SEPTEMBER 15, 2025

Land Modeling II

Biogeochemistry & Ecosystems

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Scientist V, NCAR CGD Terrestrial Sciences Section

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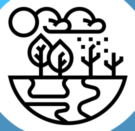
Land biogeochemistry in CESM

Why?



How?

Future directions

Land biogeochemistry in CESM

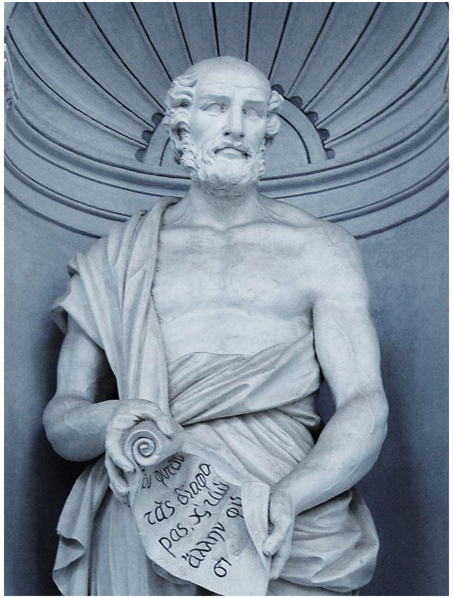
Why?

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

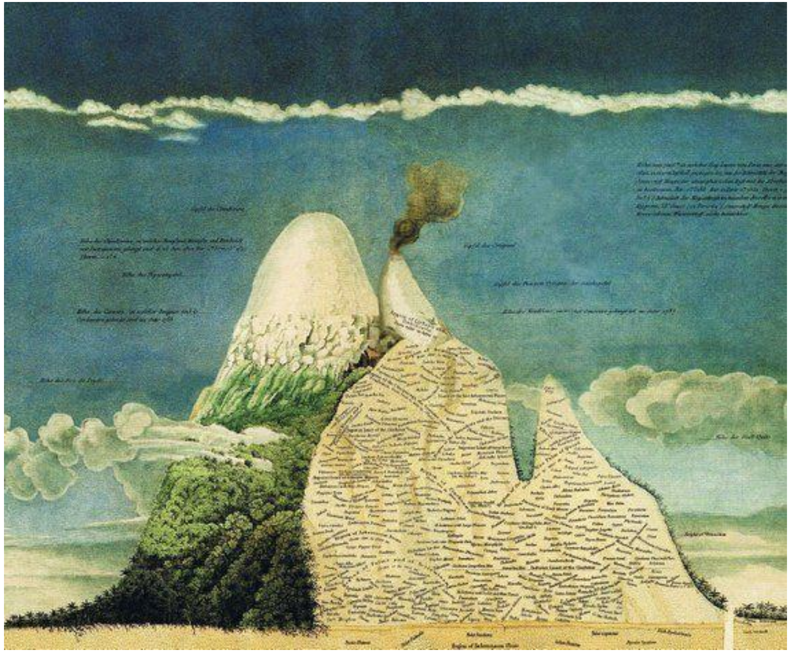
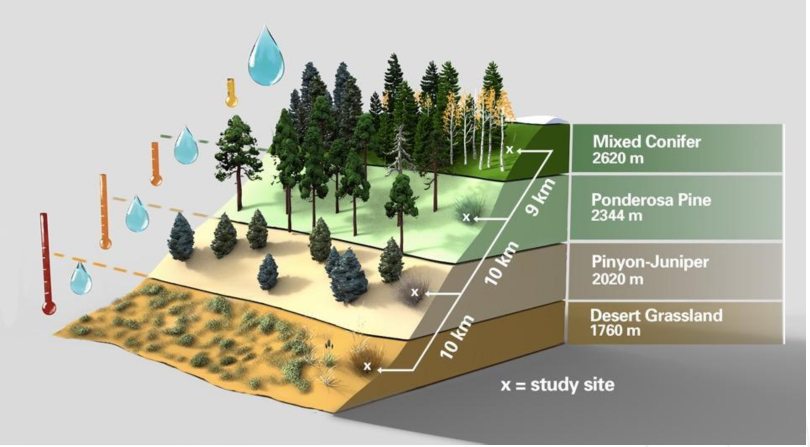
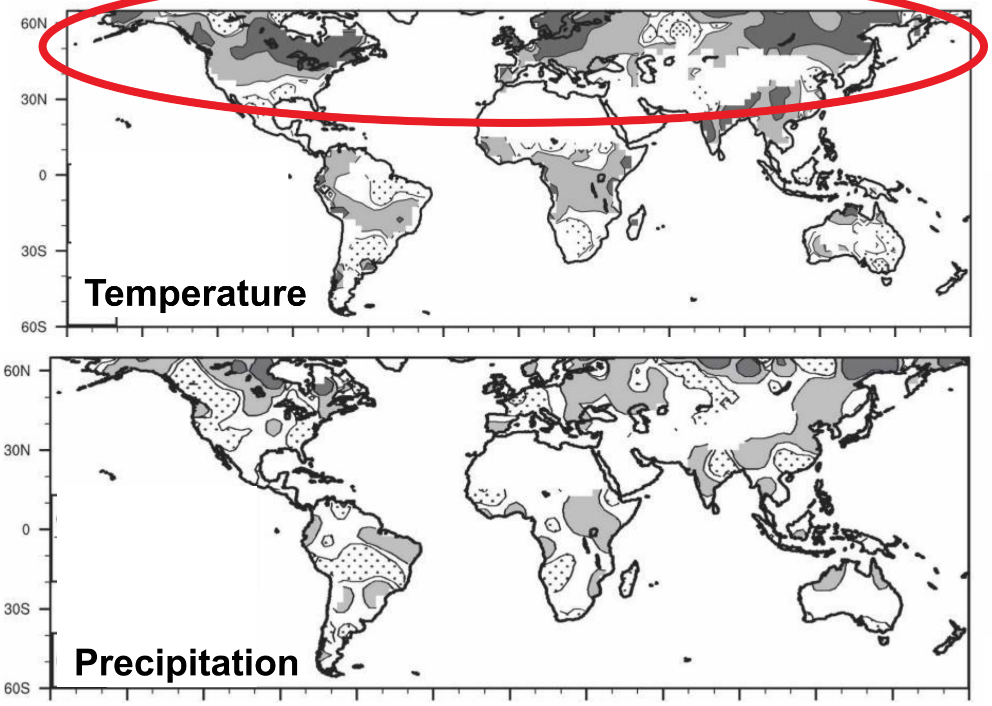


Tableau des Régions équinoxiales from Humboldt (1807)

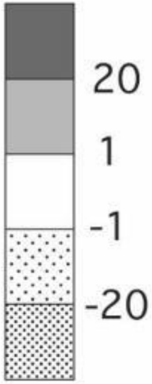


Morrissey et al. (2019) *Nature Ecology and Evolution*

Vegetation impacts climate

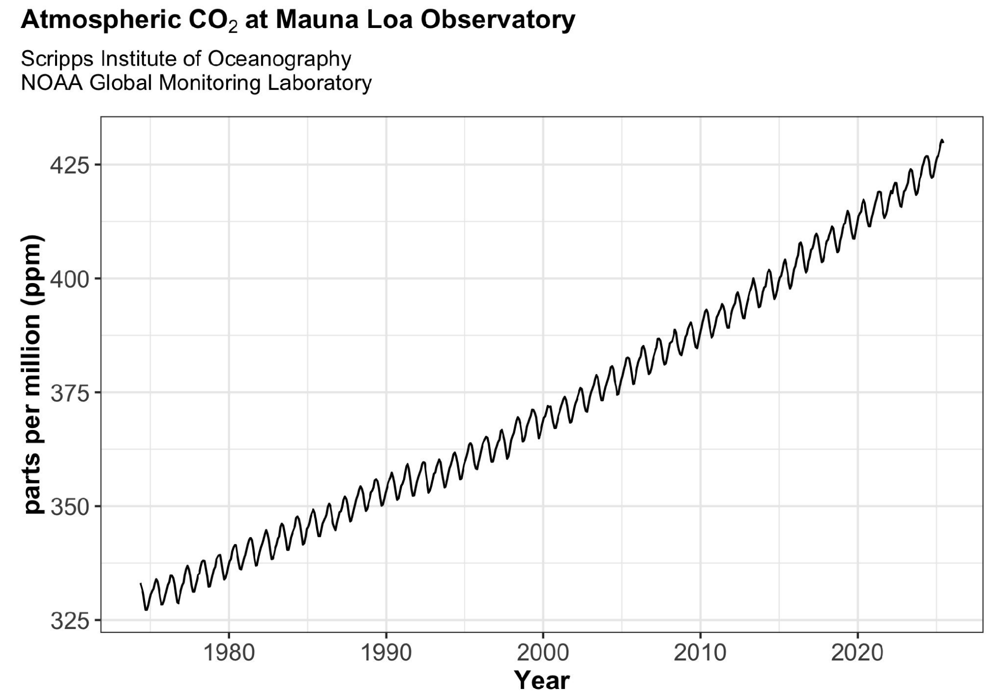


Short time scales – dominated by albedo and evapotranspiration



Liu et al. 2006 *Journal of Climate*

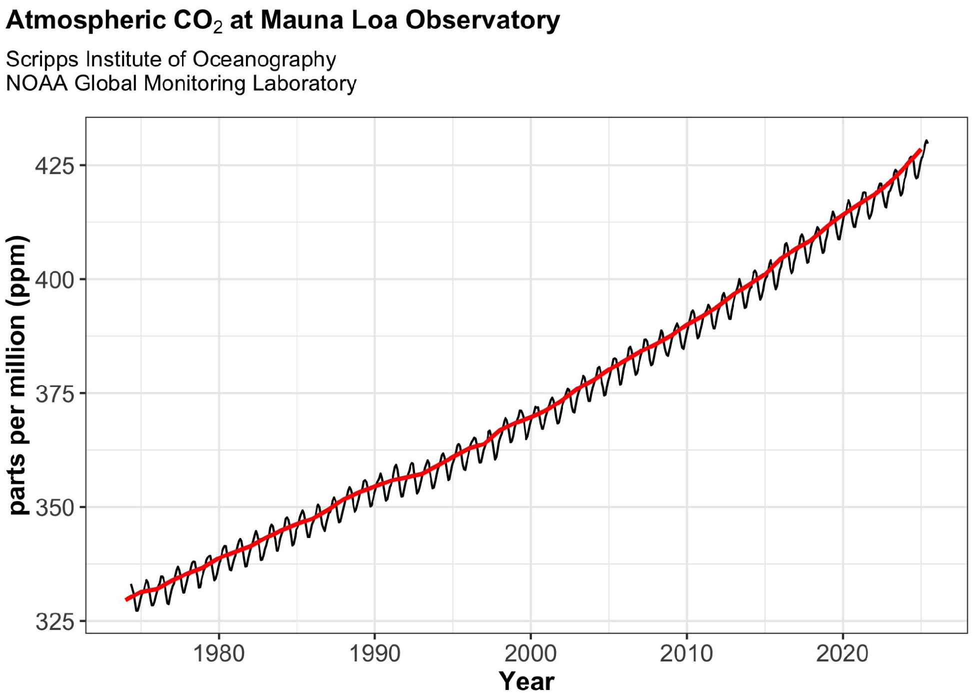
Vegetation impacts climate



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

Longer time scales –
fate of carbon

Vegetation impacts climate



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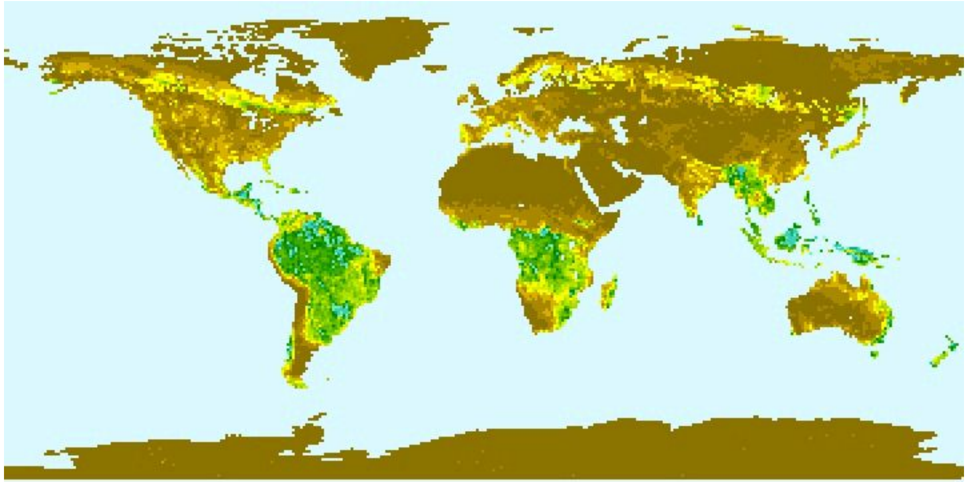
Longer time scales –
fate of carbon

Upward trend due to human activities

Vegetation impacts climate

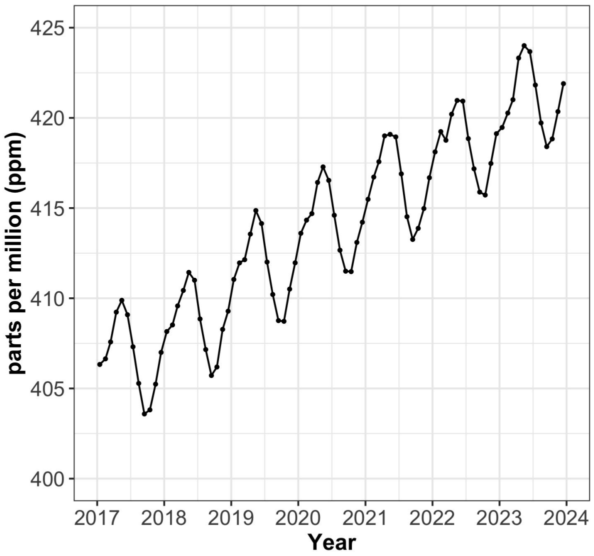


MODIS LAI

Vegetation "breathing"

Longer time scales –
fate of carbon

Recent monthly mean CO_2 at Mauna Loa Observatory



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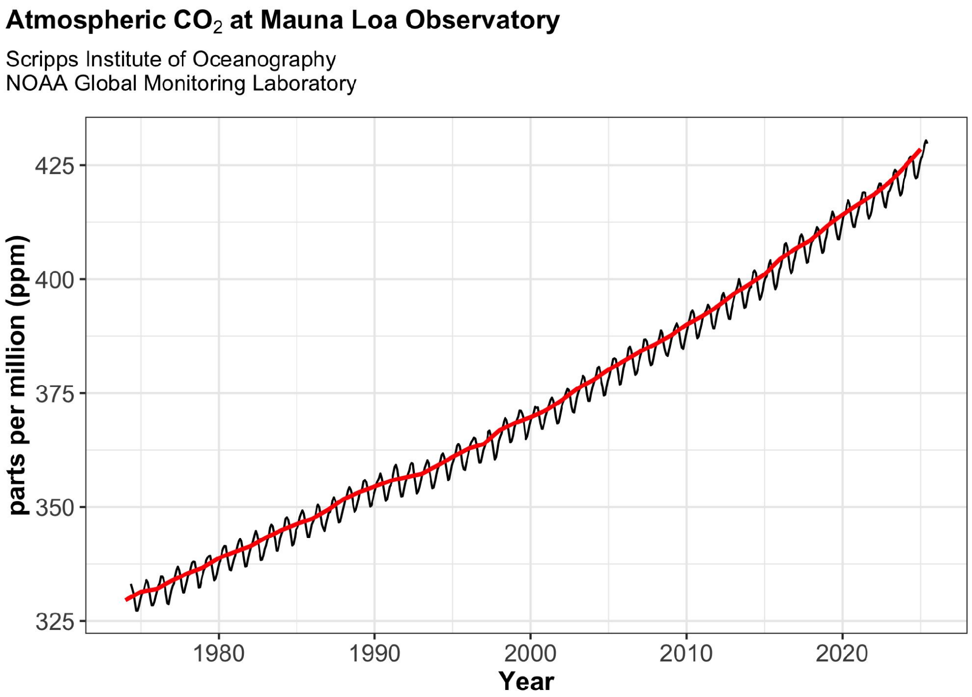

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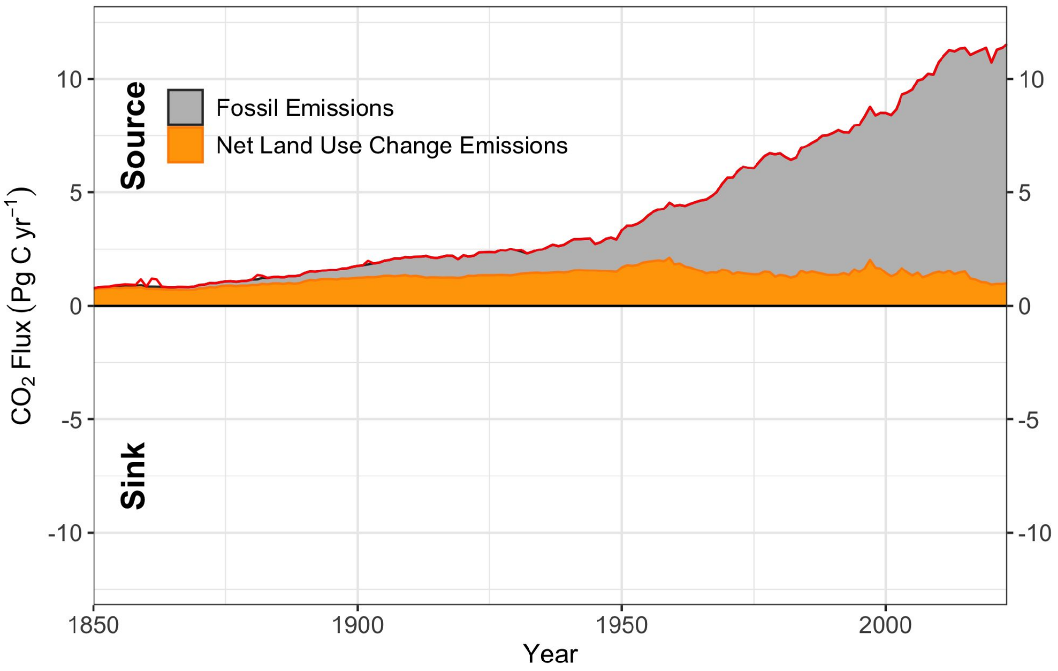
Longer time scales –
fate of carbon

Upward trend due to human activities

Annual carbon emissions

Annual Carbon Emissions and their Partitioning

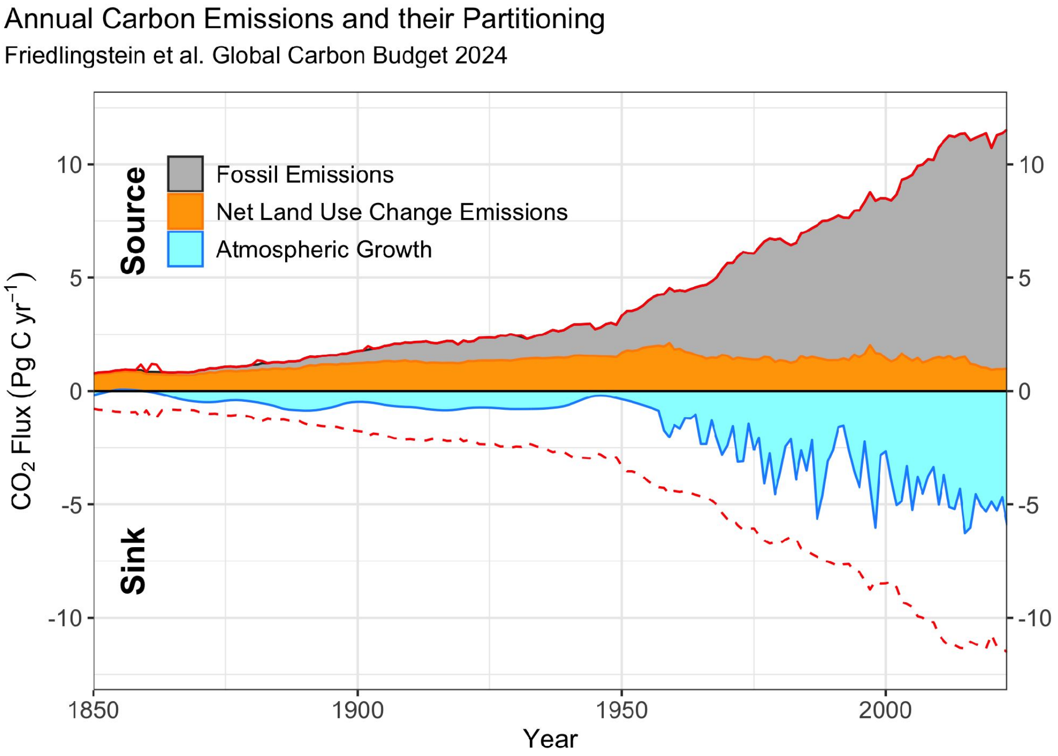
Friedlingstein et al. Global Carbon Budget 2024



Energy statistics and cement production data

Land use and land use change data

Annual carbon emissions



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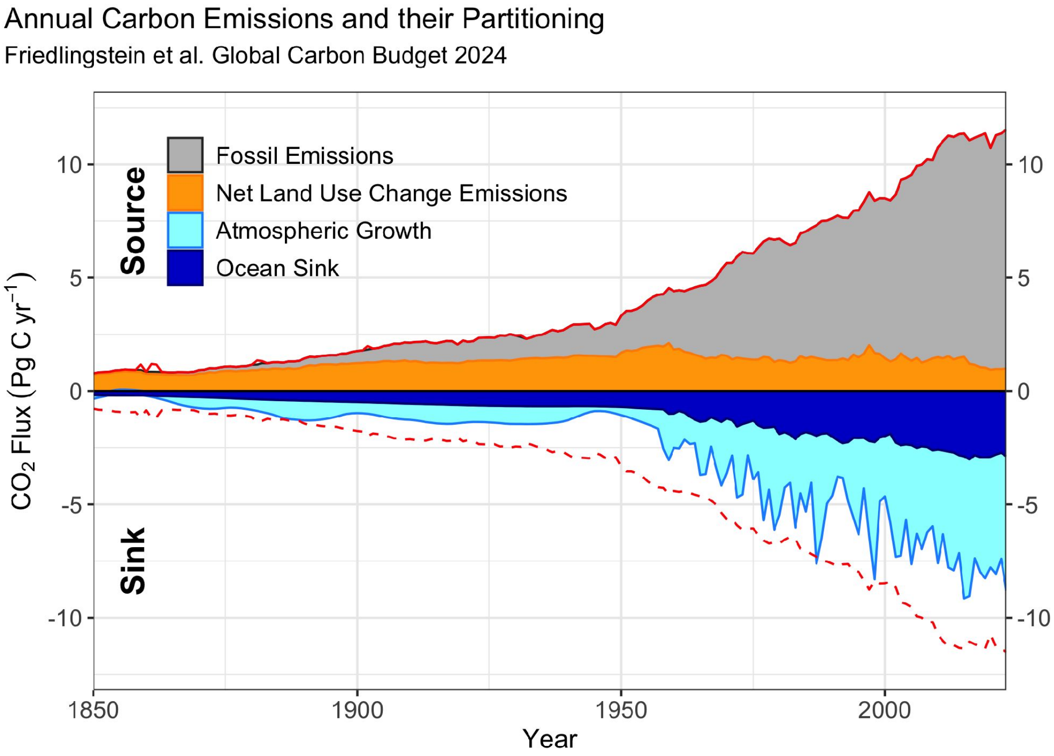
Atm. CO_2 observations

Annual carbon emissions



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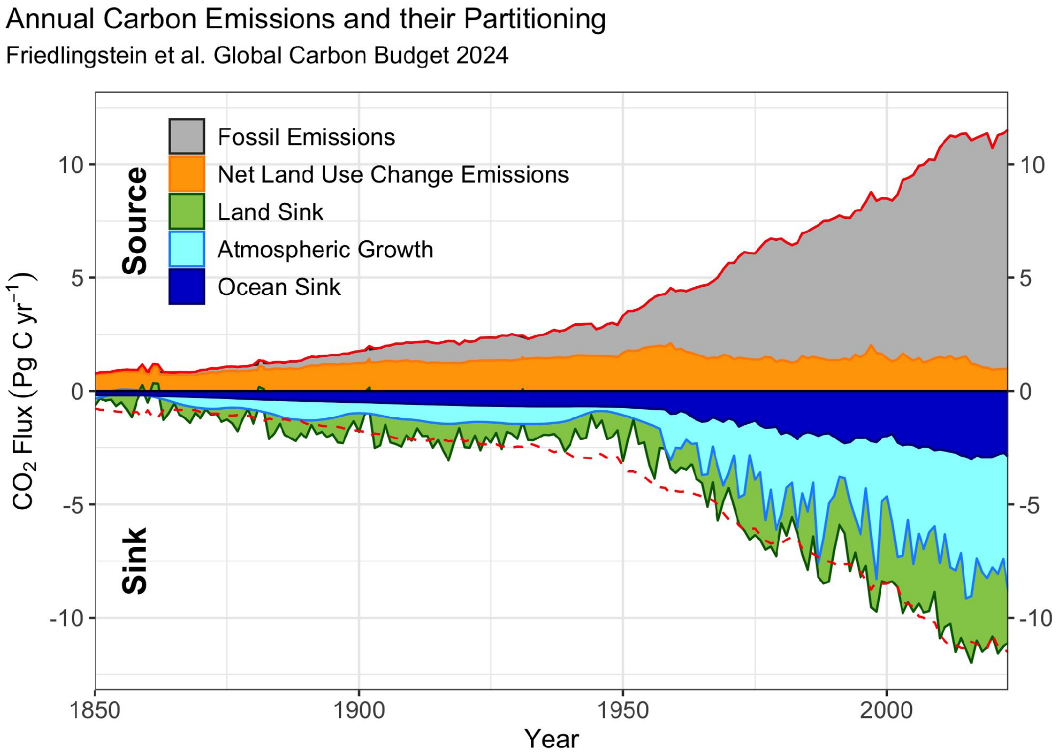
Ocean biogeochemistry models & data products

Atm. CO_2 observations

Annual carbon emissions



Energy statistics and cement production data

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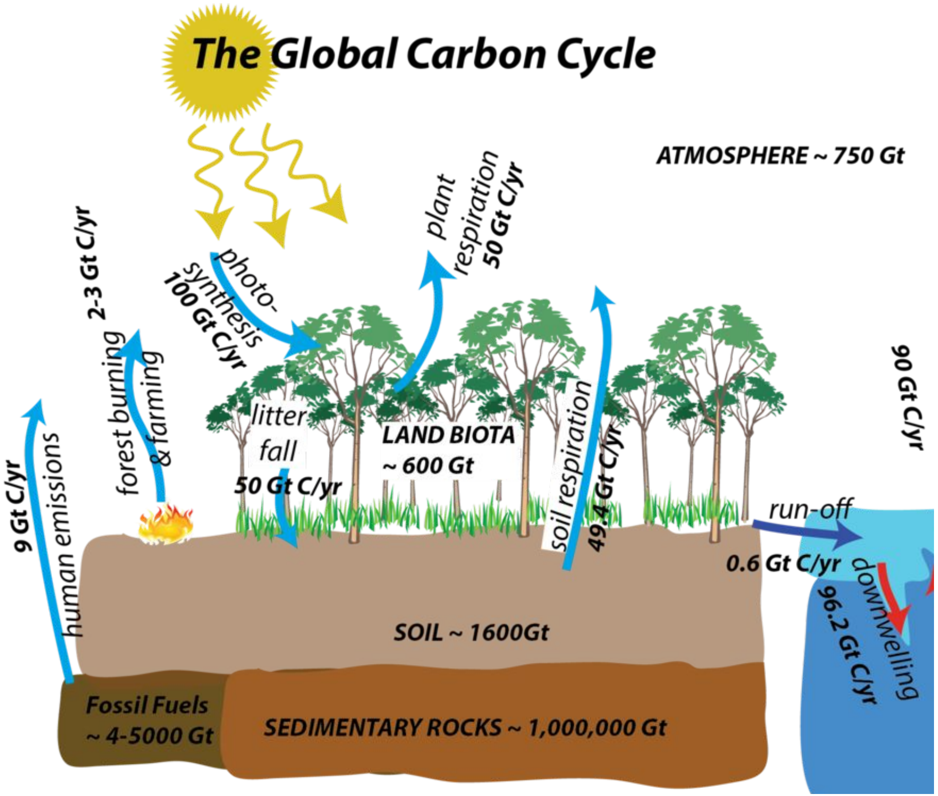
Ocean biogeochemistry models & data products

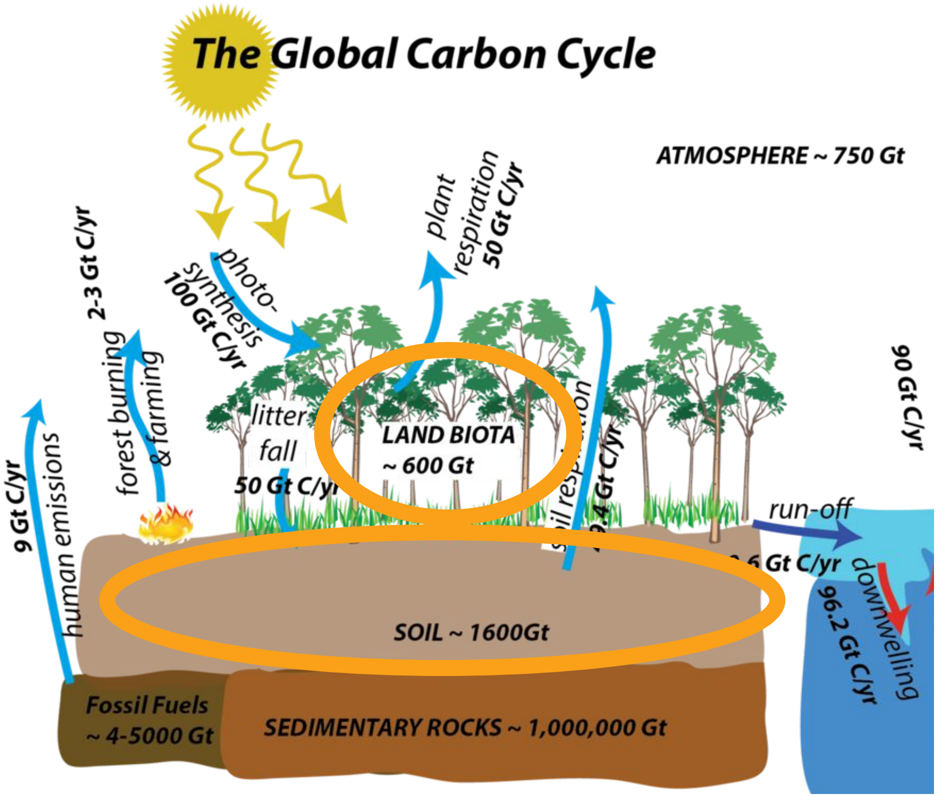
Atm. CO_2 observations

Global vegetation models

Global carbon cycle

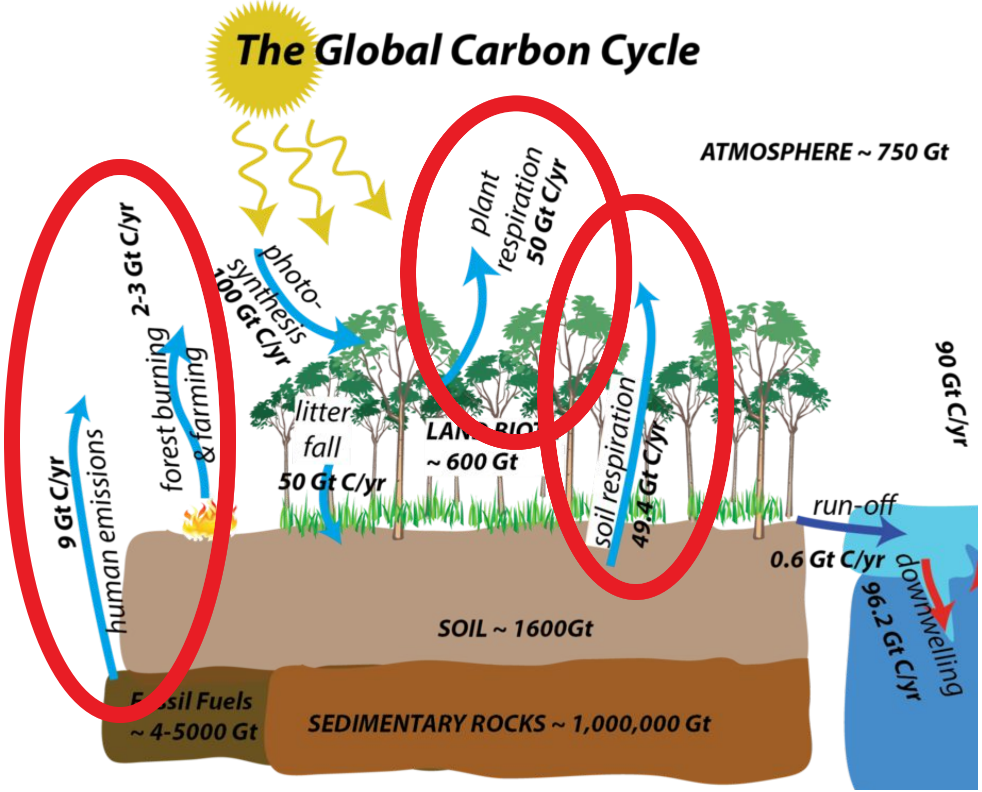


Global carbon cycle



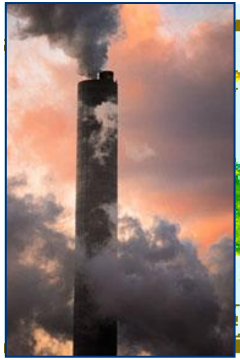
Huge pools

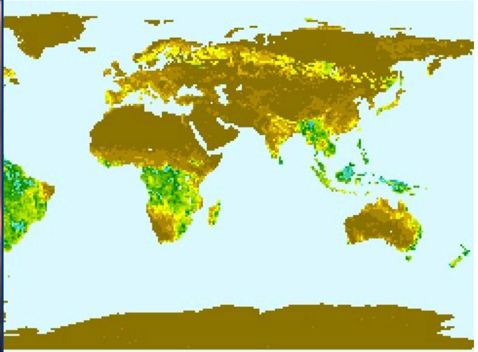
Global carbon cycle



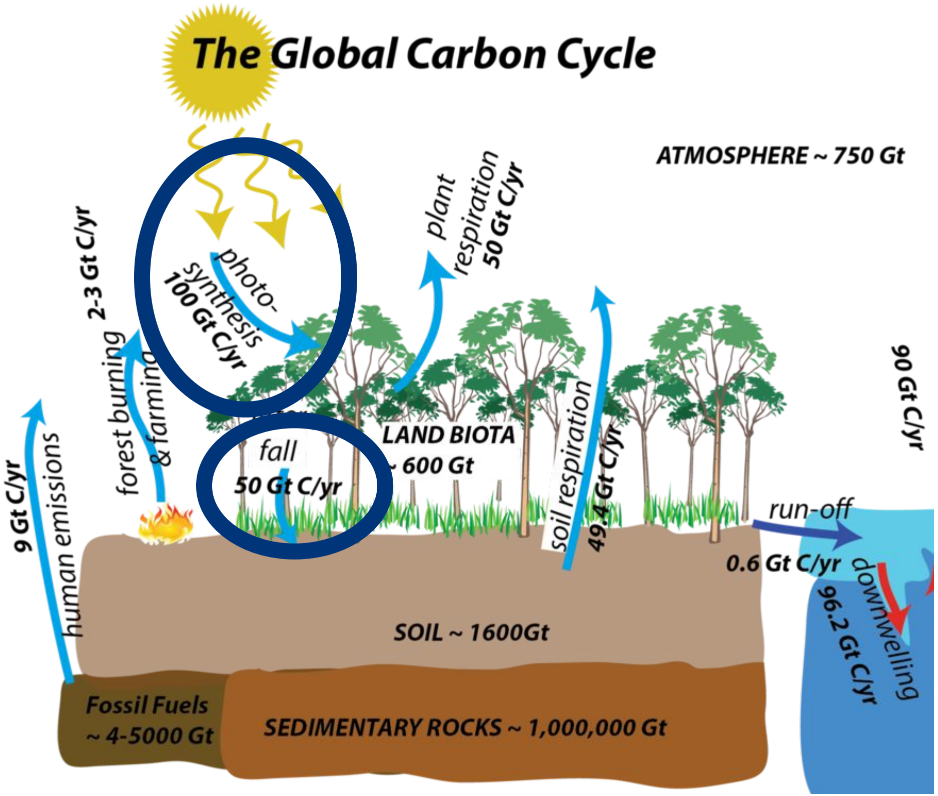
Huge pools

Large fluxes (out)

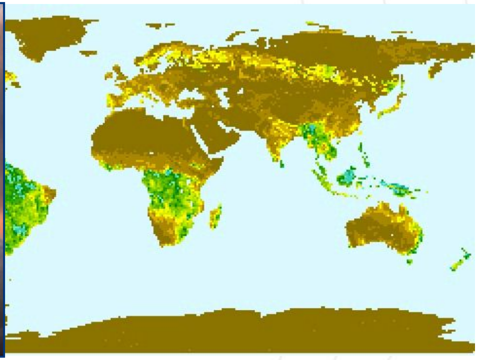




Global carbon cycle



Huge pools
Large fluxes (out)
Large fluxes (in)



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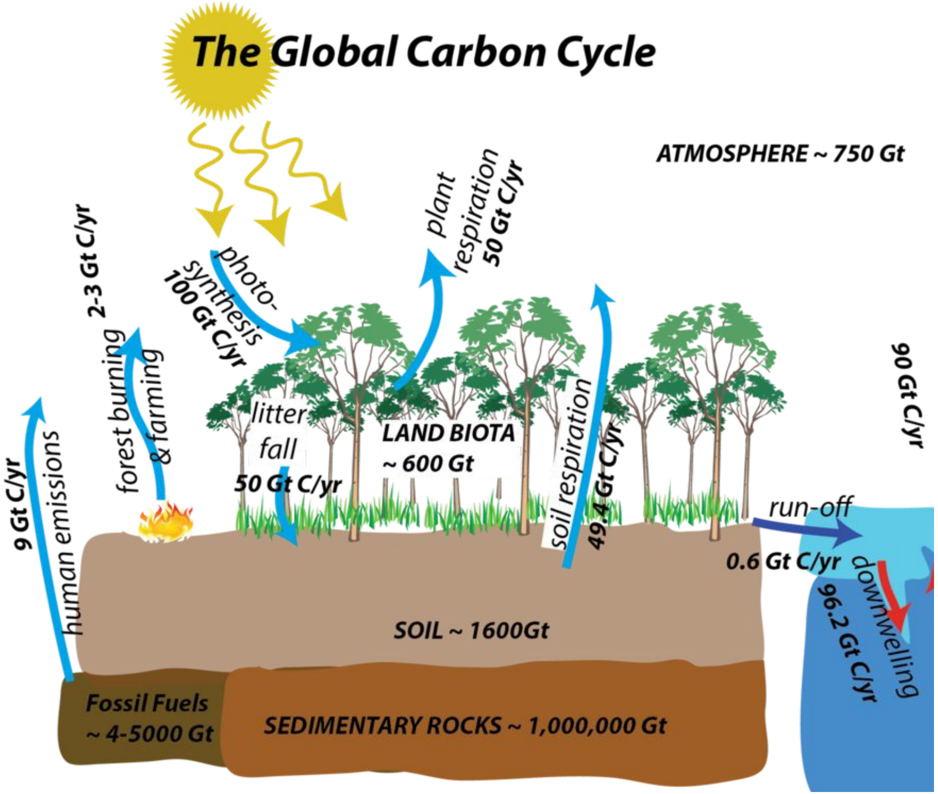
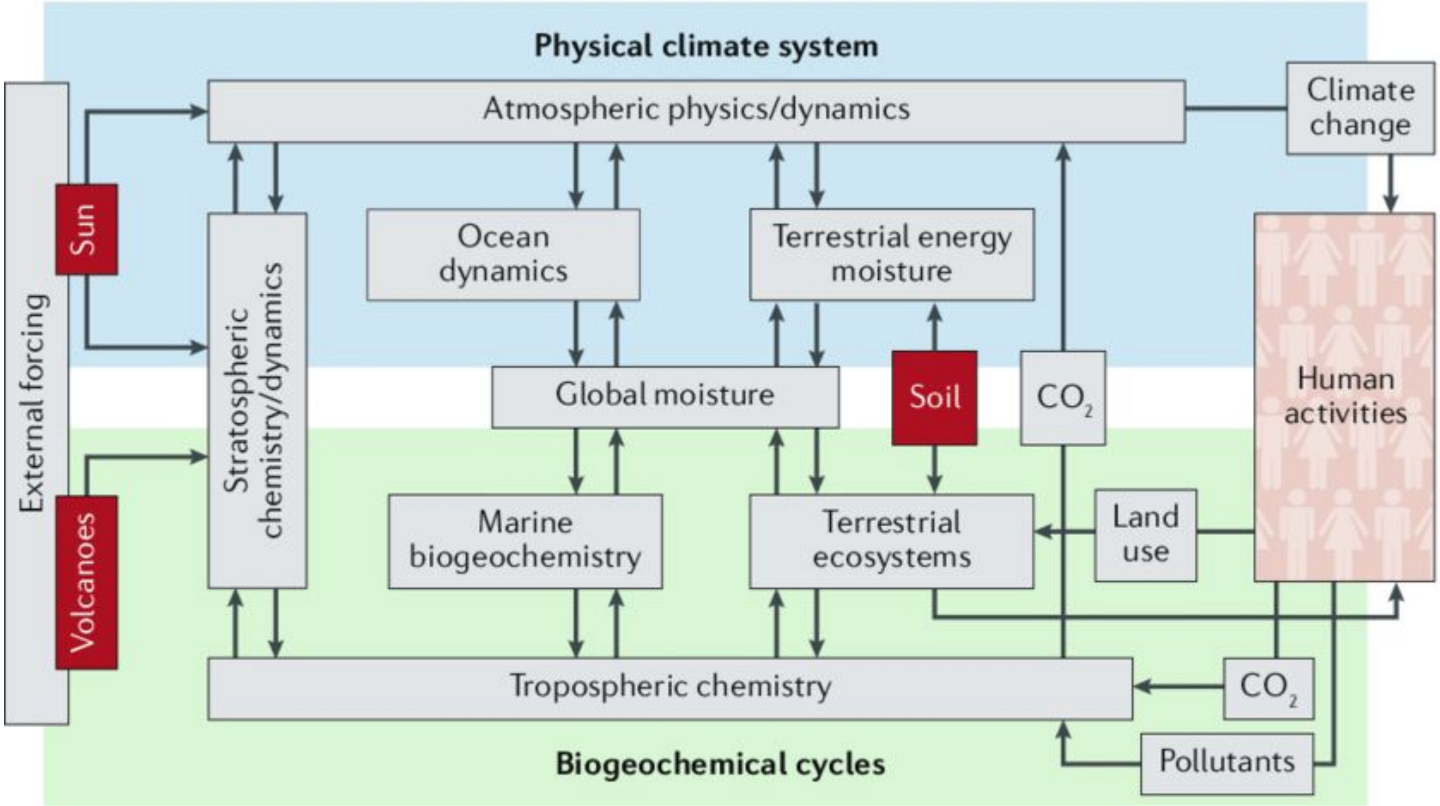


Huge pools
Large fluxes (out)
Large fluxes (in)
Sink = small residual

Land biogeochemistry in CESM

Why?

How?



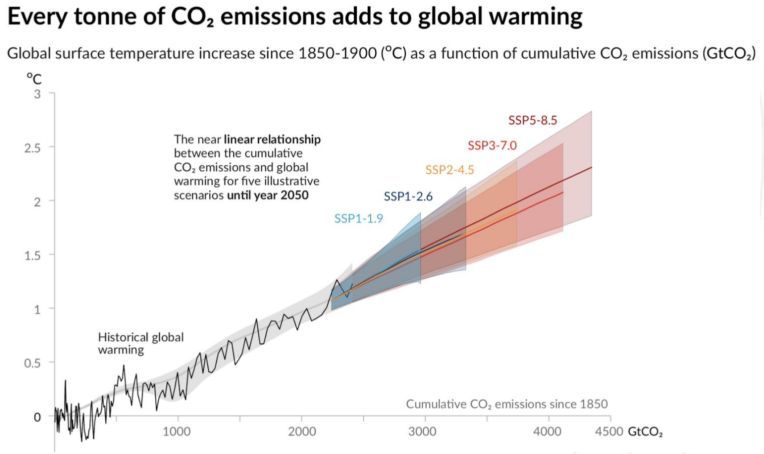
"Bretherton diagram" showing the concept of an Earth System Model

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 CO_2 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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+ Coupled C-N biogeochemistry - CESM1

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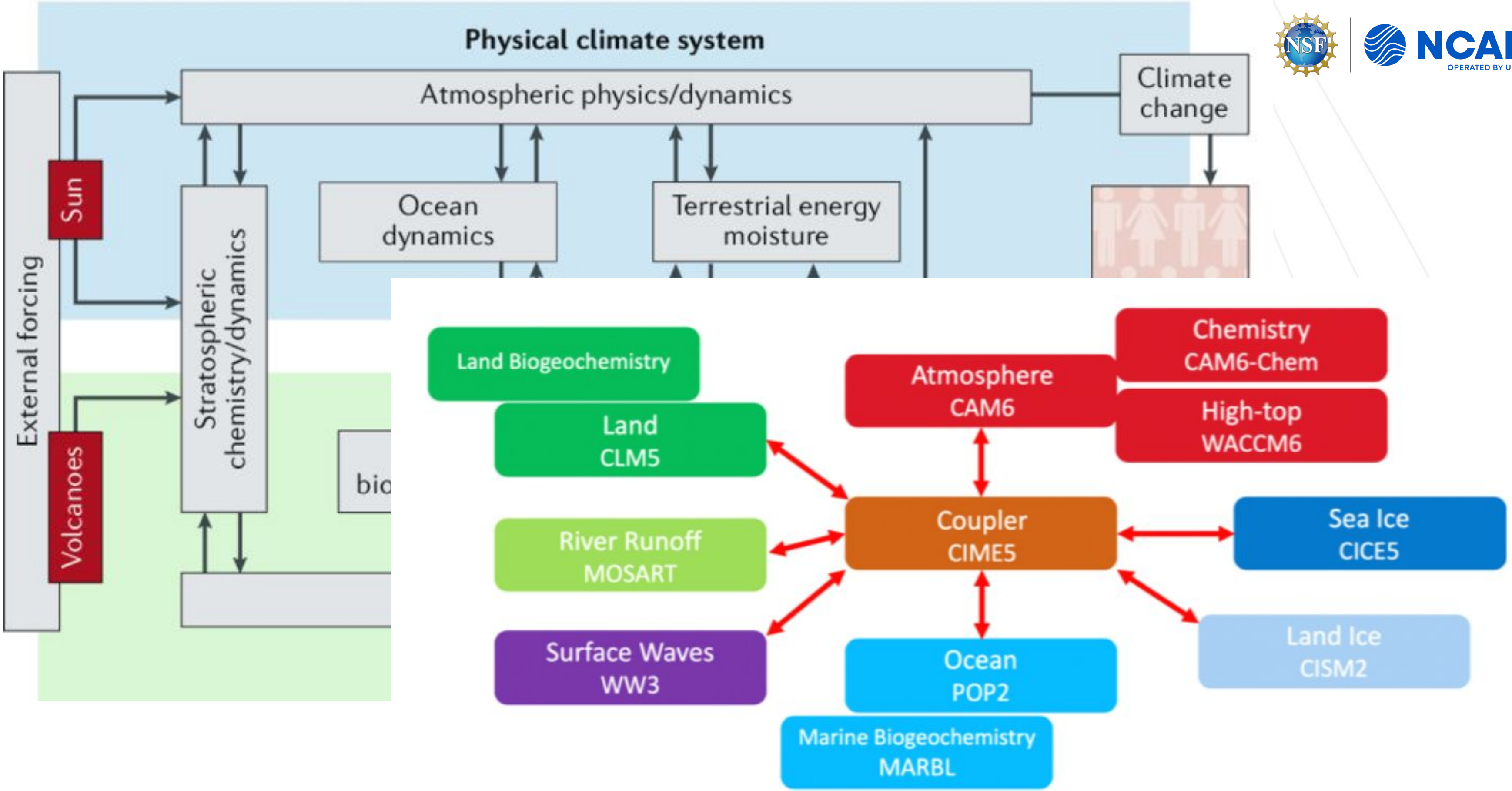
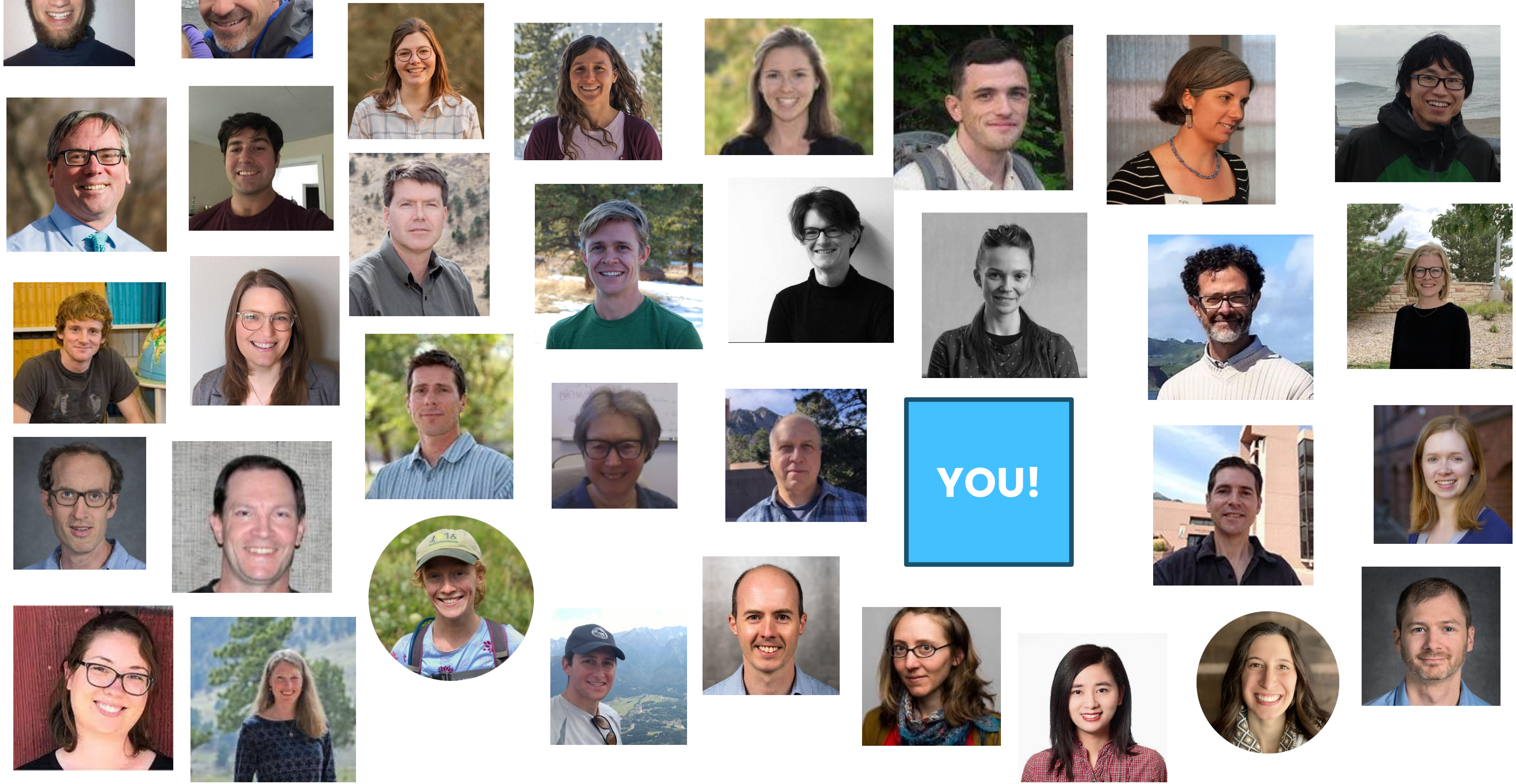
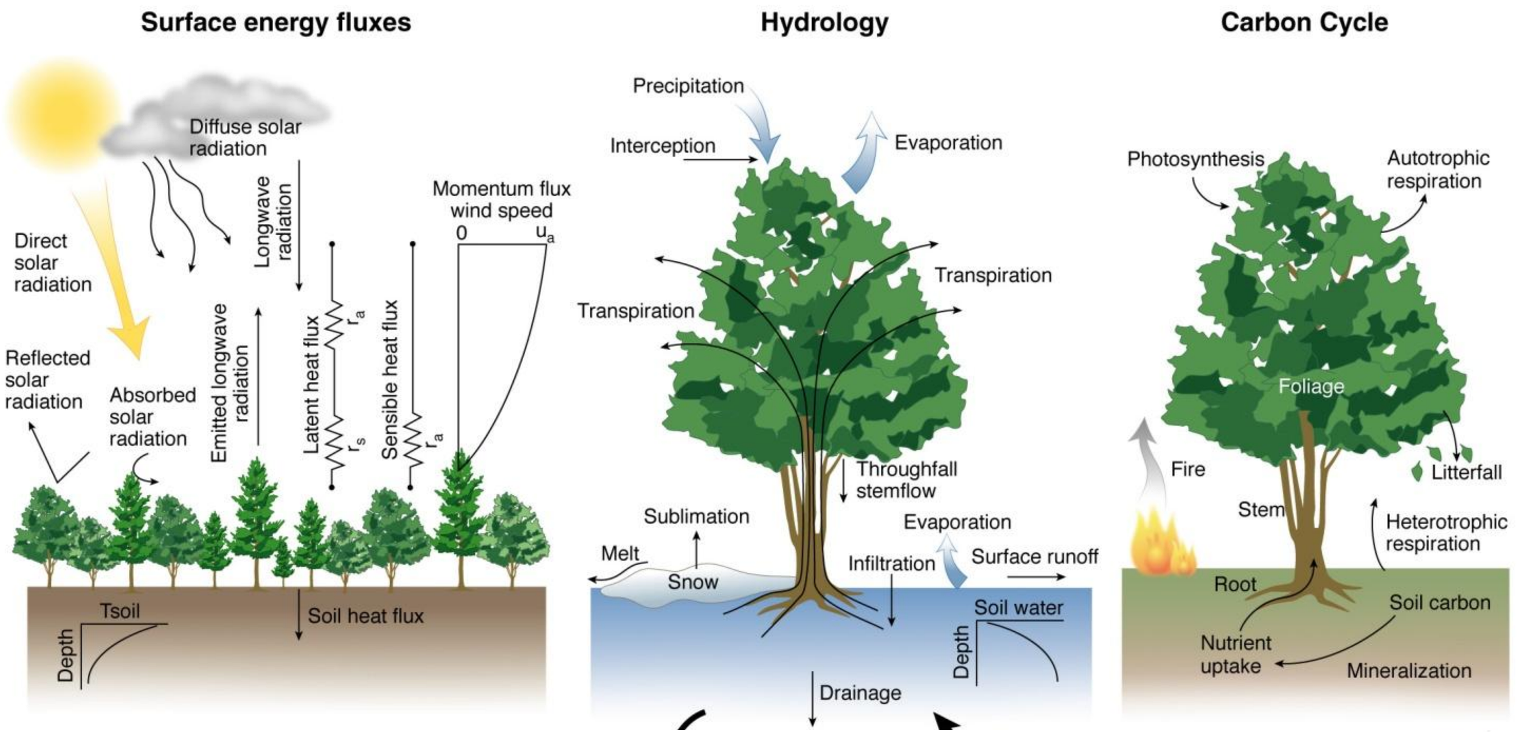
+ Coupled C-N biogeochemistry - CESM1
+ Explicit crop management - CESM2



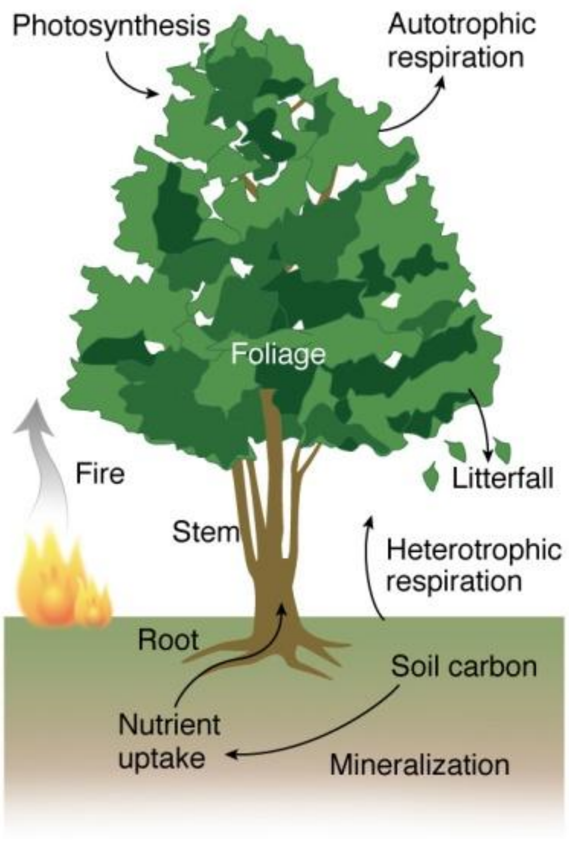
Physical climate system
Atmospheric physics/dynamics
Climate change
External forcing
Sun
Volcanoes
Stratospheric chemistry/dynamics
Ocean dynamics
Terrestrial energy moisture
Land Biogeochemistry
Land
CLM5
Atmosphere
CAM6
Chemistry
CAM6-Chem
High-top
WACCM6
River Runoff
MOSART
Coupler
CIME5
Sea Ice
CICE5
Surface Waves
WW3
Ocean
POP2
Land Ice
CISM2
Marine Biogeochemistry
MARBL

Community LAND MODEL DEVELOPMENT





Bonan 2008, Science



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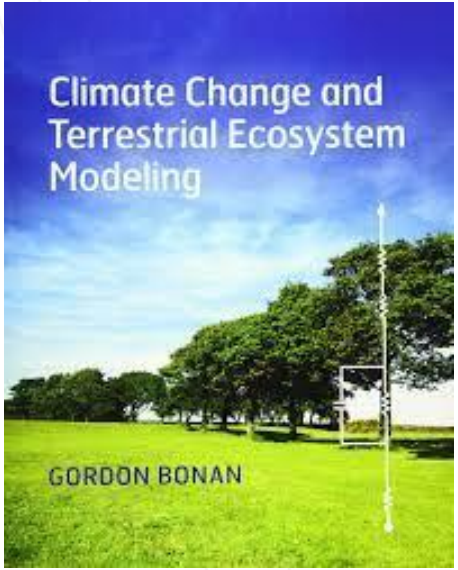

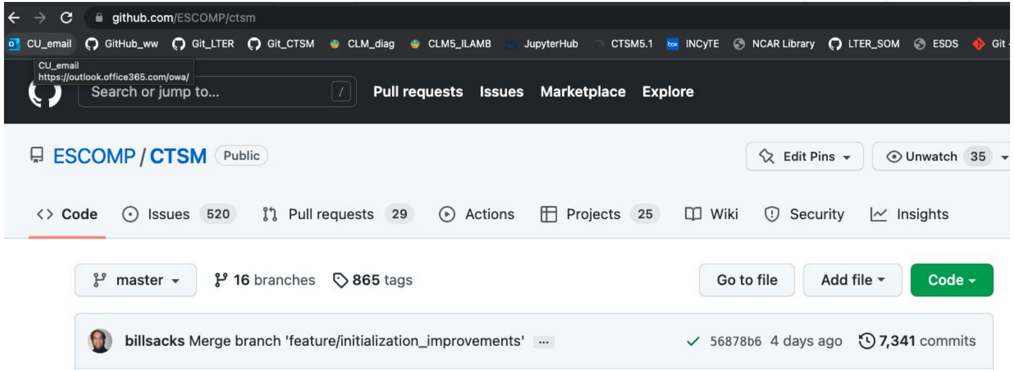

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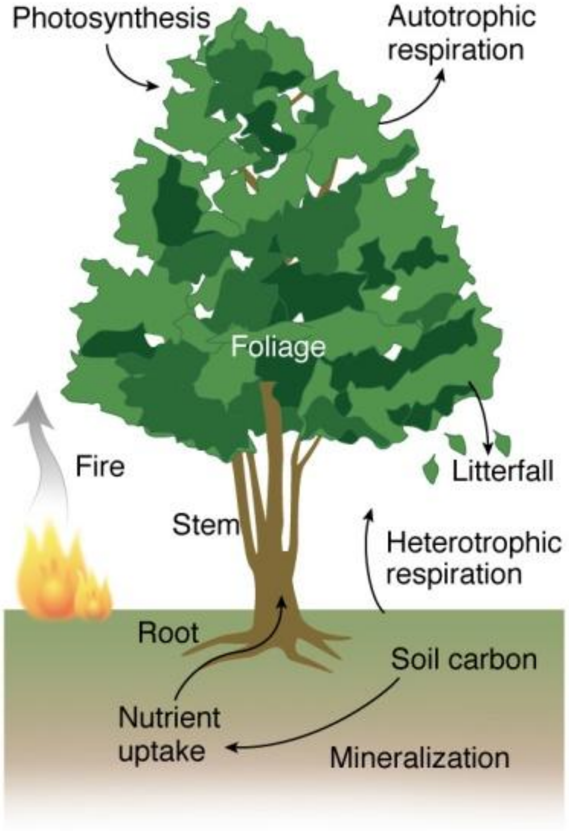
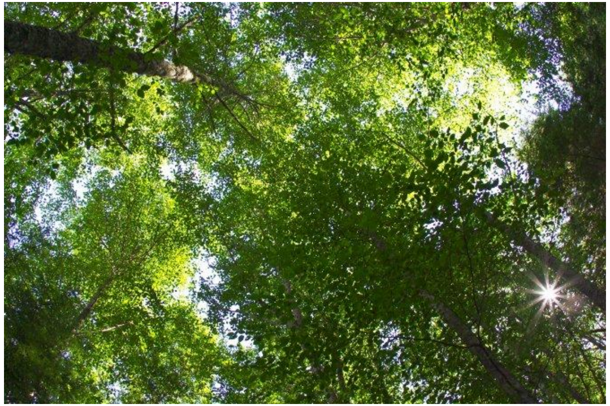
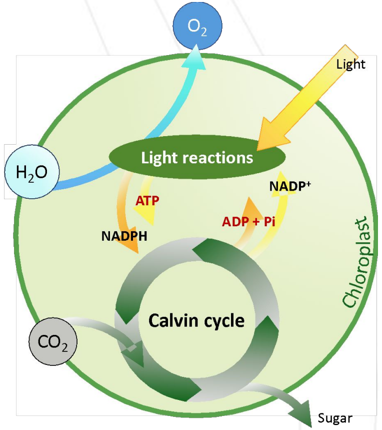


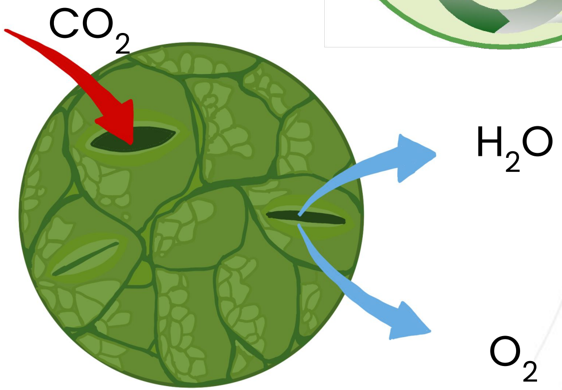
Bonan 2008, Science

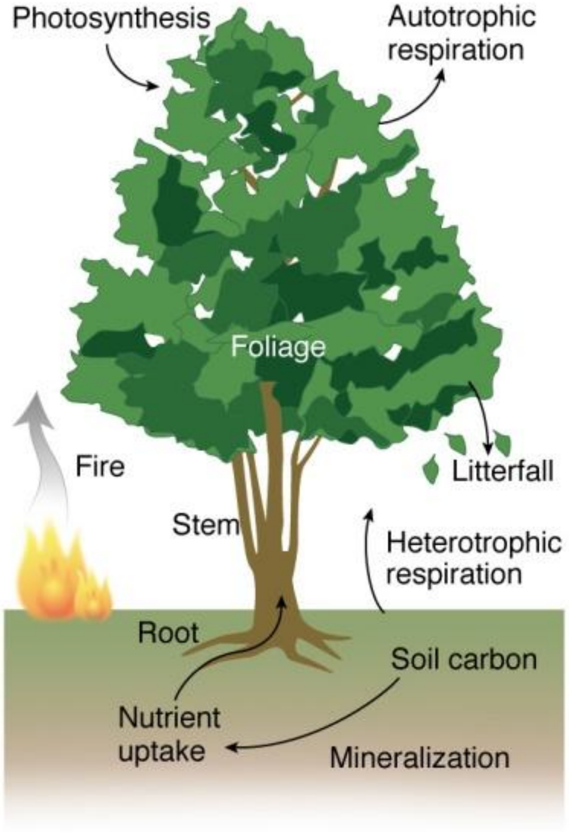
Leaves

Photosynthesis
Stomatal Conductance









Bonan 2008, Science

Leaves

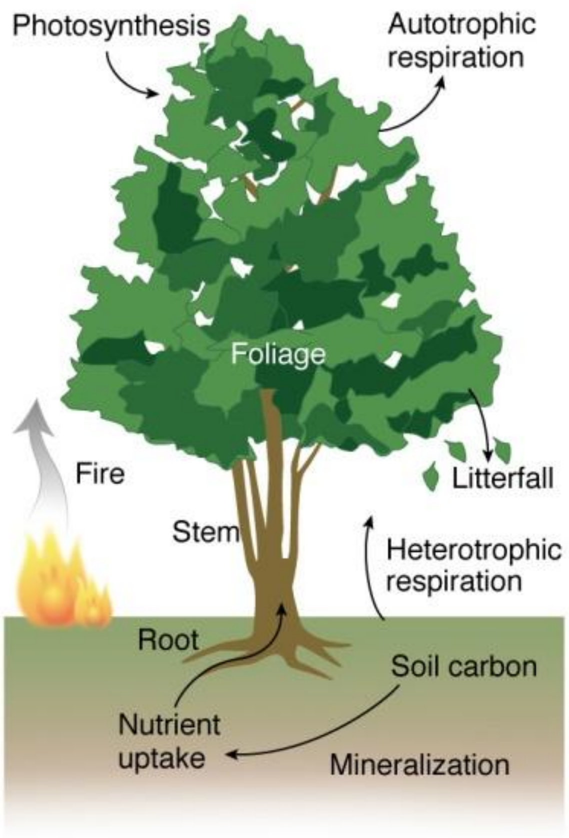
Photosynthesis

Stomatal Conductance

Canopy & Light

Two-stream radiation approximation, sunlit/shaded leaf

GPP: Gross Primary Productivity



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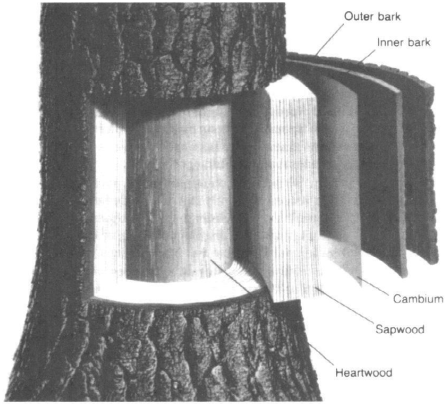
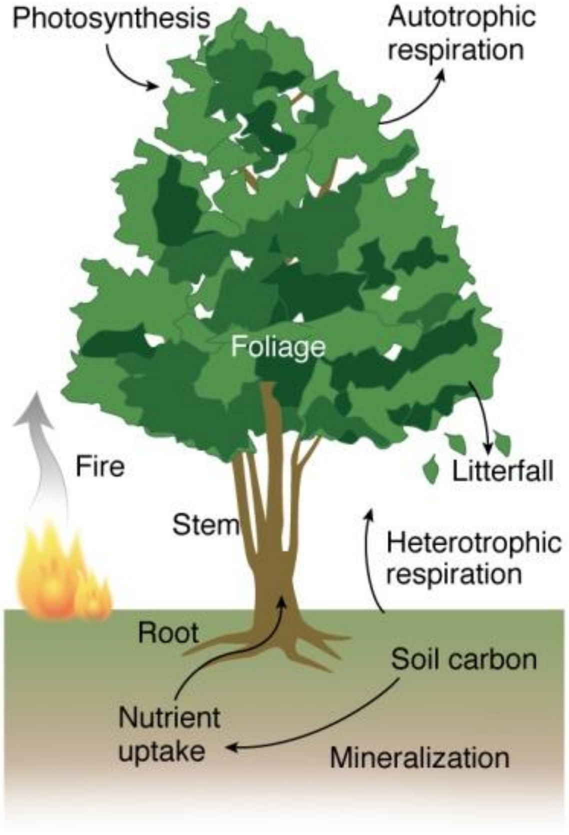
Allocation & Respiration

leaves, wood, roots

AR: Autotropic respiration

NPP: Net Primary Productivity = GPP – AR





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Canopy & Light

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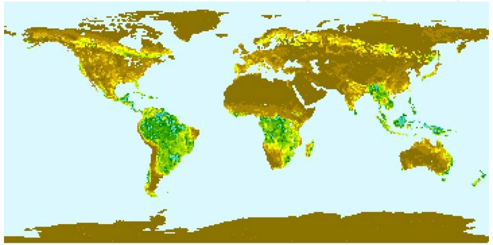
Allocation & Respiration

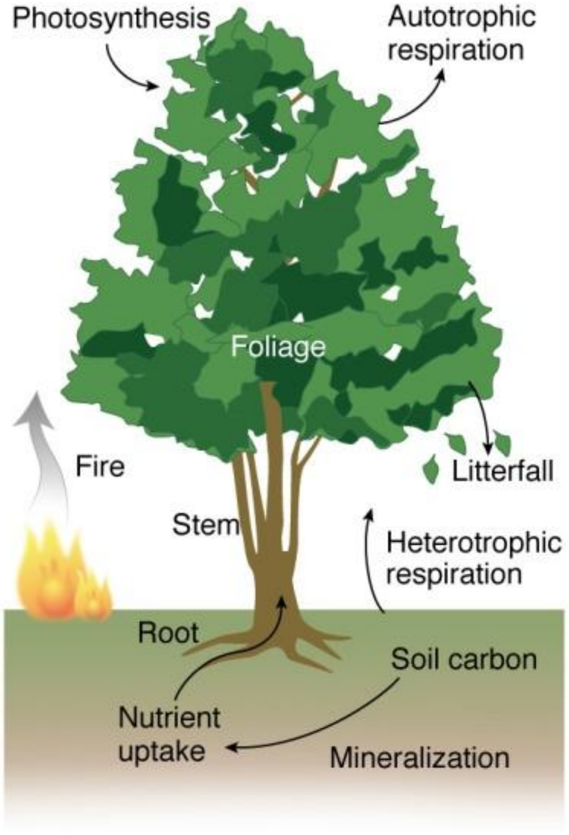
leaves, wood, roots

Phenology & Turnover

mortality, litter, etc.

LAI: Leaf area index





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Canopy & Light

Two-stream radiation approximation, sunlit/shaded leaf

Allocation & Respiration

leaves, wood, roots

Phenology & Turnover

mortality, litter, etc.

Decomposition

HR: heterotrophic respiration

GPP: Gross Primary Productivity

AR: Autotrophic Respiration

NPP: NET Primary Productivity = GPP - AR

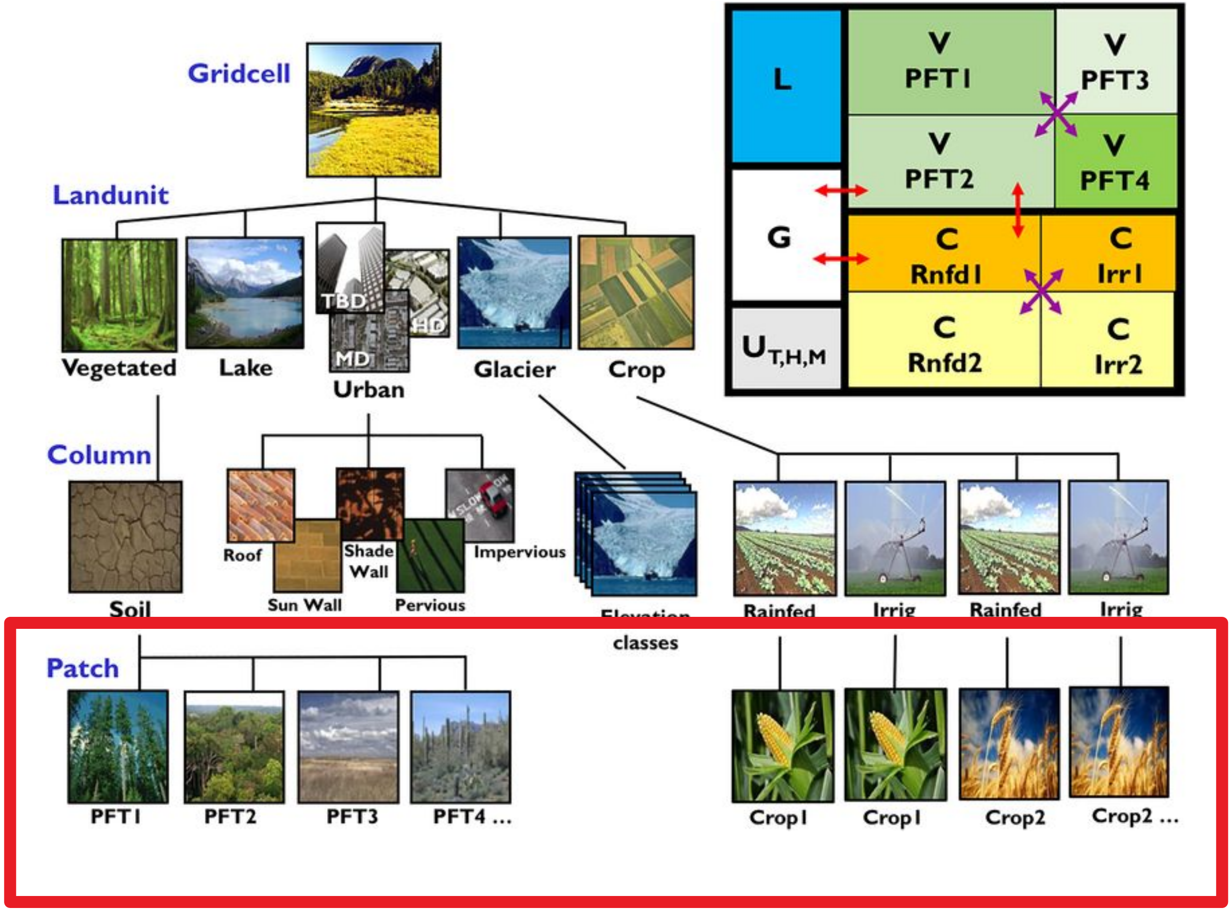
LAI: Leaf Area Index

HR: Heterotrophic Respiration

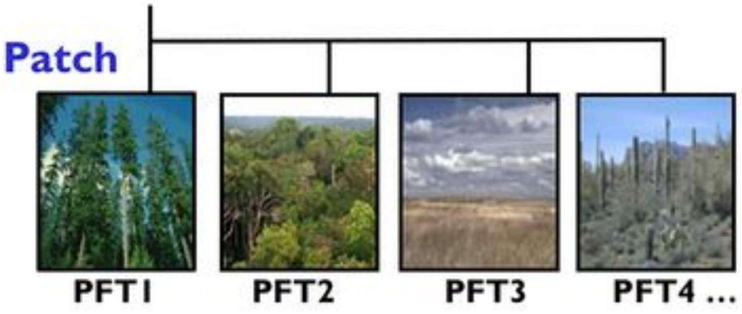
NEP: Net Ecosystem Production = GPP – AR - HR

NEE: Net Ecosystem Exchange = NEP – fire loss

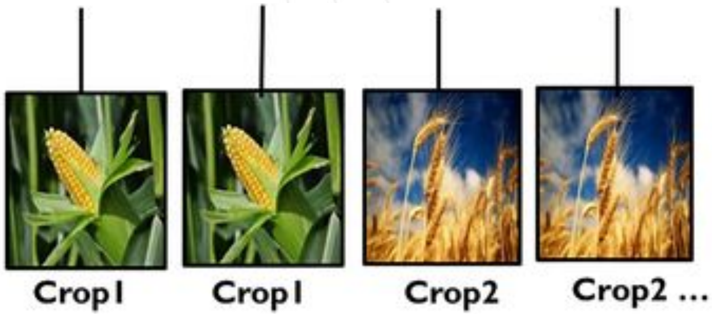
NBP: Net Biome Production = NEE – land use - harvest

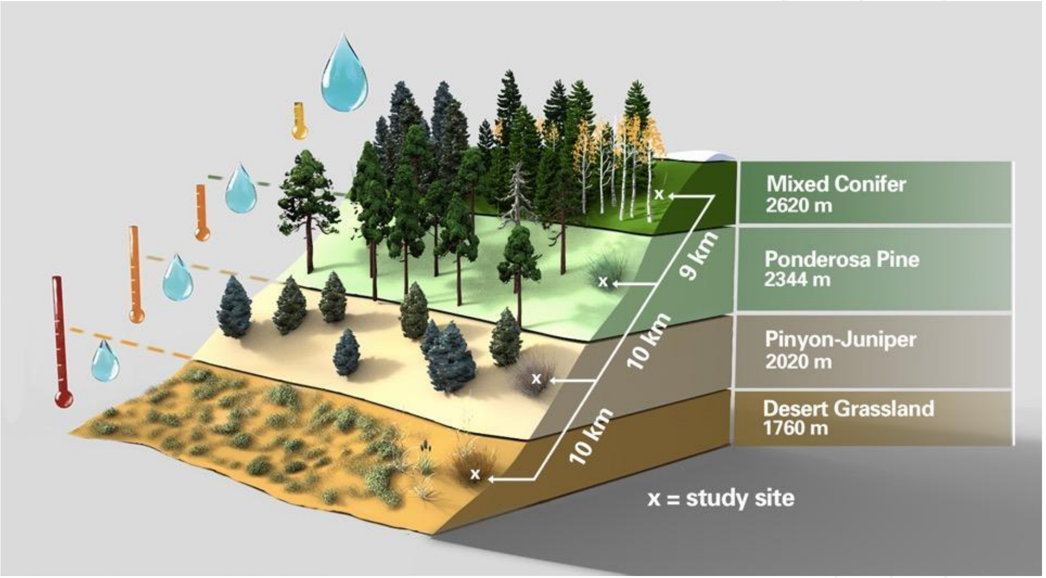


Lawrence et al 2019, JAMES
https://github.com/ESCOMP/ctsm



classes





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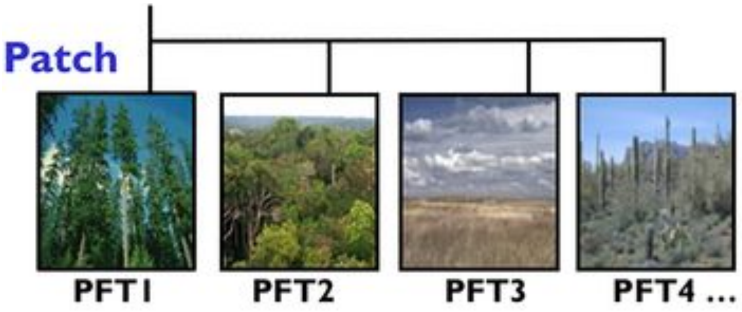

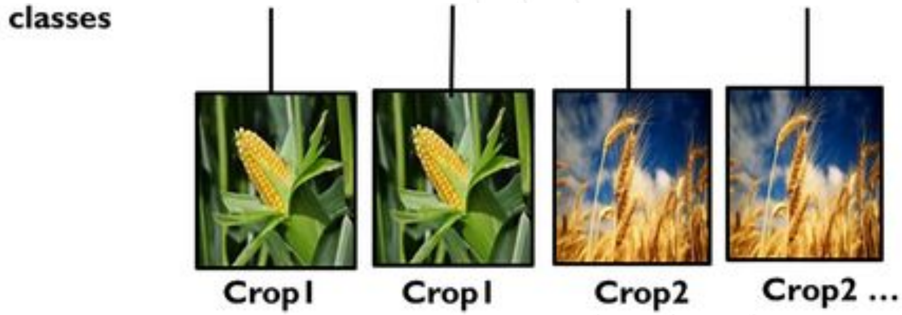

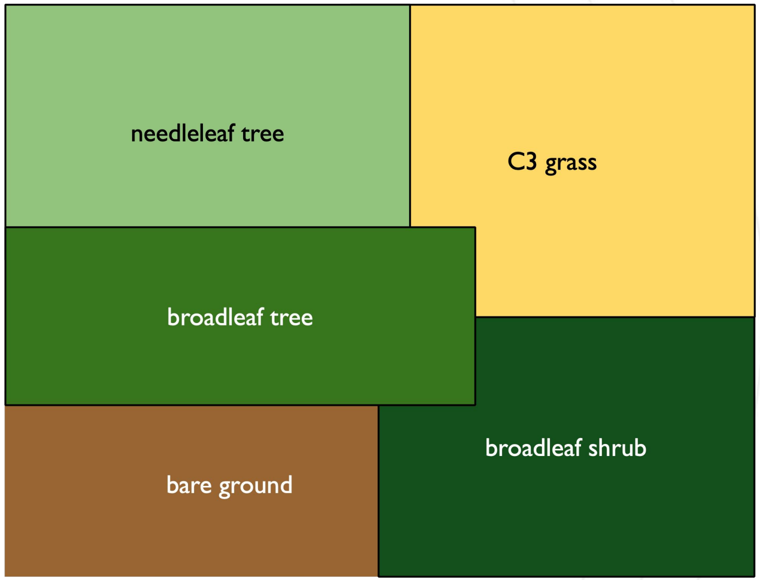

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Agriculture in CLM

Agriculture in CLM

Fertilize

Irrigate

Transient fertilizer and irrigation (1850 – 2100)

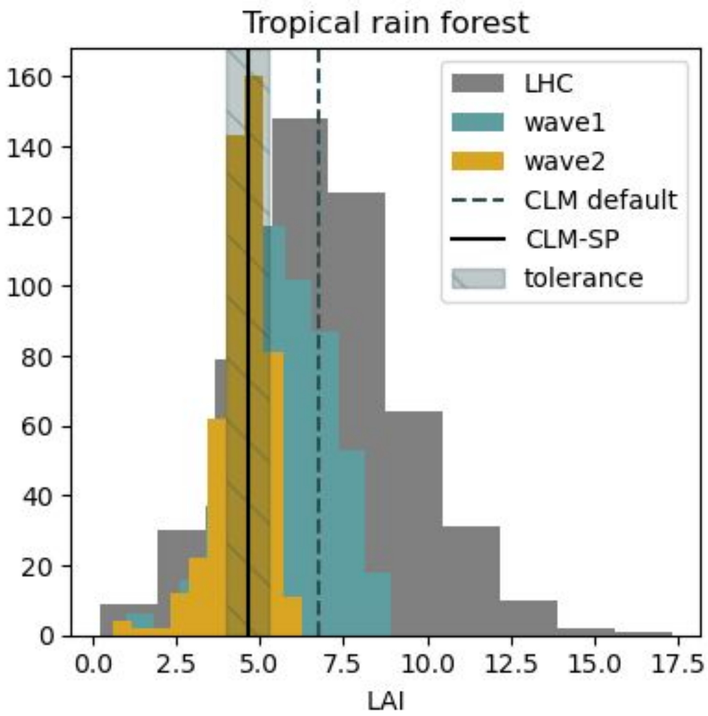
Where do parameter values come from?

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

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

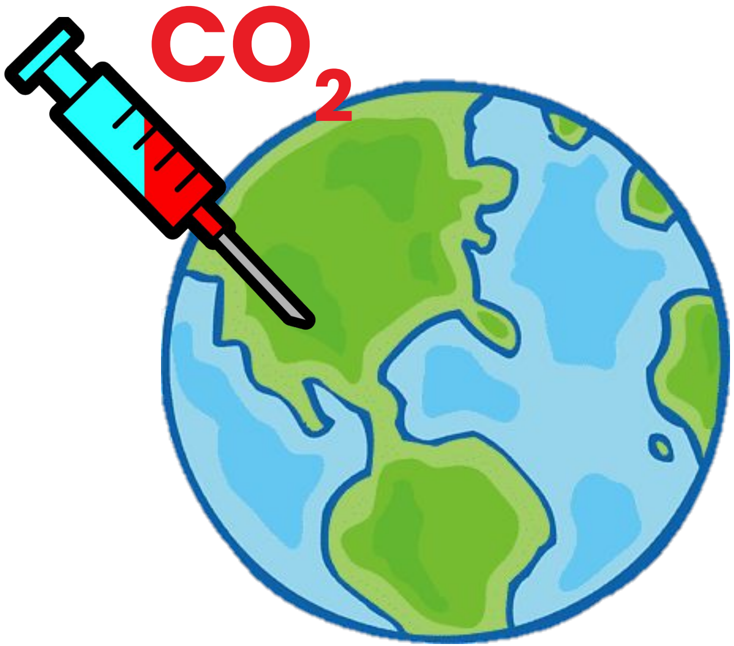
Optimality theory: plants try to optimize things like water use efficiency
e.g., FUN and LUNA modules

Calibration!



Hawkins, et al. in prep

Idealized experiments

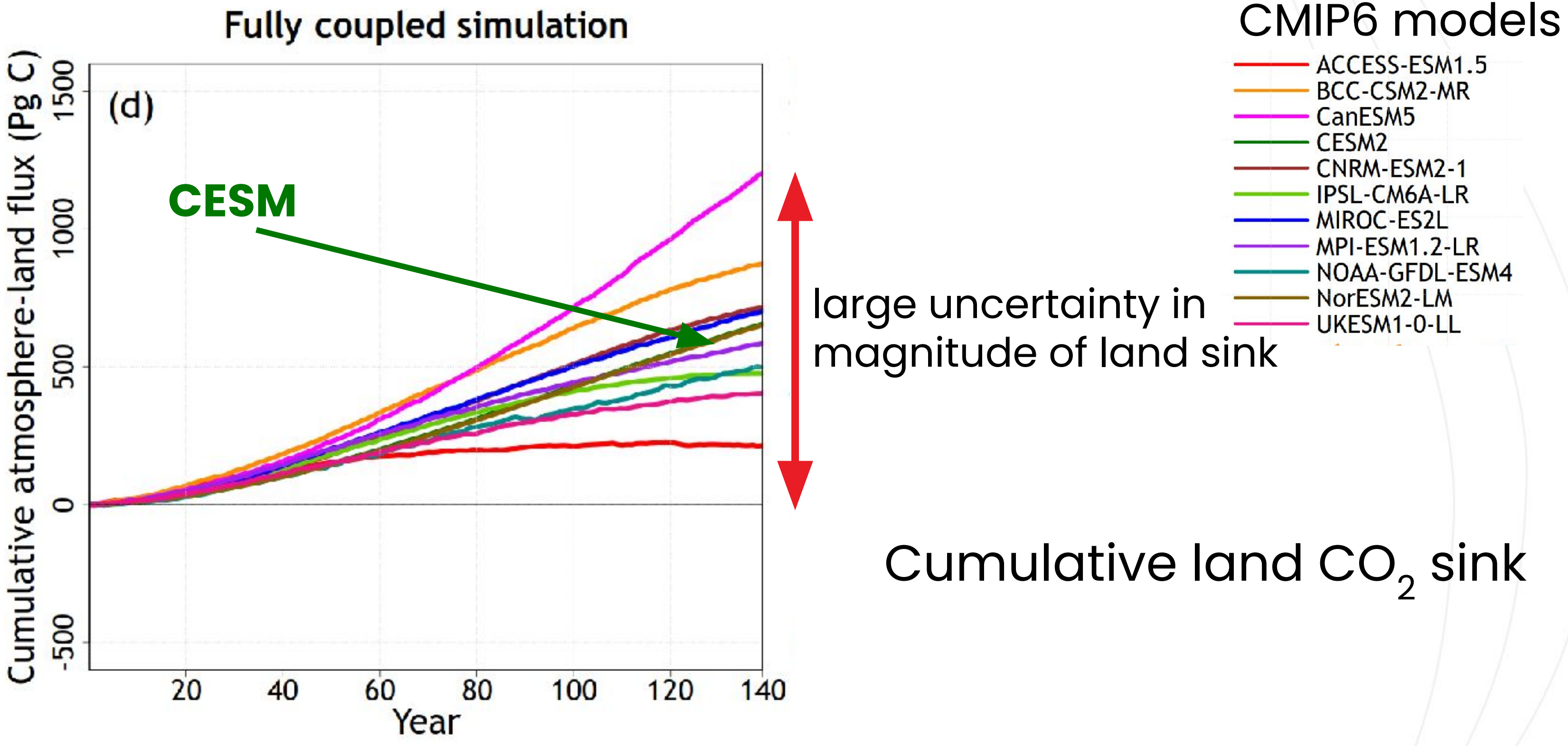


1% CO2 / year
Land & Ocean uptake
Temperature change

Three experiments:

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

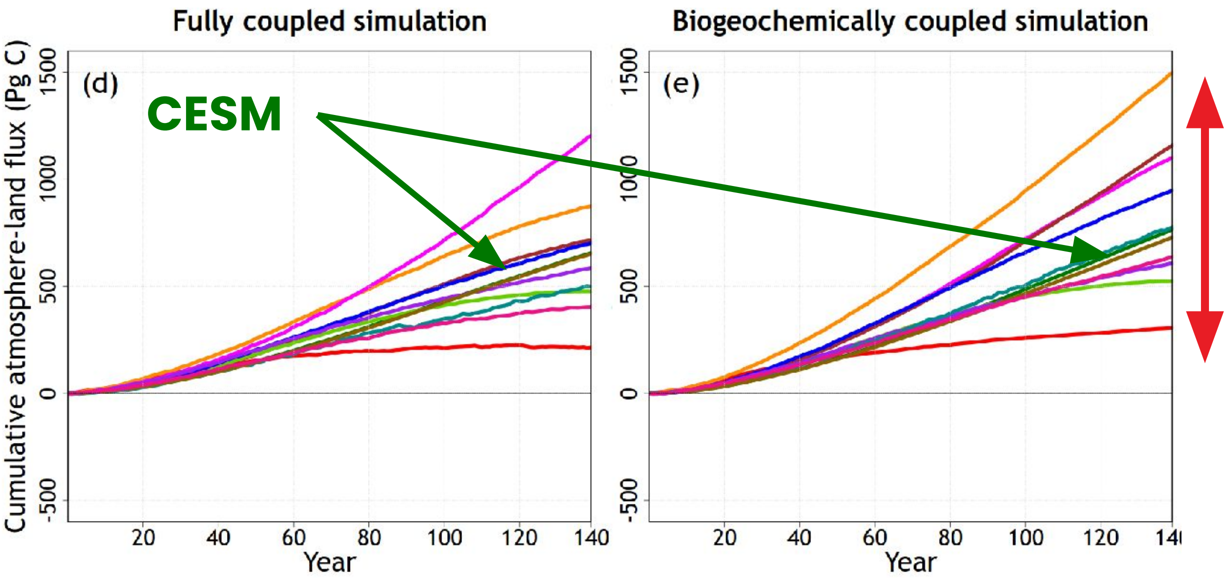
Idealized experiments



Cumulative land CO_2 sink

Idealized experiments

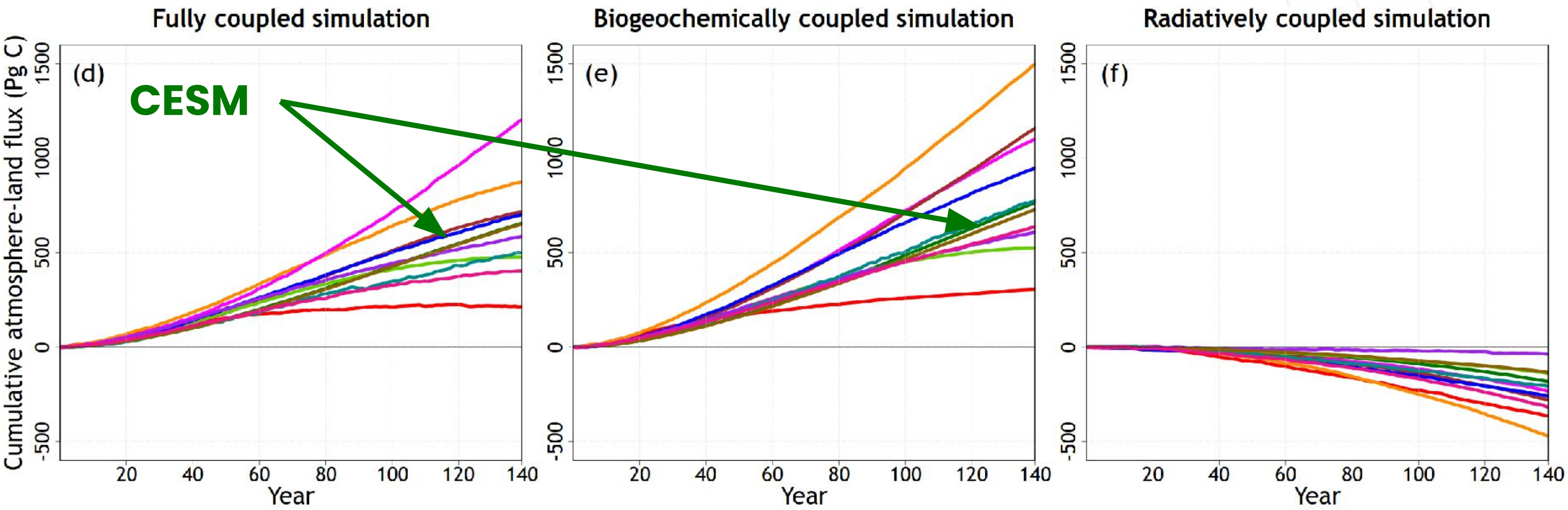
Cumulative land CO_2 sink



still large uncertainty in magnitude of land sink

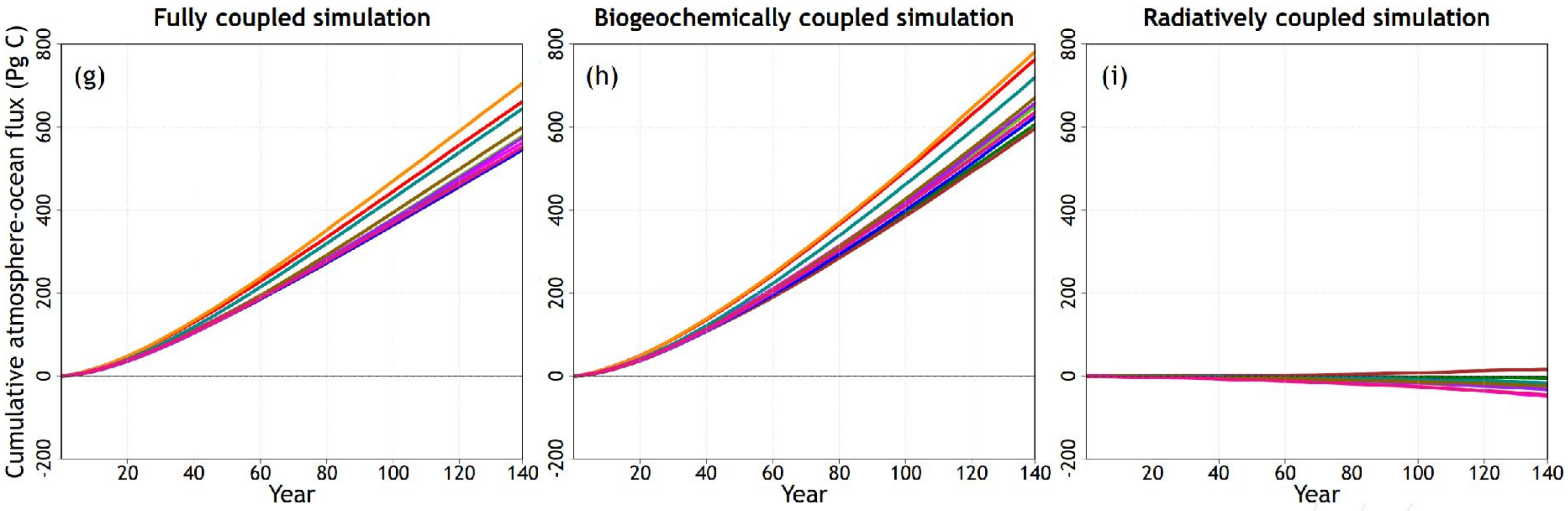
Idealized experiments

Cumulative land CO_2 sink



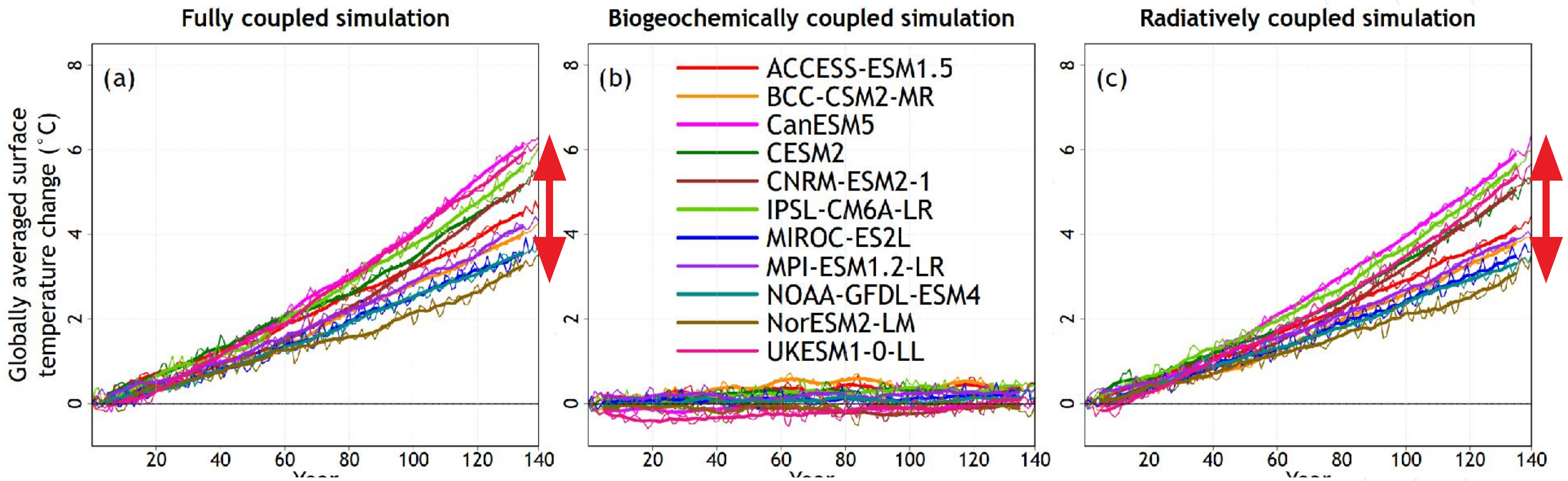
Idealized experiments

Cumulative ocean CO_2 sink



Idealized experiments

Global average surface temperature change (°C)



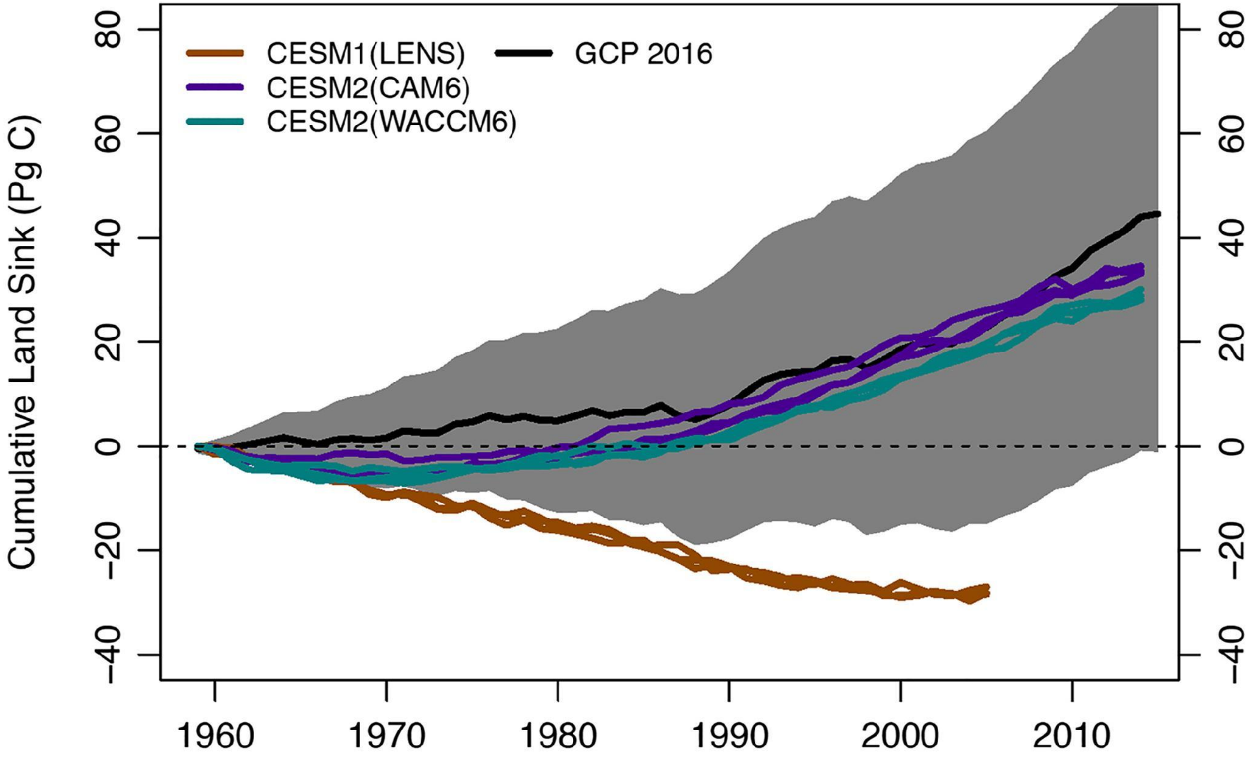
Land biogeochemistry in CESM

Why?

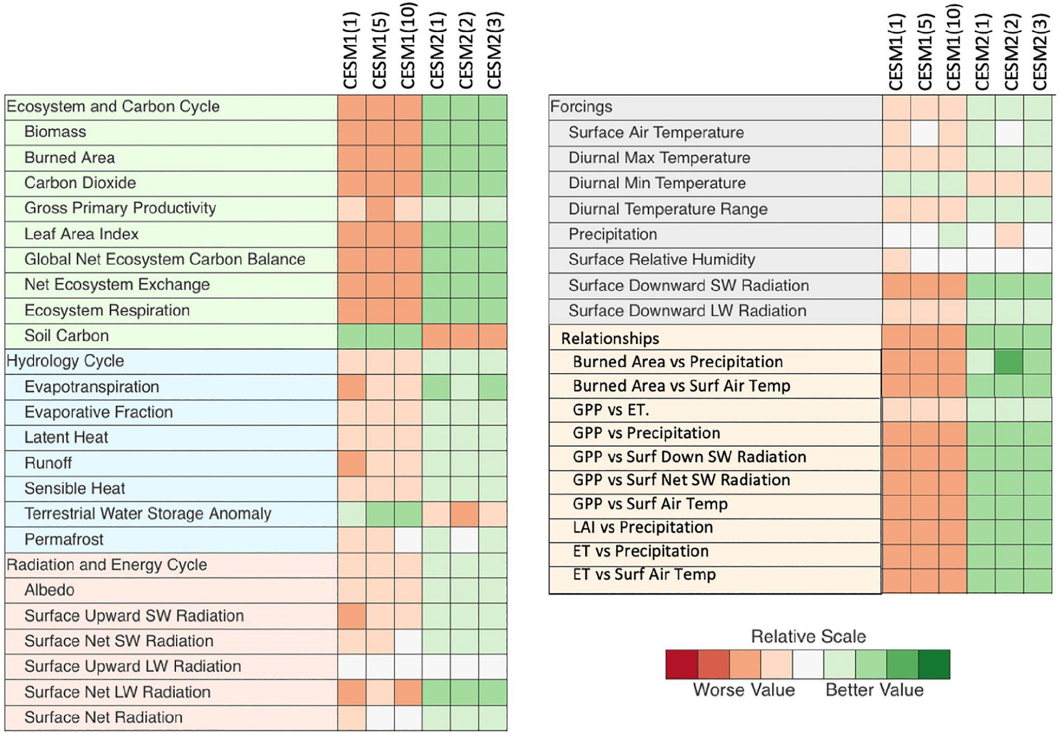
How?

Future directions

Representing the land sink



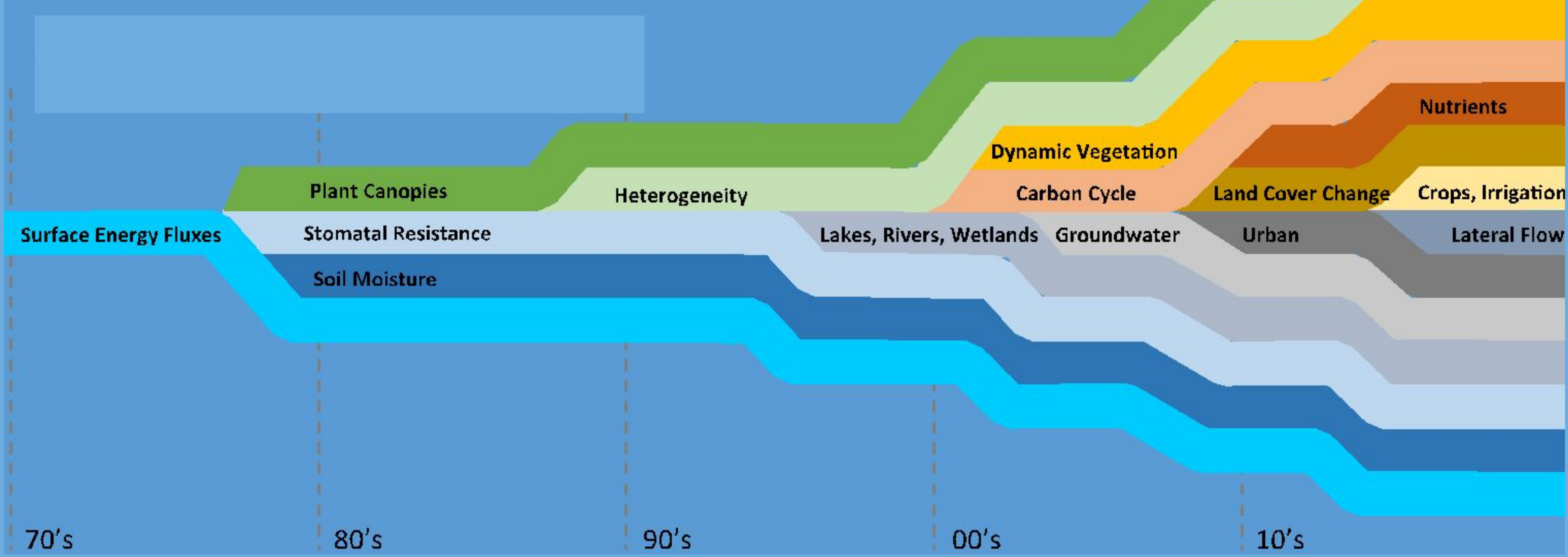
Representing the land sink

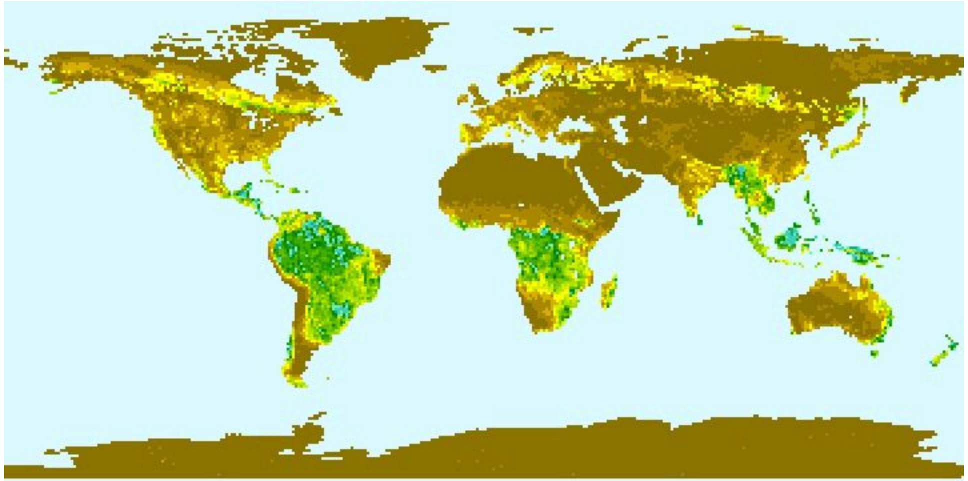


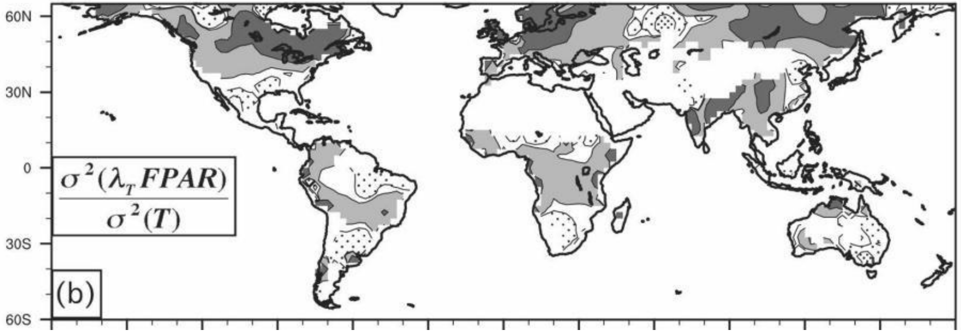
ILAMB –
International Land Model Benchmarking package

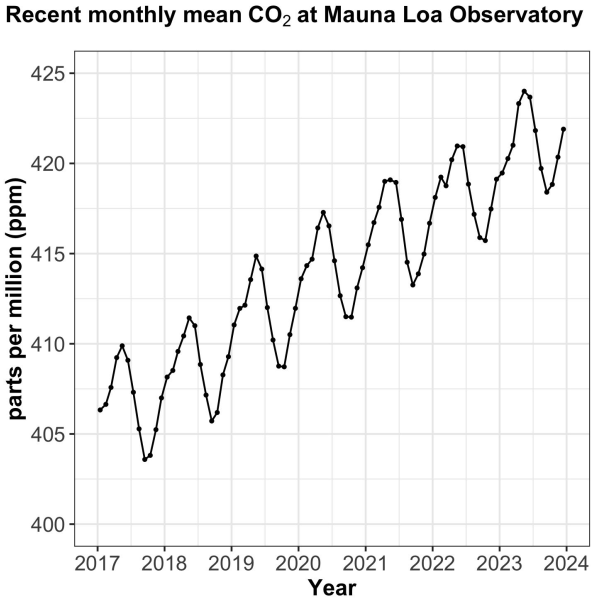
the Evolution of land modeling

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

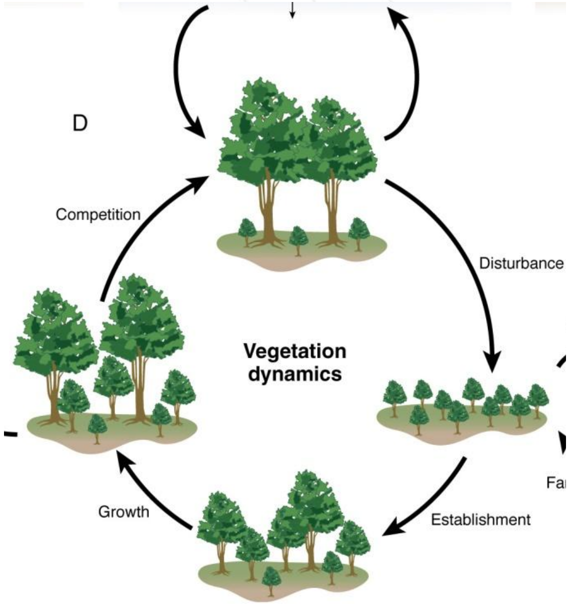




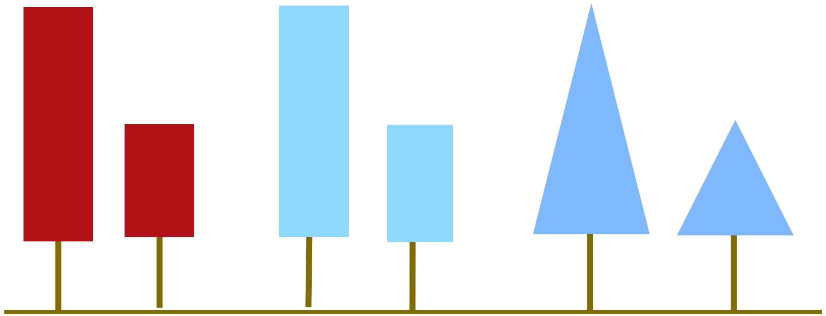

60N
30N
0
30S
60S
$\frac{\sigma^2(\lambda_T FPAR)}{\sigma^2(T)}$
(b)

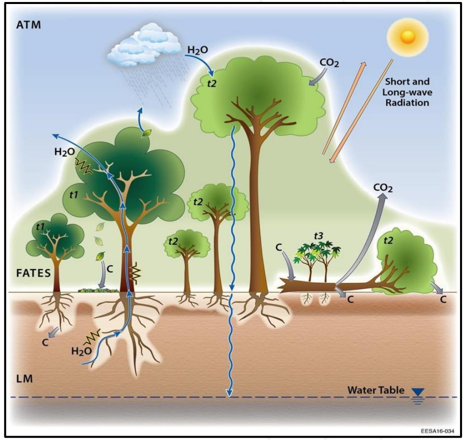

Recent monthly mean CO_2 at Mauna Loa Observatory
parts per million (ppm)
425
420
415
410
405
400
2017
2018
2019
2020
2021
2022
2023
2024
Year

Forests are a mosaic of patches



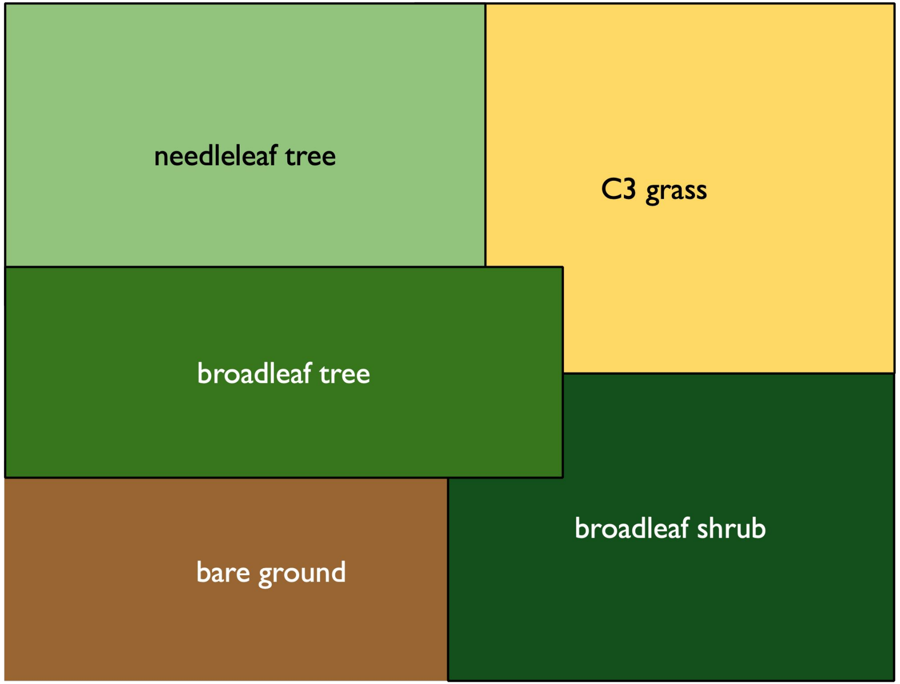
FATES: Functionally Assembled Terrestrial Ecosystem Simulator





- cohort-specific model
- 30-minute photosynthesis and fluxes
- daily growth and allocation
- dynamic vegetation!

Tiling differences

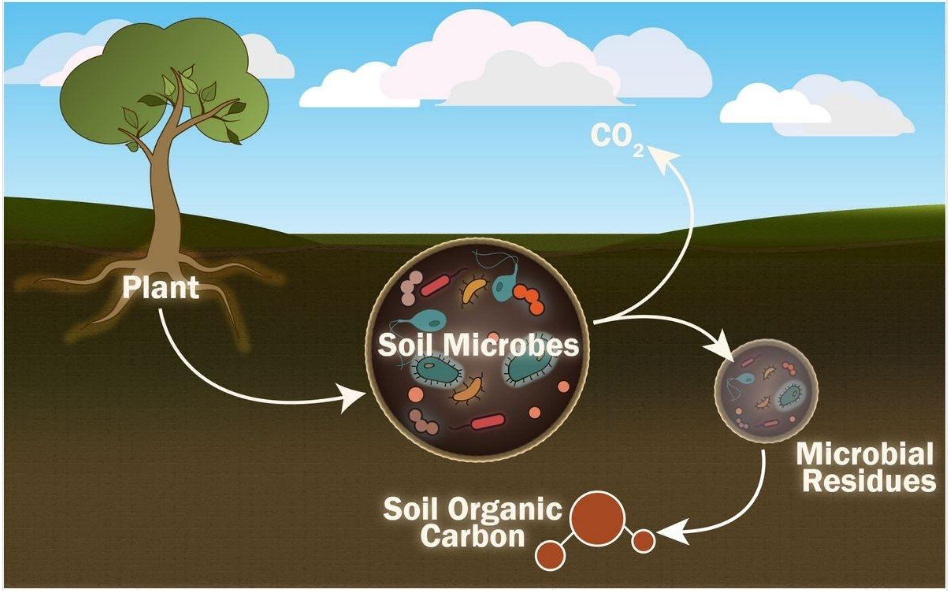


Tiling differences

Each tile contains cohorts of plants of different PFT and size

MIMICS: modeling microbial controls on soil carbon dynamics

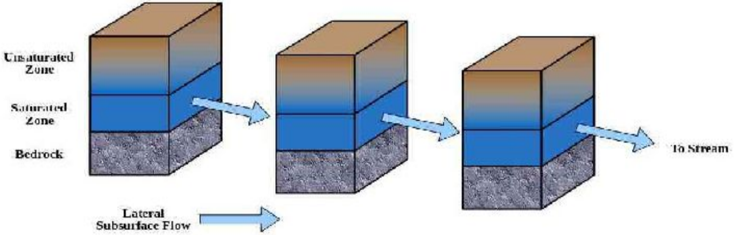
Soil C model that considers relationships among litter quality, functional tradeoffs in microbial physiology, and microbial byproducts



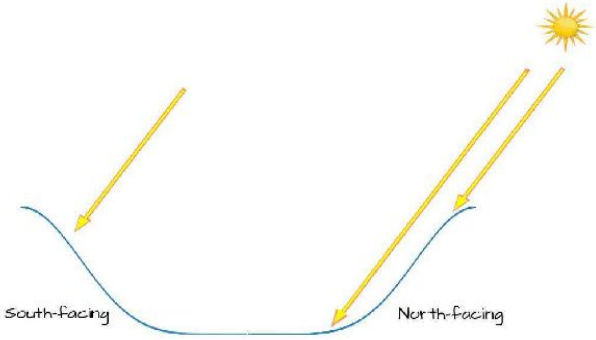
More accurately represents C response to N enrichment

Representative hillslope model

Explicit Lateral Flow Within Gridcell



Downscaled Meteorology



How will ecosystems change when climate changes?

Community Terrestrial Systems Model: Land model used for climate change that can be run at single points (~ 1 ha) to global scale.

FATES: Represents vegetation demographics, traits, and recovery from disturbance (feature within CTSM).

MIMICS: Soil biogeochemistry model (explicitly represent microbial activity and physiological diversity).

Hillslope Hydrology: Considers effects of aspect, elevation, and hydrologic connectivity on water availability (feature within CTSM).