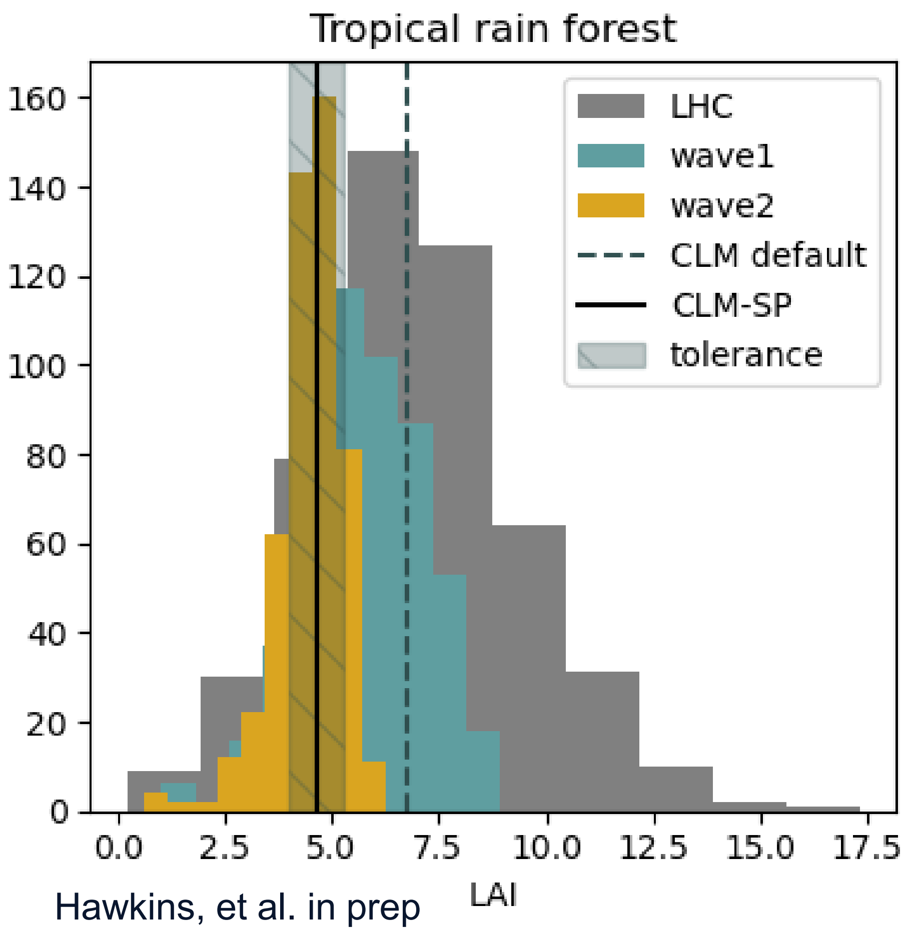
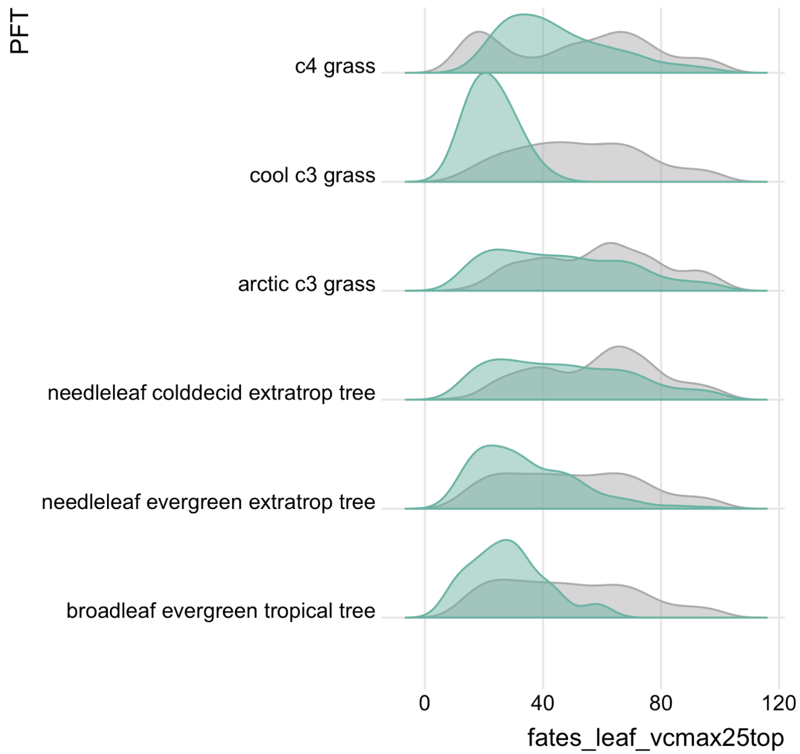



Hawkins, et al. in prep

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# Land biogeochemistry in CESM

Why?

How?

**Future directions**


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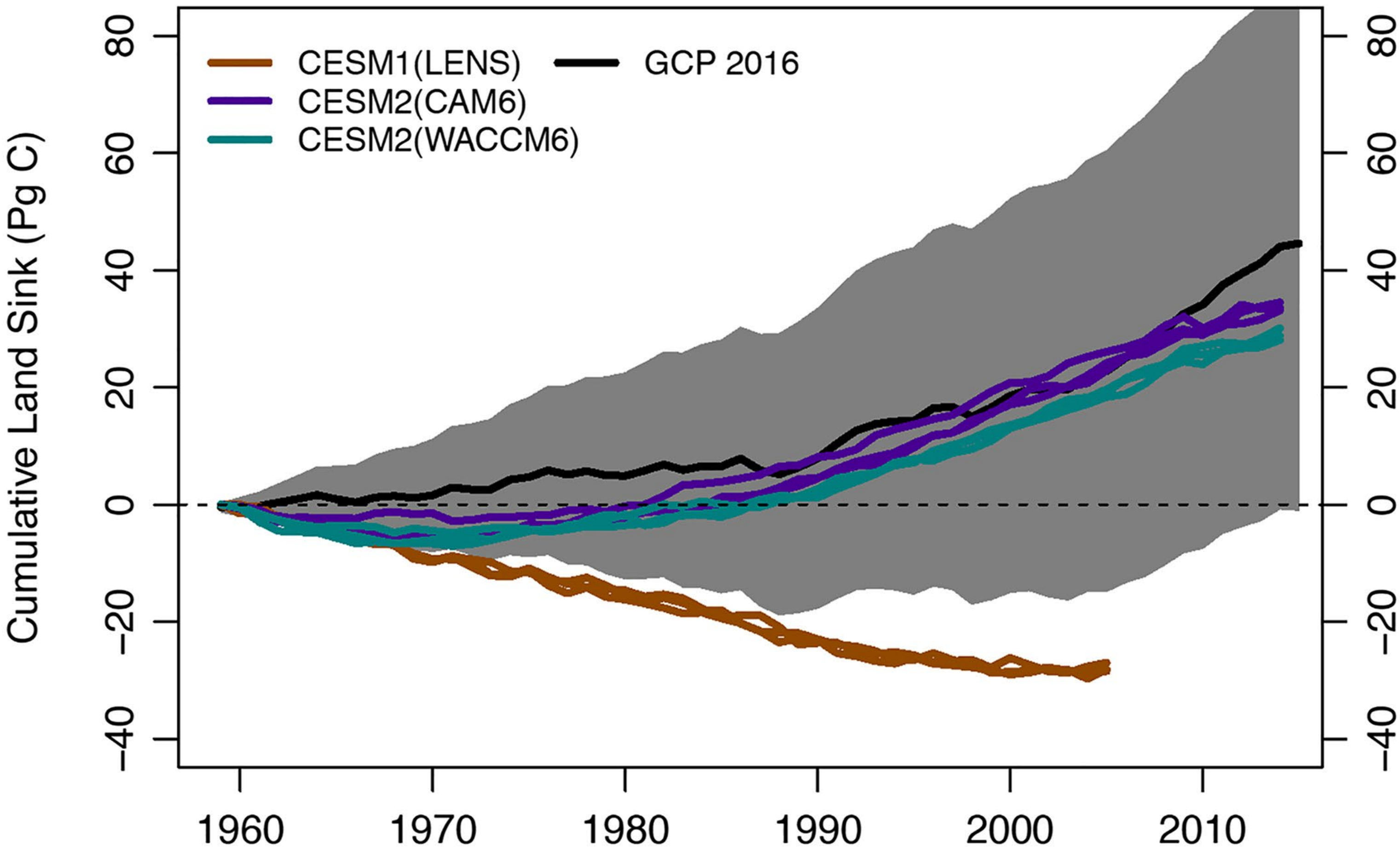
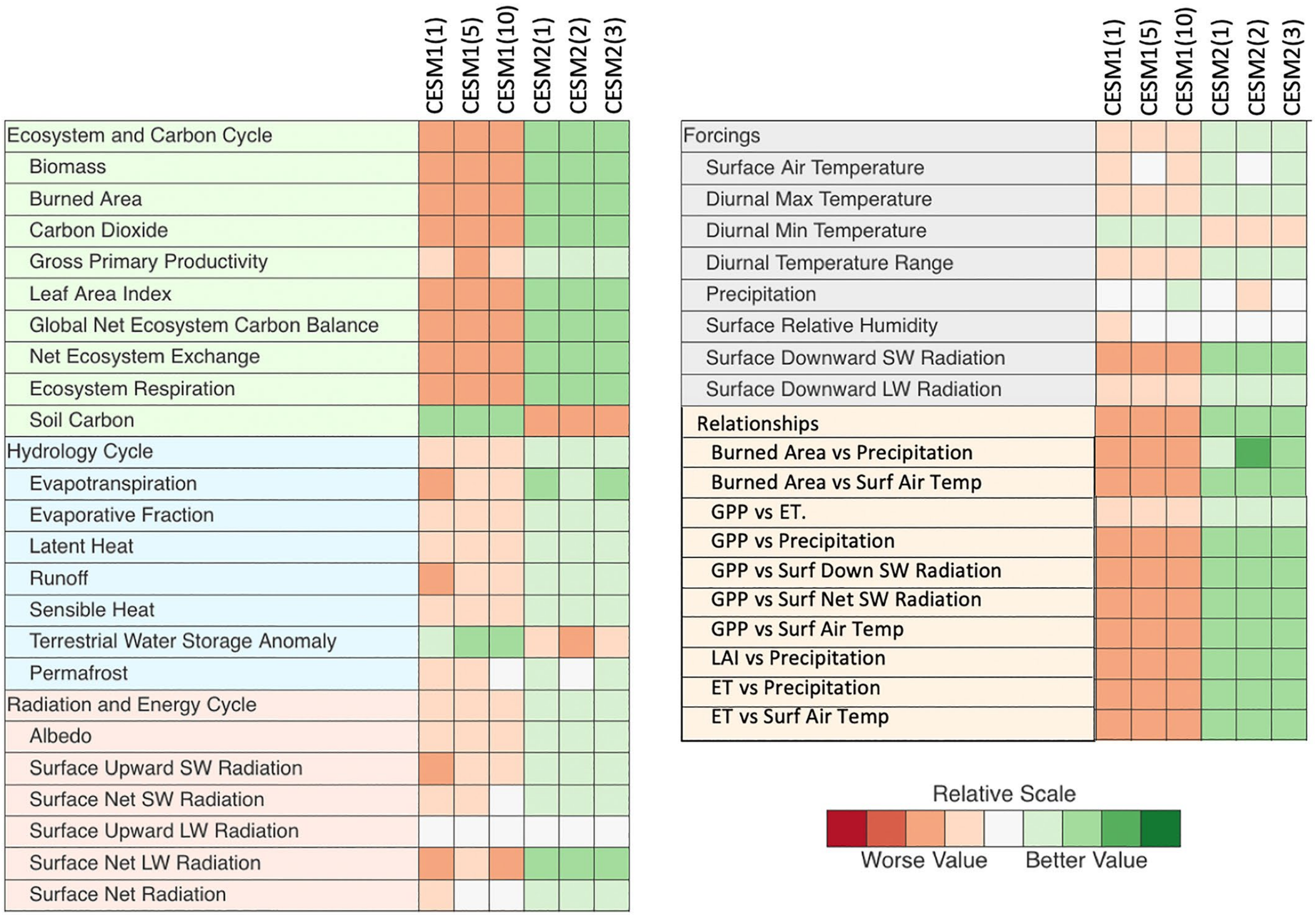
# Representing the land C sink




Danabasoglu et al 2020 JAMES

# Model benchmarking

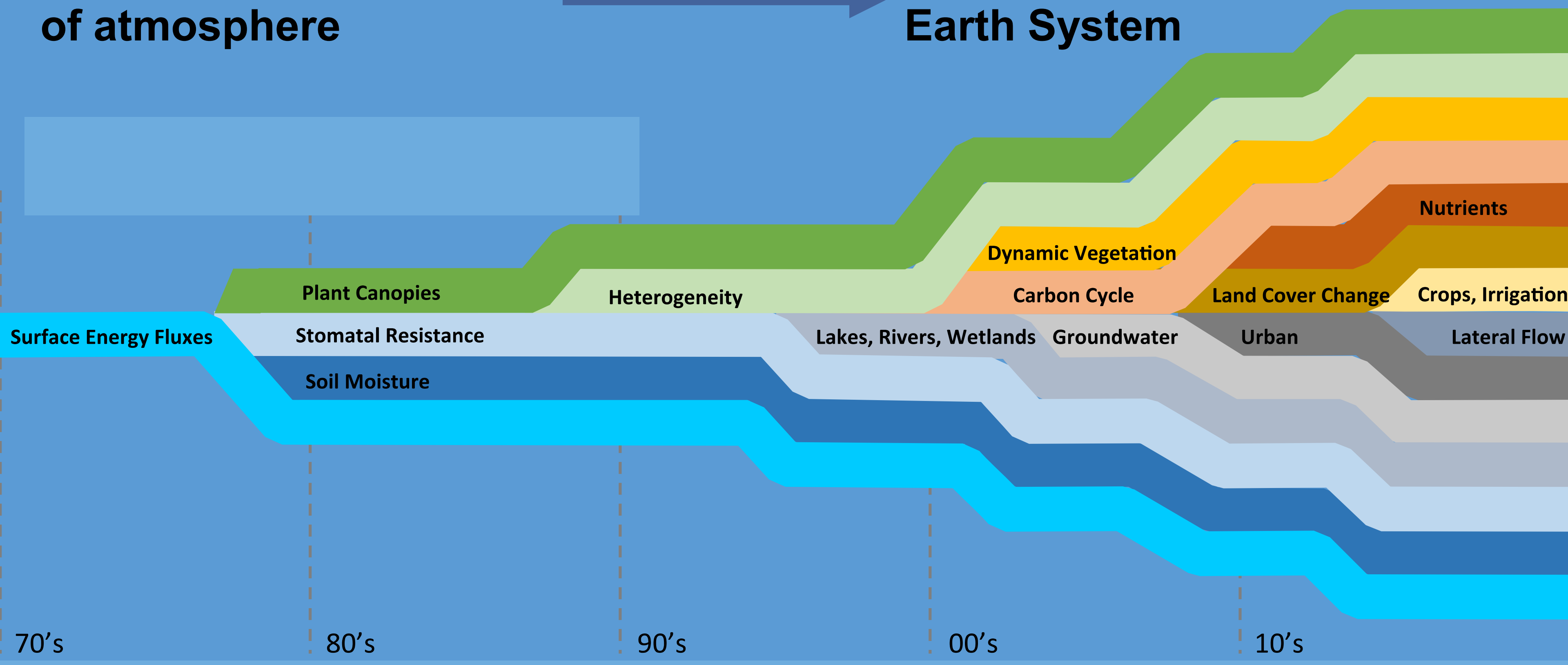



**ILAMB** – International Land Model Benchmarking package

Danabasoglu et al 2020 JAMES

# the Evolution of land modeling

**Land as lower boundary of atmosphere** → **Land as integral component of Earth System**



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# How do ecosystems change when climate changes?



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# How will ecosystems change with climate change?



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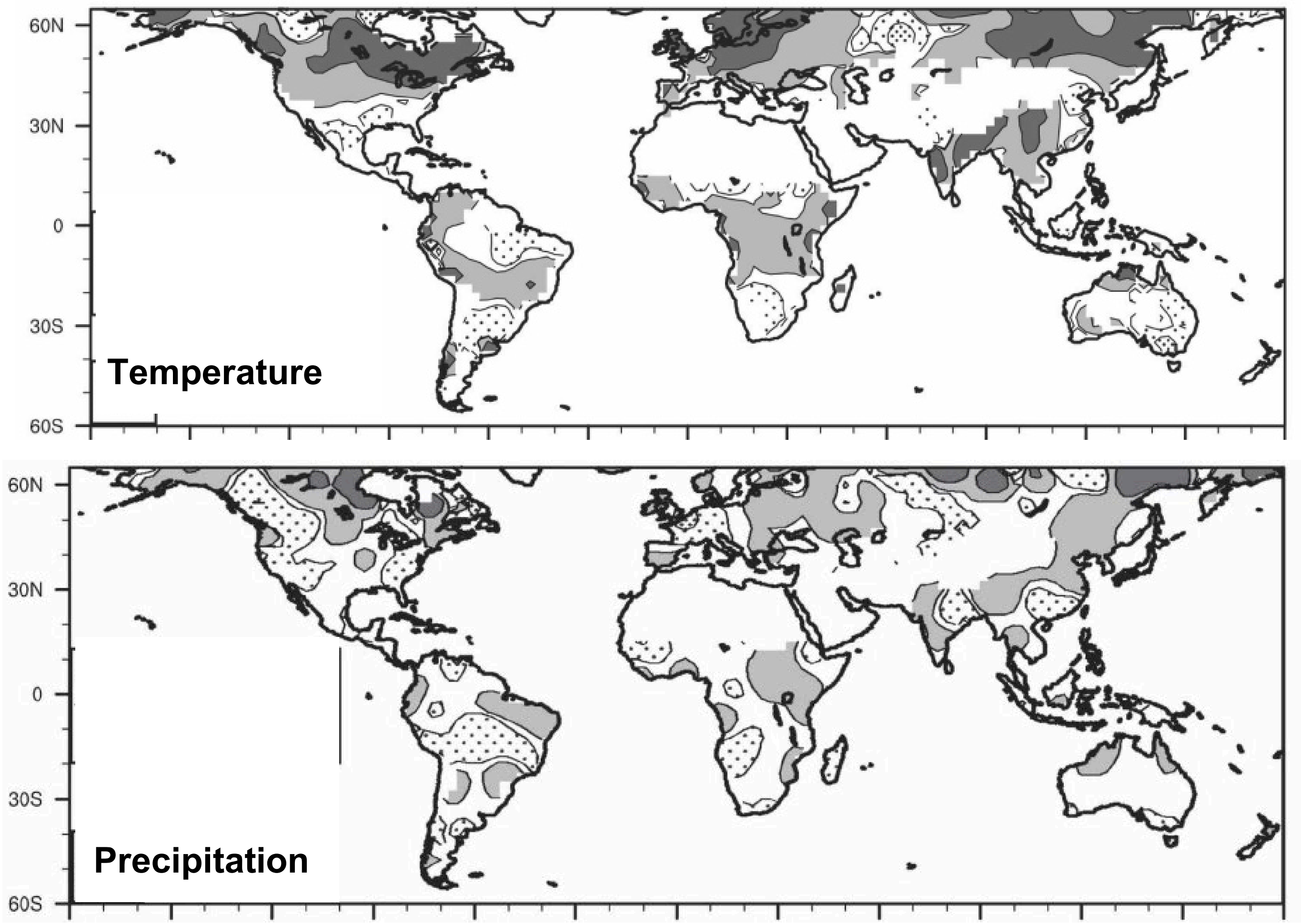


Liu et al. 2006 *Journal of Climate*

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



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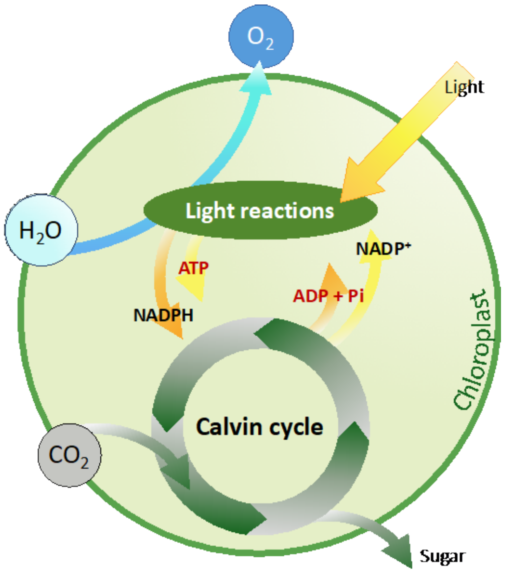
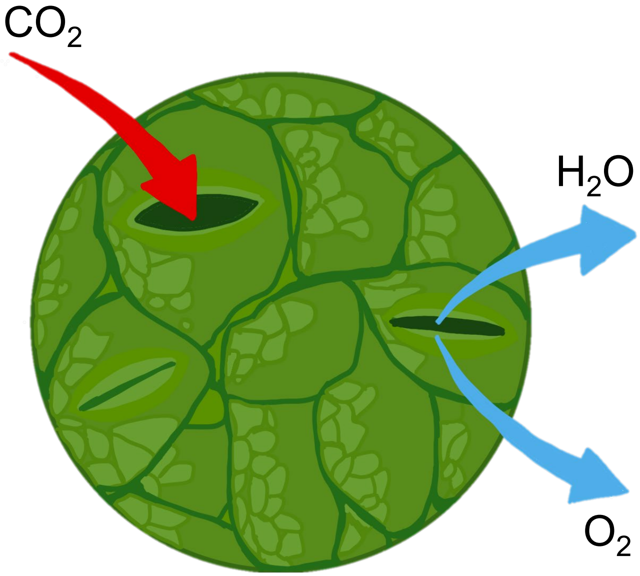
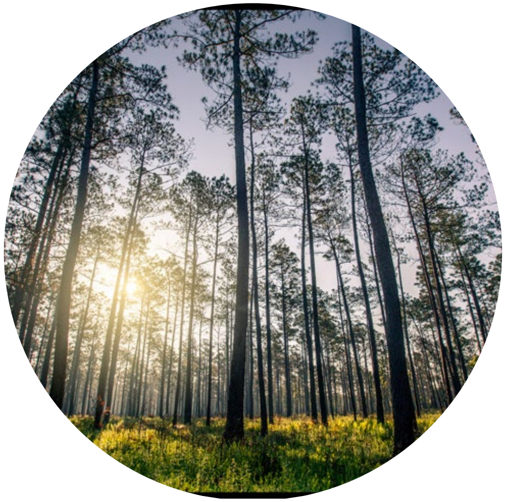
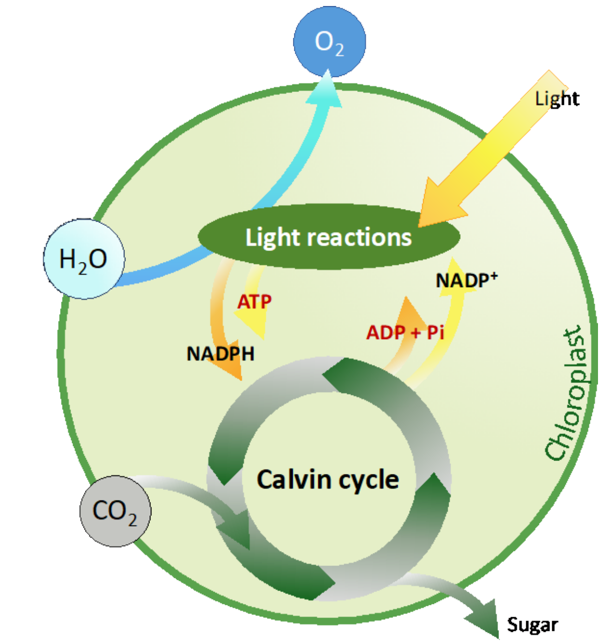

$O_2$
Light
$H_2O$
Light reactions
ATP
NADP+
ADP + Pi
NADPH
Chloroplast
Calvin cycle
$CO_2$
Sugar

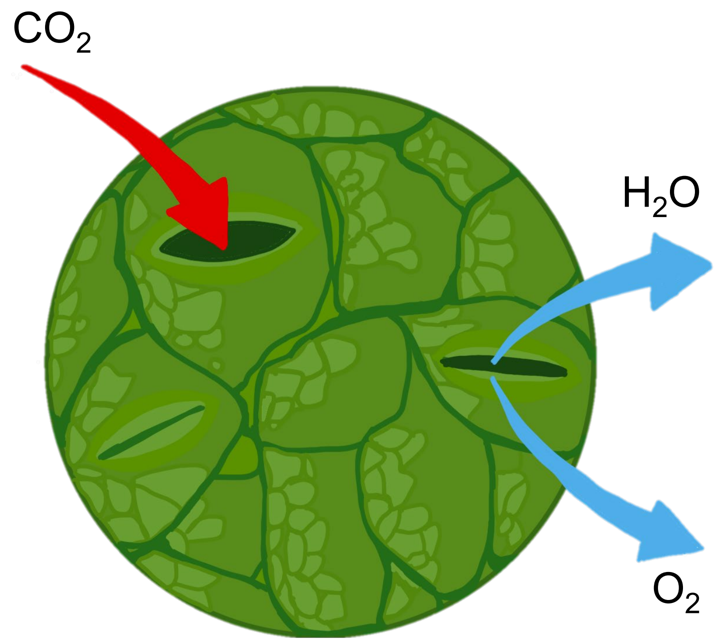

$CO_2$
$H_2O$
$O_2$


sun leaf
shade leaf

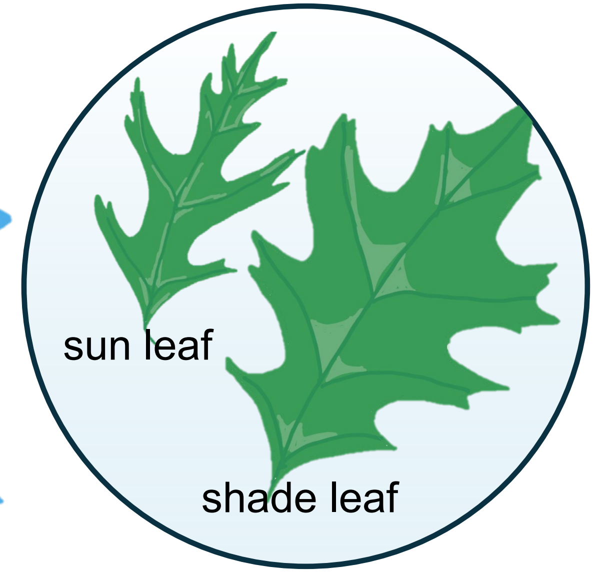




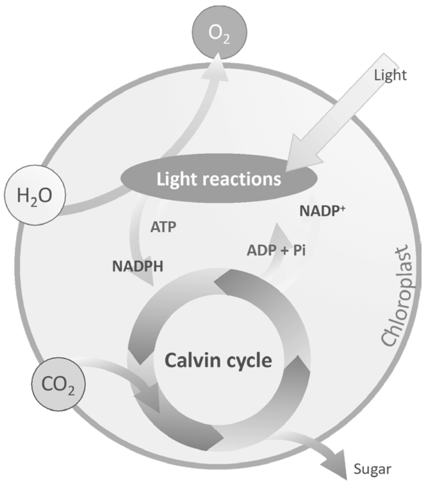
$O_2$
Light
$H_2O$
Light reactions
ATP
NADPH
NADP⁺
ADP + Pi
Chloroplast
Calvin cycle
$CO_2$
Sugar

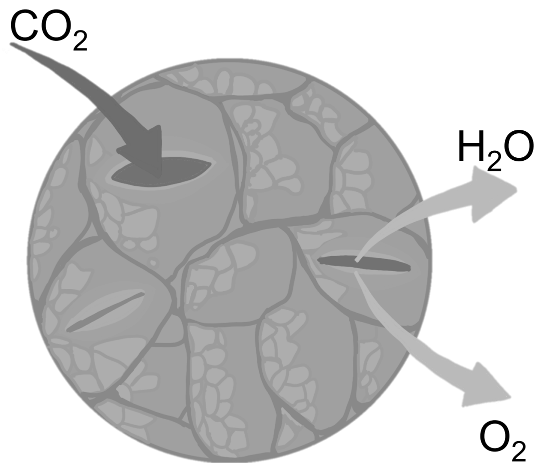



$CO_2$
$H_2O$
$O_2$

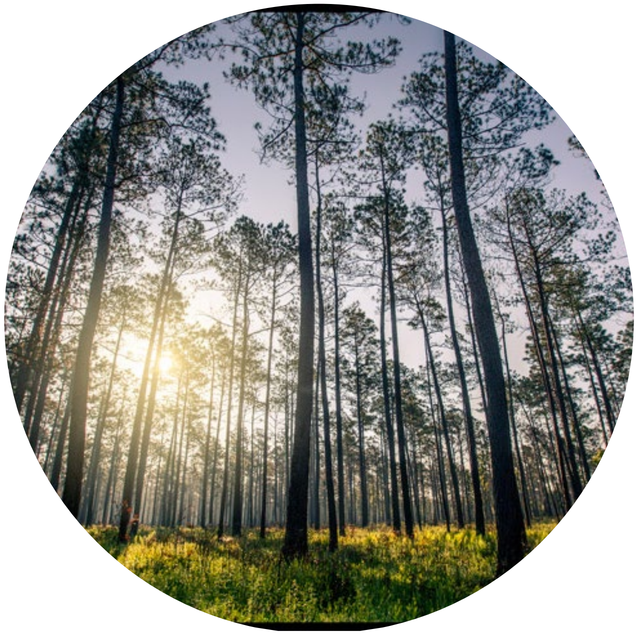



sun leaf
shade leaf



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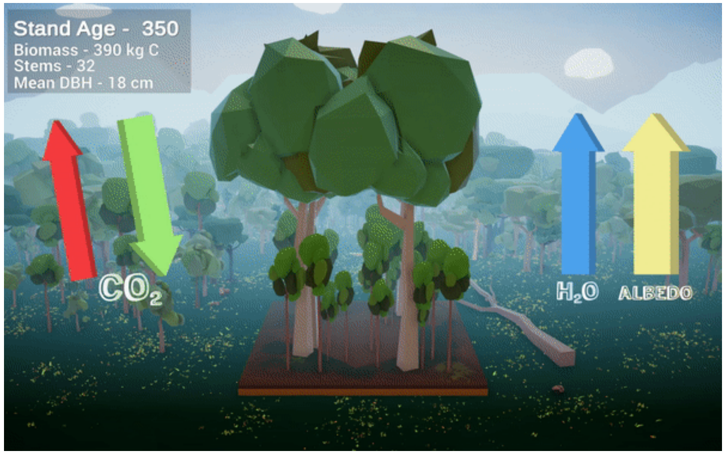
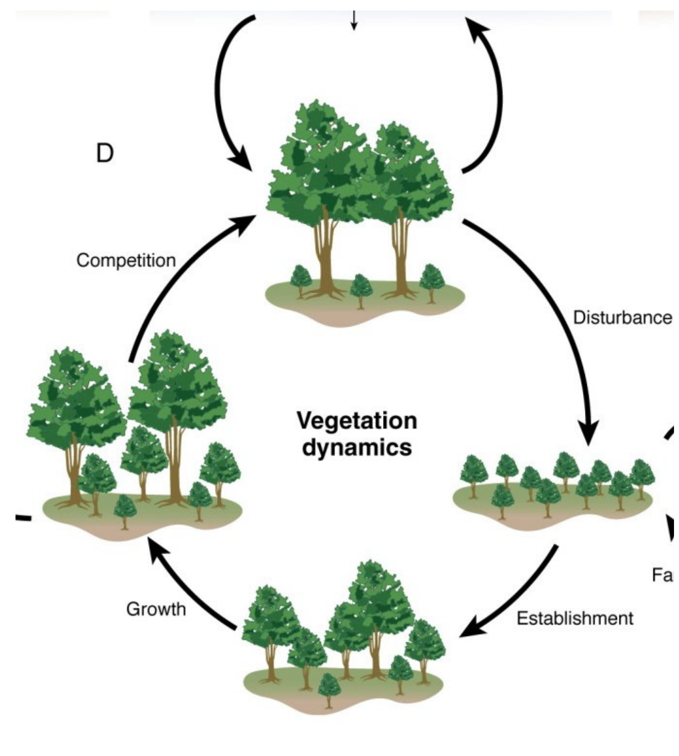
# Forests are a mosaic of patches

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







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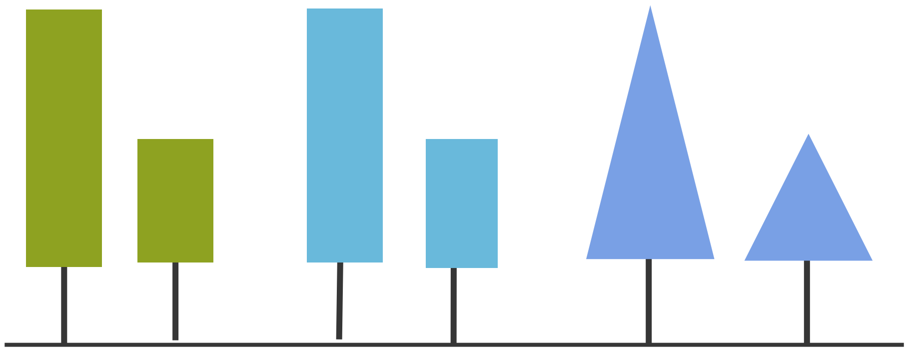
# Functionally Assembled Ecosystem Simulator (FATES)

FATES

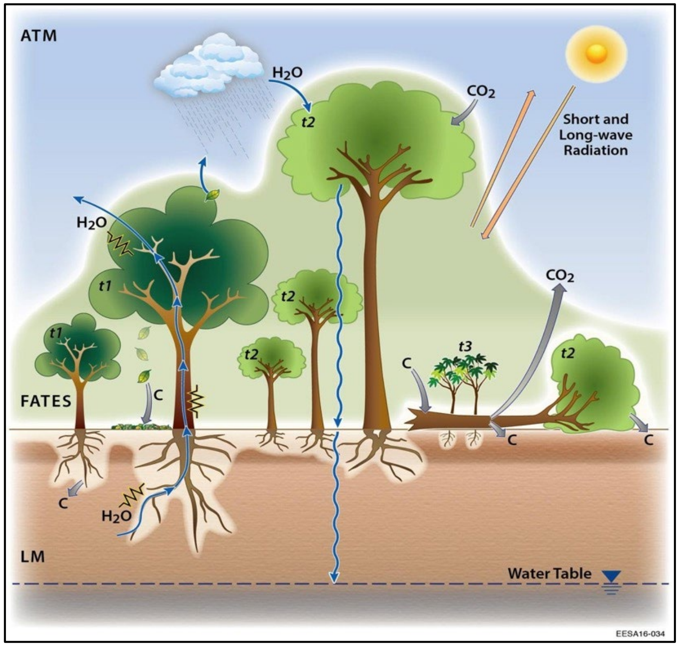


**cohort-specific model**

**30-minute photosynthesis and fluxes**

**daily growth and allocation**

**dynamic vegetation!**



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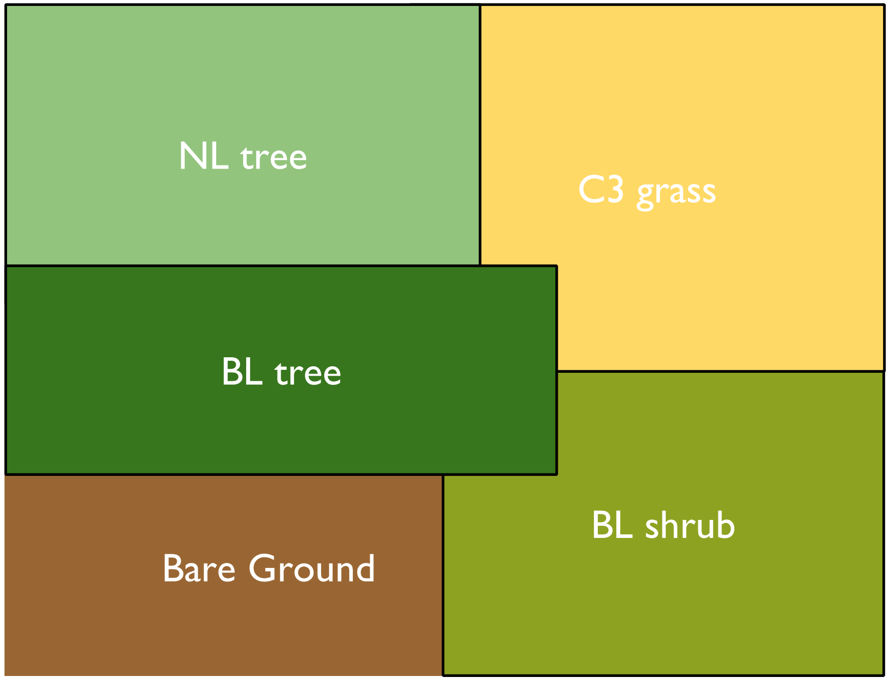
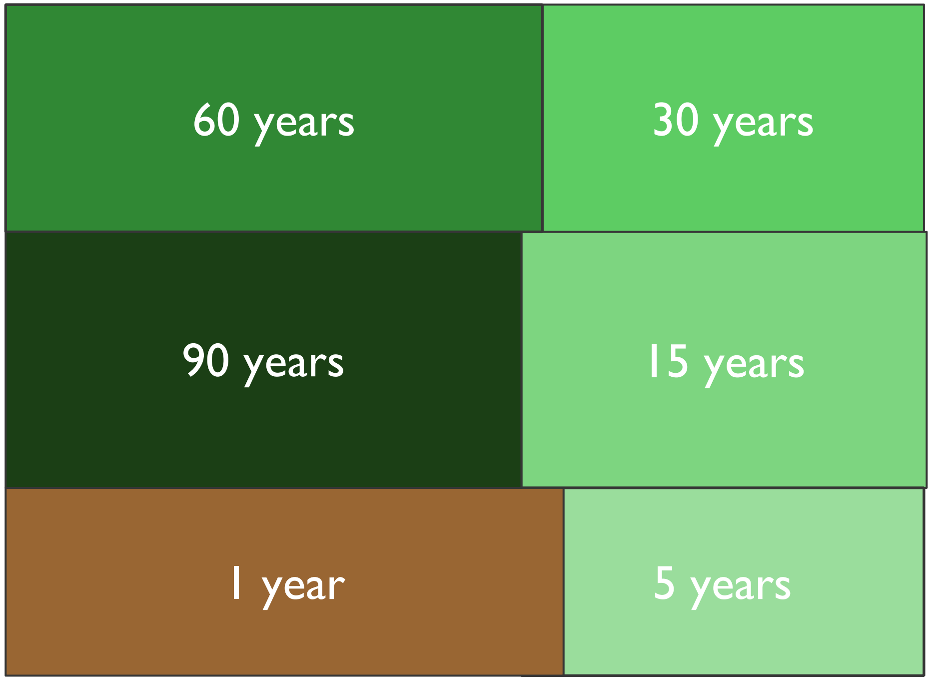
# FATES vs. CLM (BL) tiling

## CLM (BL): Tile by PFT




## FATES: Tile by age-since-disturbance





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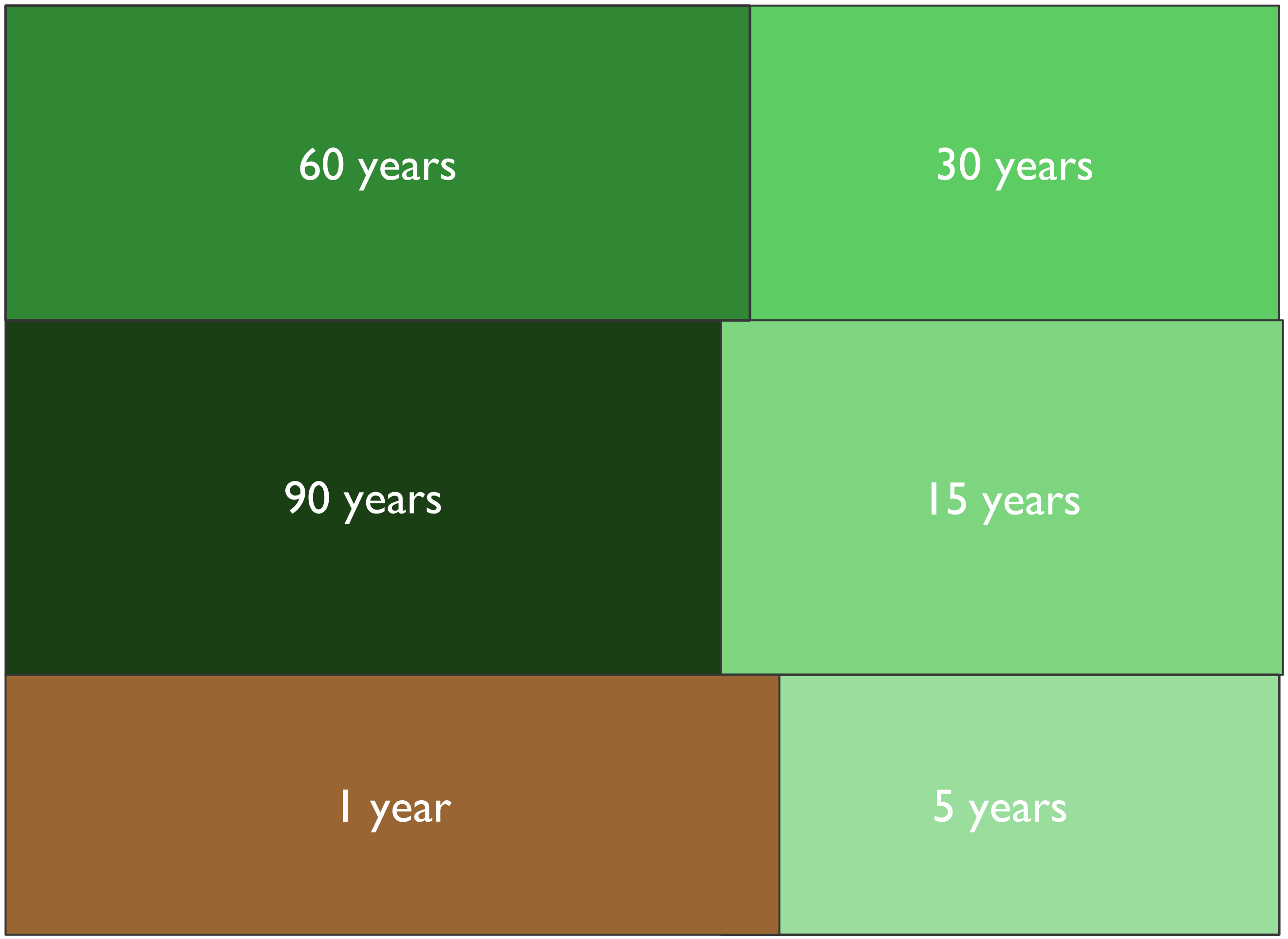
# FATES vs. CLM (BL) tiling





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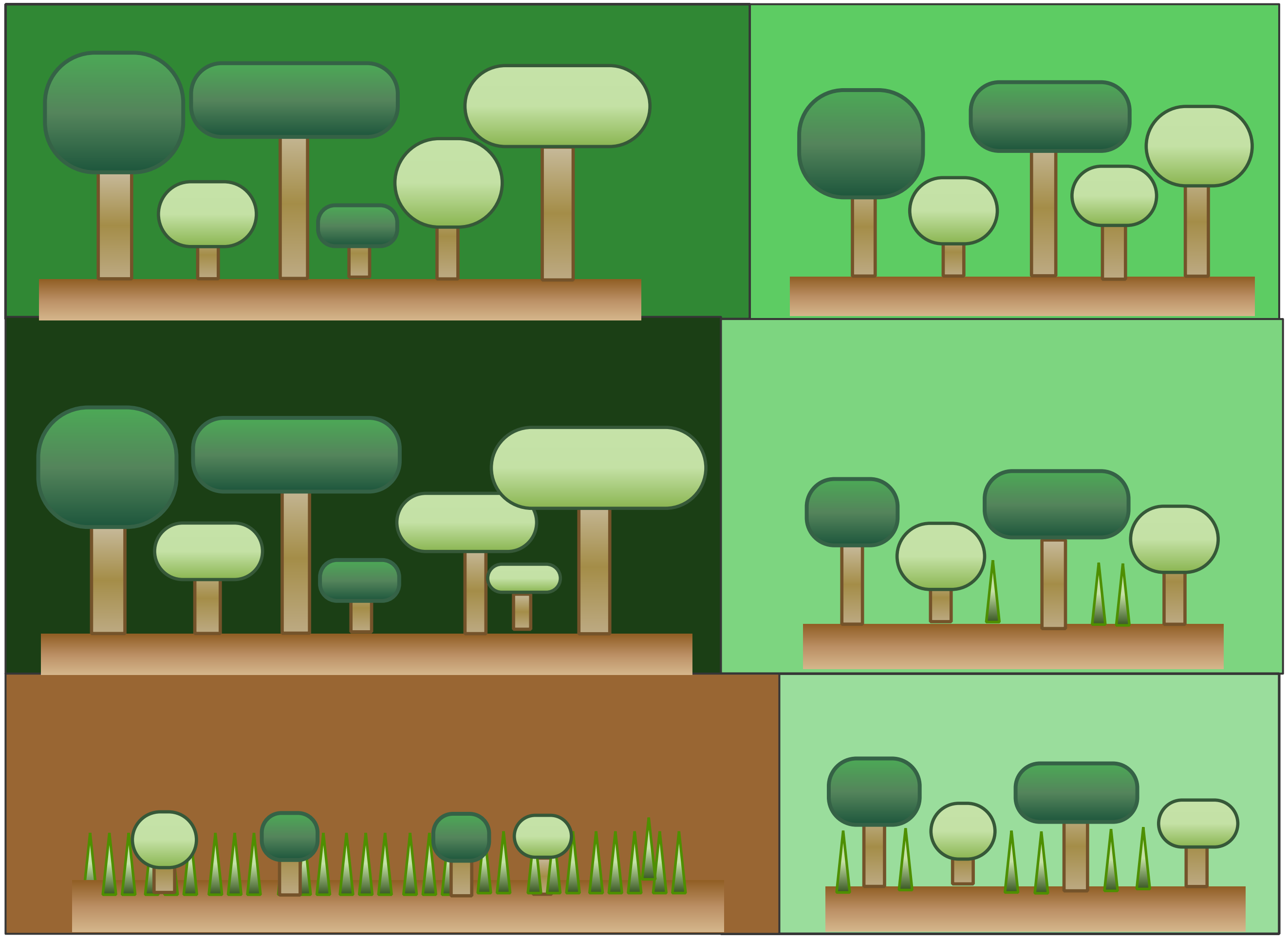
# FATES vs. CLM (BL) tiling



Each tile contains cohorts of plants of different PFT and size



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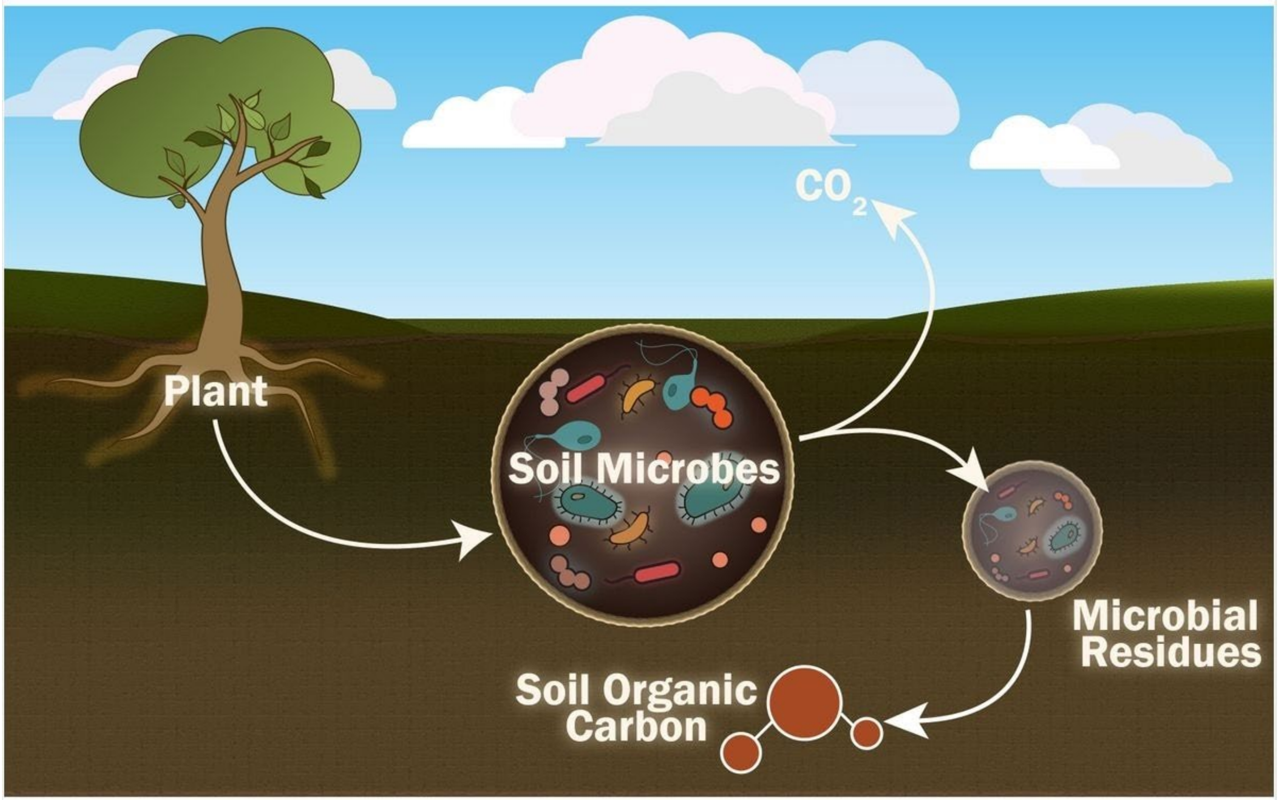
# MIMICS: modeling microbial controls on soil carbon dynamics

Soil C model that considers relationships among litter quality, functional tradeoffs in microbial physiology, and microbial byproducts




**More accurately represents C response to N enrichment**



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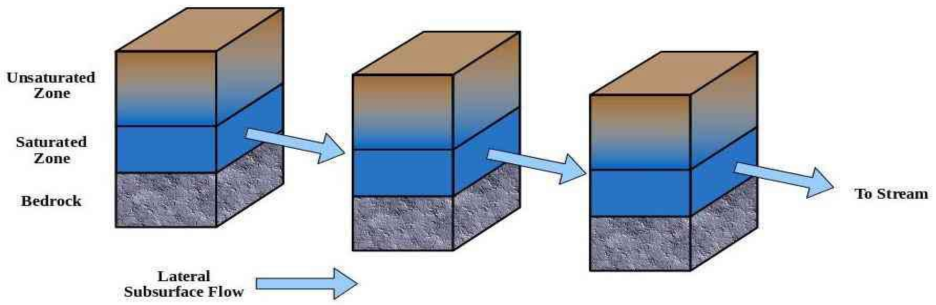
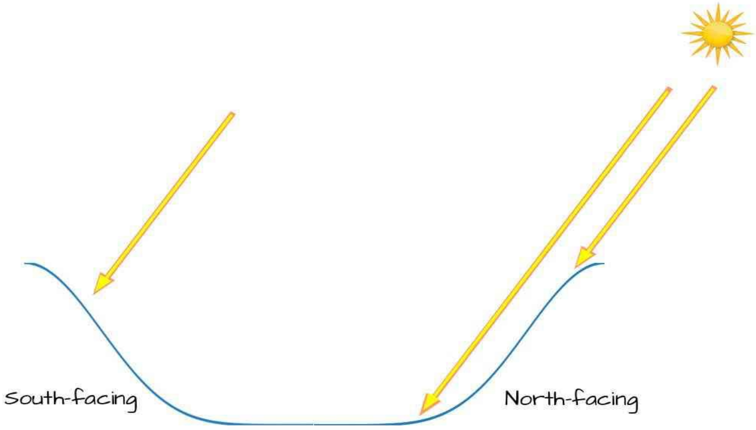
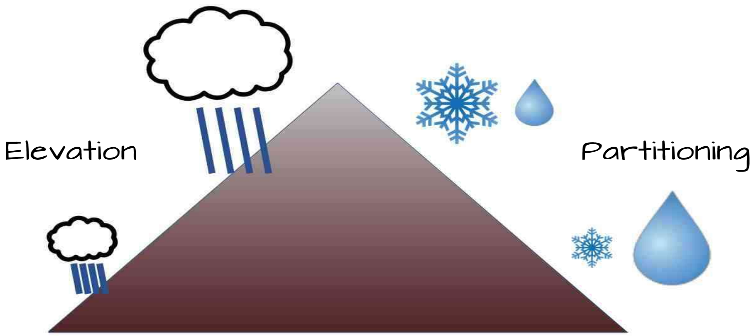
# Representative hillslope model

Explicit Lateral Flow Within Gridcell




Downscaled Meteorology





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# How will ecosystems change with climate change?



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**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).


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