Introduction to

Biogeochemical cycles

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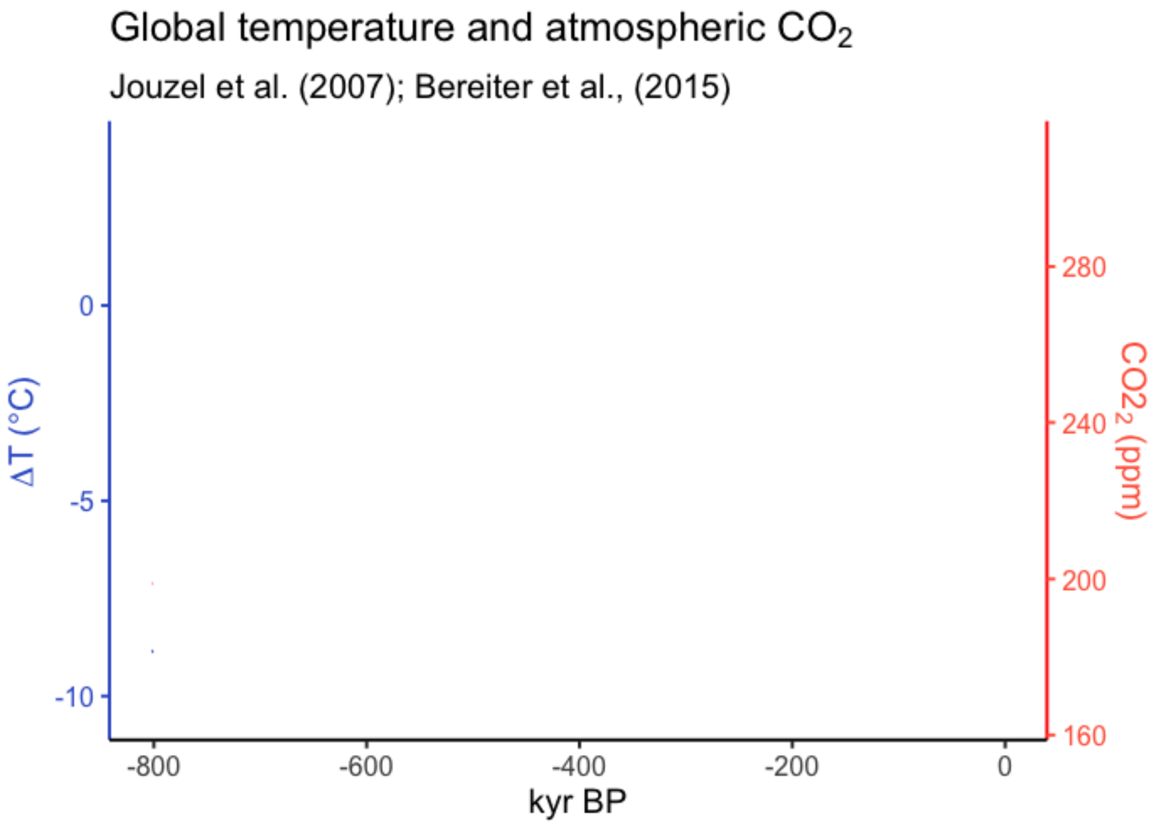
Global Change Biology, Spring semester 2020, ETH Zürich

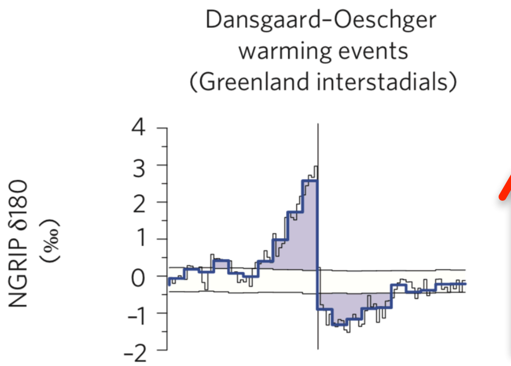
Overview

1. **Lessons from the past**
2. **Definitions, numbers, and the current state**
3. **Current and future global change and research challenges**

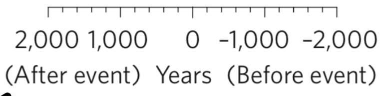
CO_2 and global temperatures over glacial-interglacial cycles



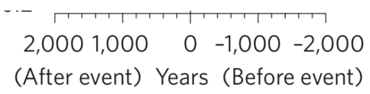
Greenhouse gases over rapid warming events



Temperature



Time



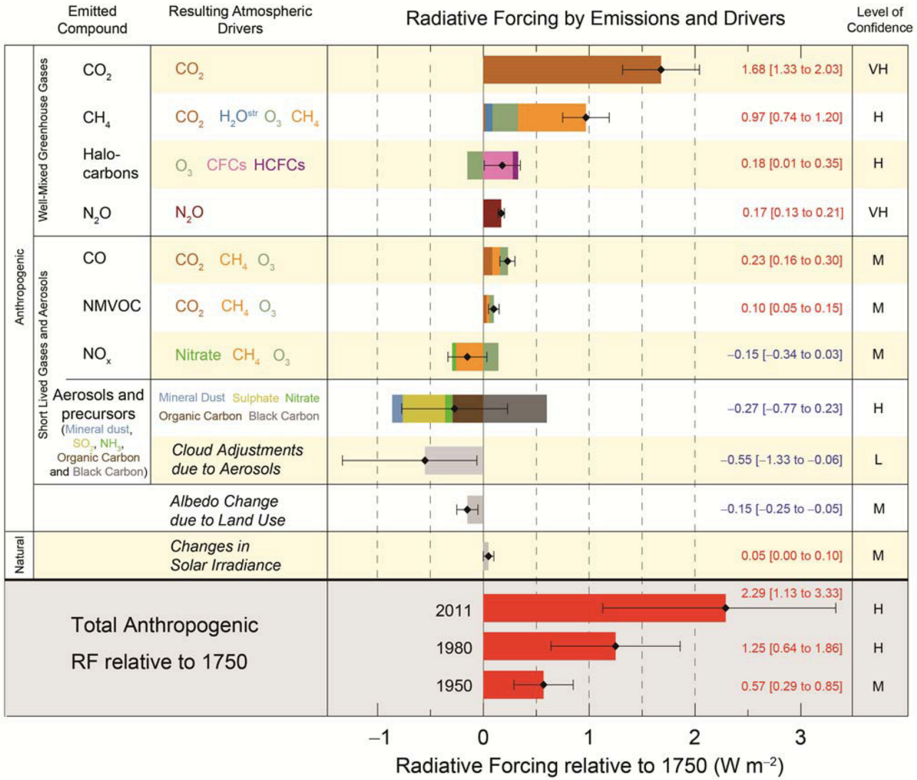
Time

Arneth et al., 2010
Nature Geosci.

Greenhouse gases over rapid warming events

ΔT ➔ **eGHG**

Radiative forcing since 1750 CE

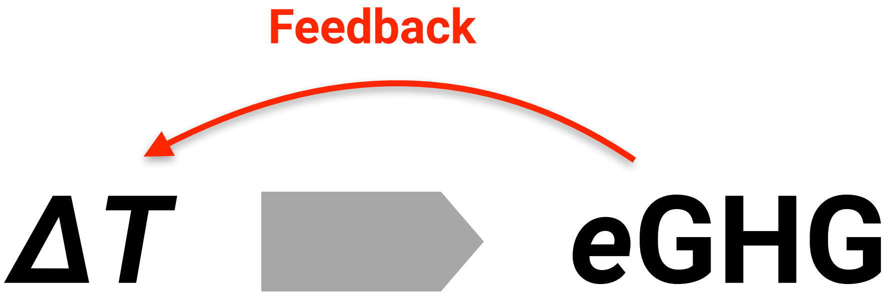


Carbon dioxide: CO_2
Methane: CH_4

Nitrous oxide: N_2O

Stocker et al., 2013 *IPCC SPM*

Feedback between climate and greenhouse gas emissions

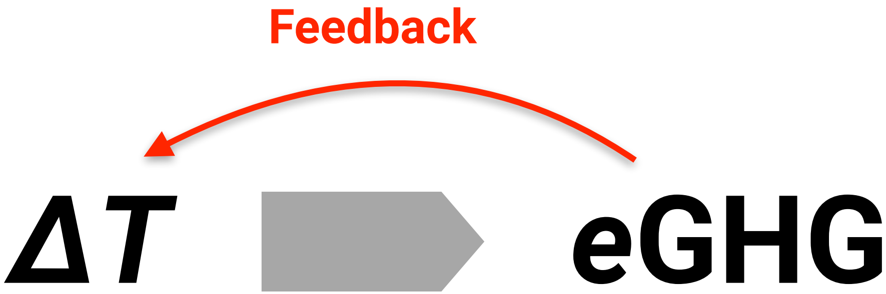


2.Definitions, numbers, and the current state

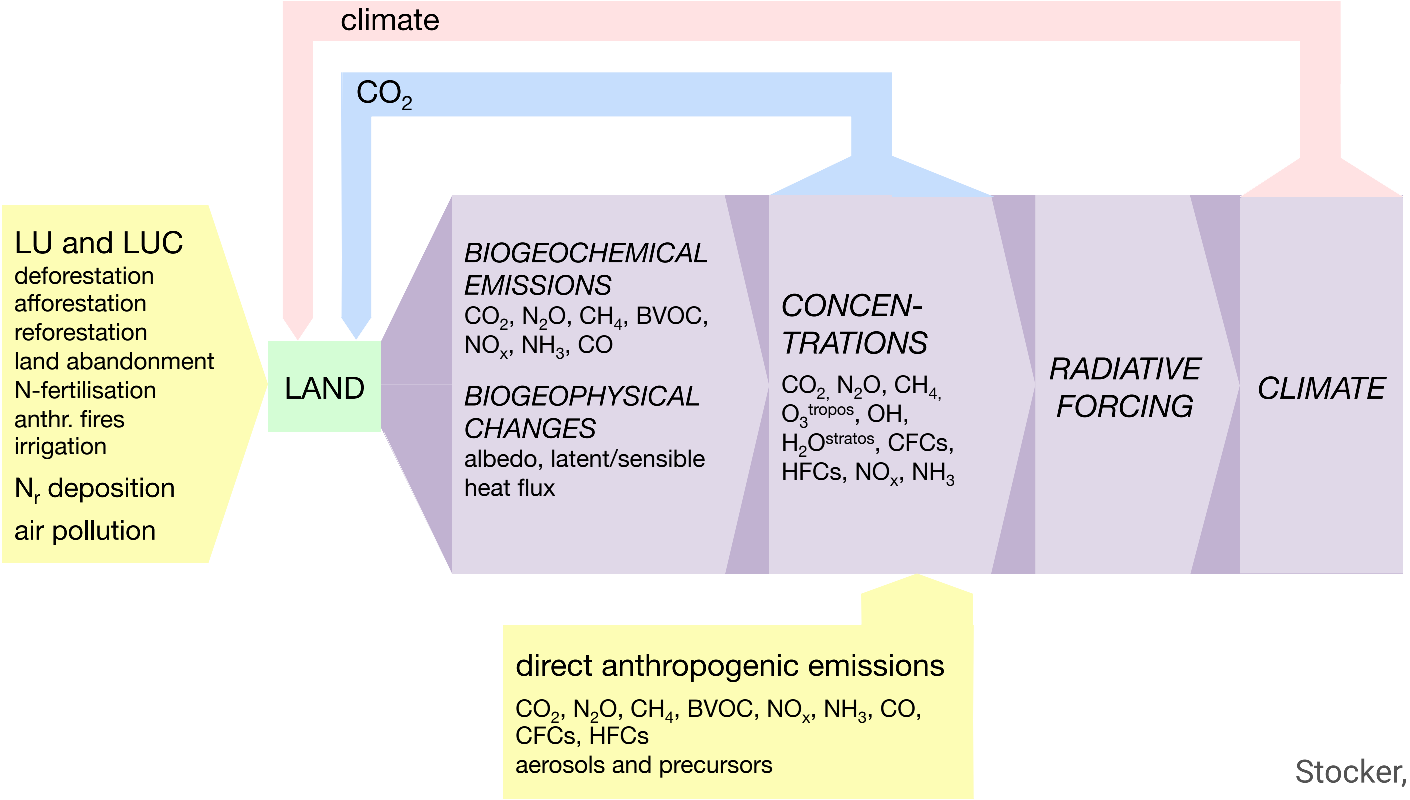
Biogeochemical cycles

Biogeochemistry is the study of element **cycling** among the biosphere, geosphere, and atmosphere. *Bonan, 2016*

Feedback between climate and greenhouse gas emissions

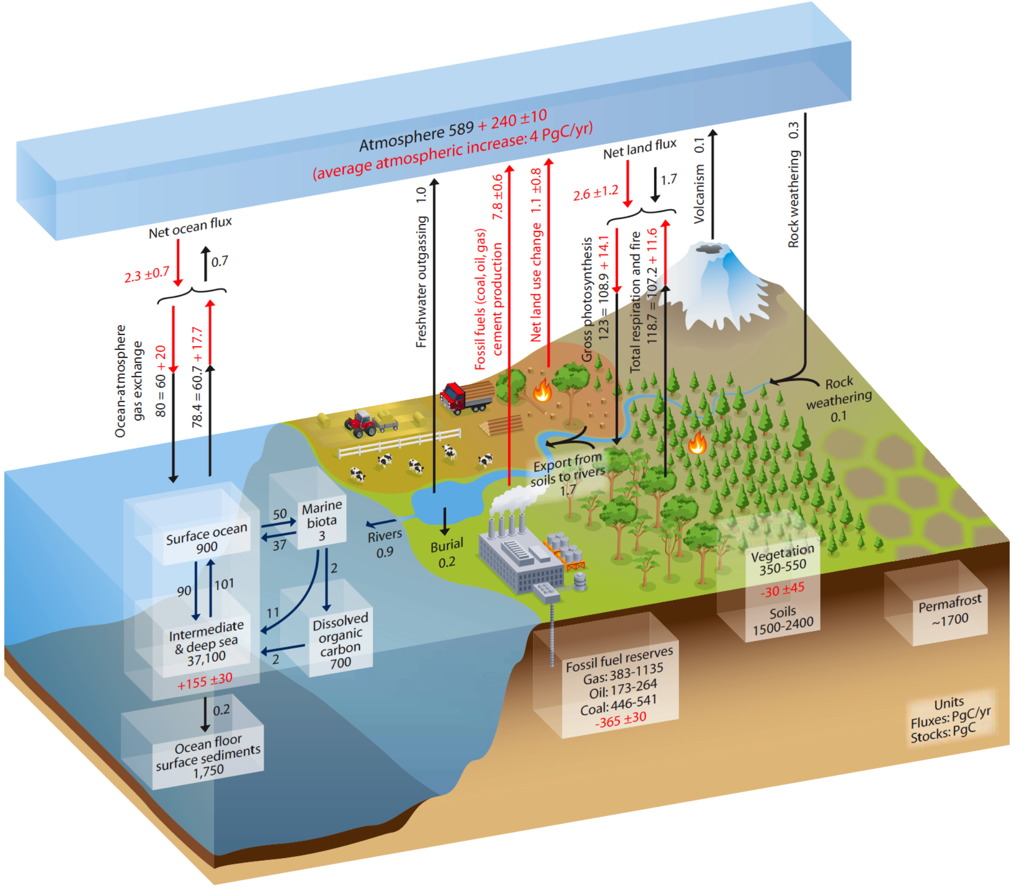


Terrestrial biosphere in the Earth system



Stocker, 2013 *PhD thesis*

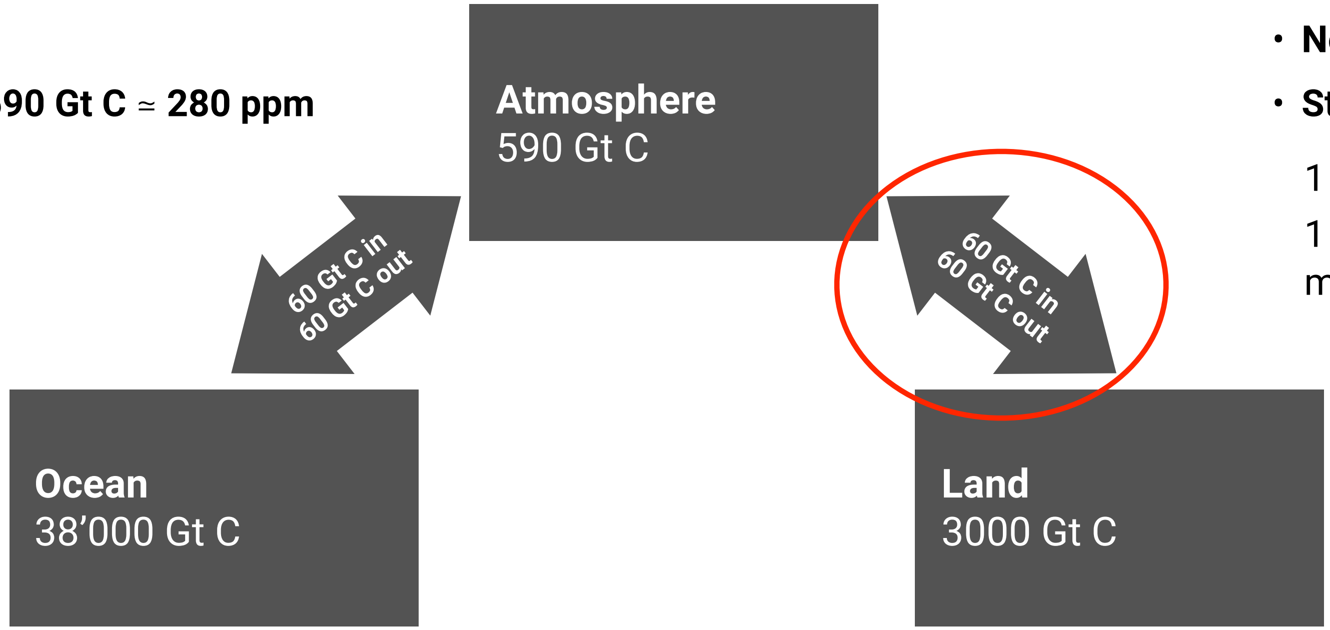
The carbon cycle



Ciais et al. (2013) IPCC AR5 Ch. 6

The carbon cycle simplified at preindustrial steady state

590 Gt C ≃ 280 ppm

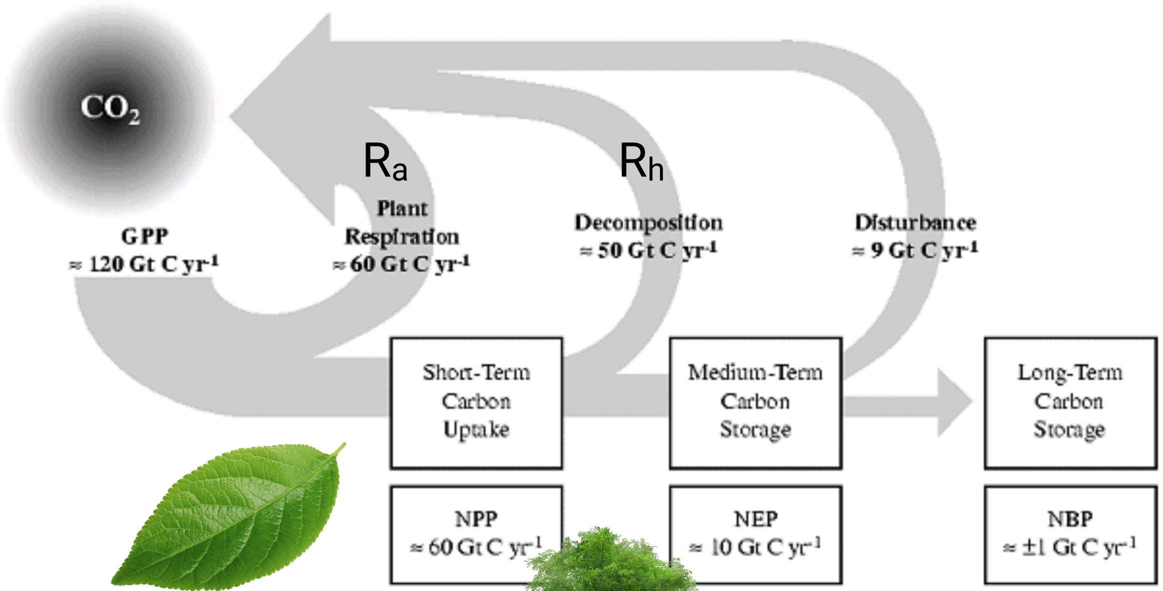


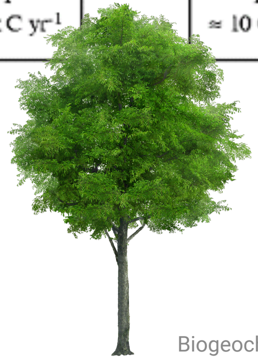
- **No net fluxes**
- **No change in reservoir size**
- **Steady state (equilibrium)**

1 Gt C = 1 Pg C = 10^{15} g C

1 ppm = 2.124 Gt C (well-mixed atmosphere)

Terrestrial carbon fluxes





LULUCF SR, IPCC, 2007
https://archive.ipcc.ch/ipccreports/sres/land_use/index.php?idp=24

GPP: Gross primary production

NPP: Net primary production

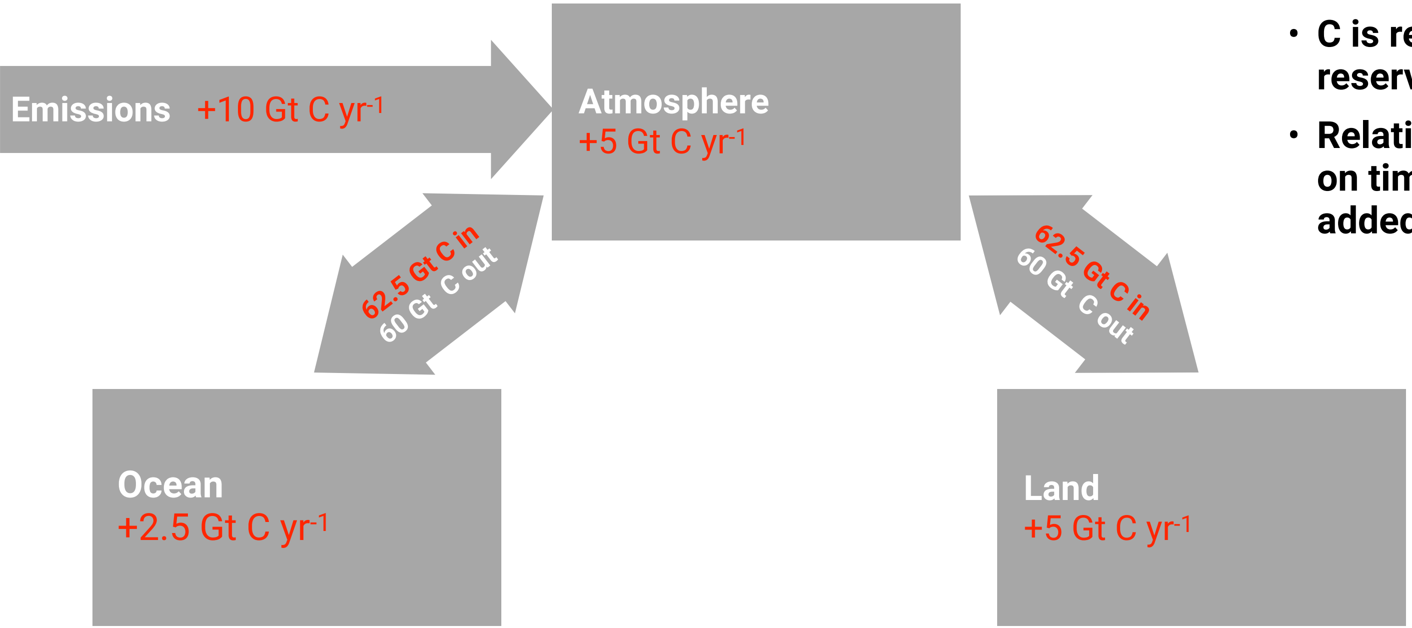
NEP: Net ecosystem production

NEE: Net ecosystem exchange*

NBP: Net biome production

*used in ecosystem flux measurements

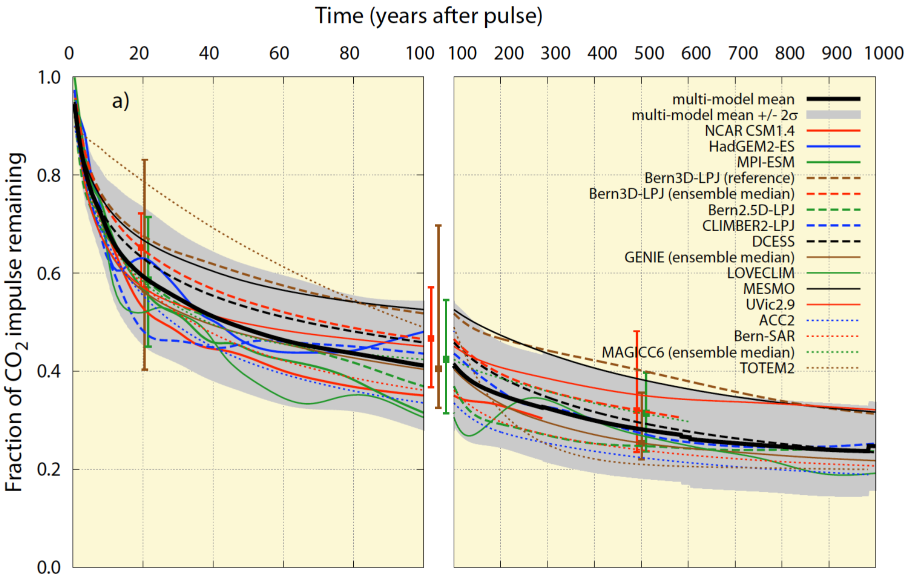
The perturbed carbon cycle (rough numbers)



- On "relevant" time scales, CO_2 has no sink.
- C is redistributed between reservoirs.
- Relative redistribution depends on time scale and amount of added C (non-linearity!).

Atmospheric fraction

Emissions → **Atmosphere** → **Land + ocean uptake**



Joos et al., 2013

The global carbon budget (2009-2018)

Fossil fuel emissions +9.5 ± 0.5 Gt C yr^{-1}
Land use change emissions +1.5 ± 0.7 Gt C yr^{-1}

Atmosphere
865 Gt C (407 ppm)
+4.9 ± 0.02 Gt C yr^{-1}

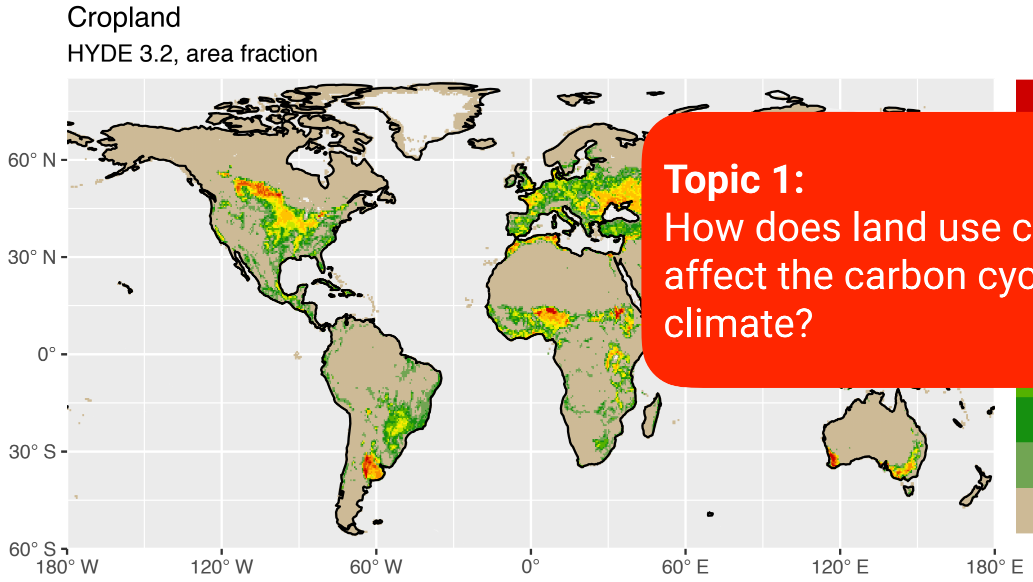
Ocean
2.5 ± 0.6 Gt C yr^{-1}

Land
3.2 ± 0.6 Gt C yr^{-1}

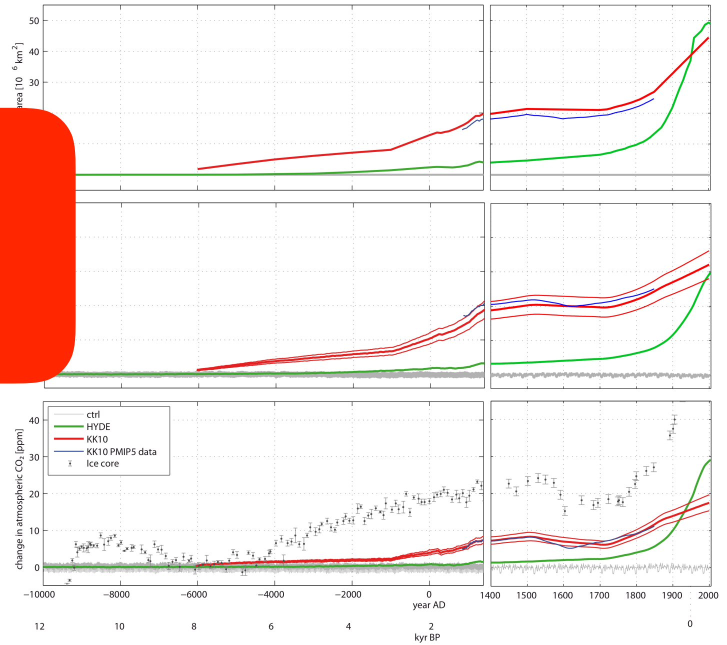
$$E_{\mathrm{FF}} + E_{\mathrm{LUC}} = G_{\mathrm{ATM}} + S_{\mathrm{OCEAN}} + S_{\mathrm{LAND}} \; (+ B_{\mathrm{IM}})$$

Global Carbon Budget 2019
Friedlingstein et al., 2019 *ESSD*

Land use change



Topic 1:
How does land use change affect the carbon cycle and climate?



Terrestrial C storage as a 1-box model

I = 60 Gt C yr^{-1} (NPP)

Terrestrial C storage
C = 3000 Gt C

Residence time
$\tau = C/I$ = 50 yr

O = 60 Gt C yr^{-1} (R_H)

Dynamics: $$\frac{dC}{dt} = I(t) - kC(t)$$

Steady state: $$\frac{dC}{dt} = 0 \Rightarrow C^* = \frac{1}{k} I = \tau I$$

Controls on GPP

- Diffusion across the leaf surface (through stomata)
  Fick's Law

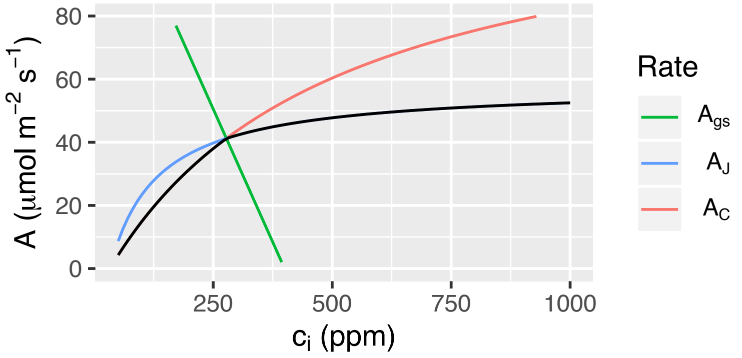
➔ A_{gs}

$$A_{gs} = g_s(c_a - c_i)$$

- A: CO_2 assimilation rate
- g_s: stomatal conductance to CO_2
- c_a: ambient CO_2 concentration
- c_i: leaf-internal CO_2 concentration

- Biochemical rates
  Farquhar et al., 1980

➔ $\min(A_J, A_C)$



- **Increasing CO_2**

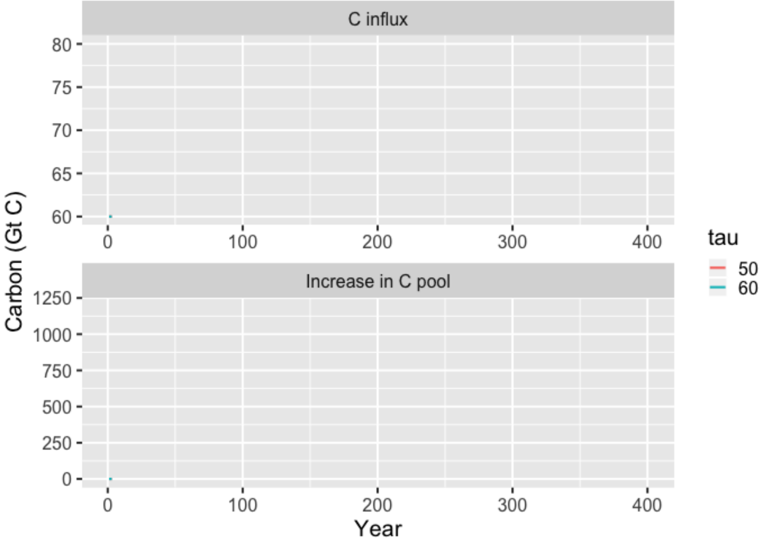
➔ increasing *A*

Step change in input flux

I = 60 Gt C yr^{-1} ➔ 80 Gt C yr^{-1}

Terrestrial C storage

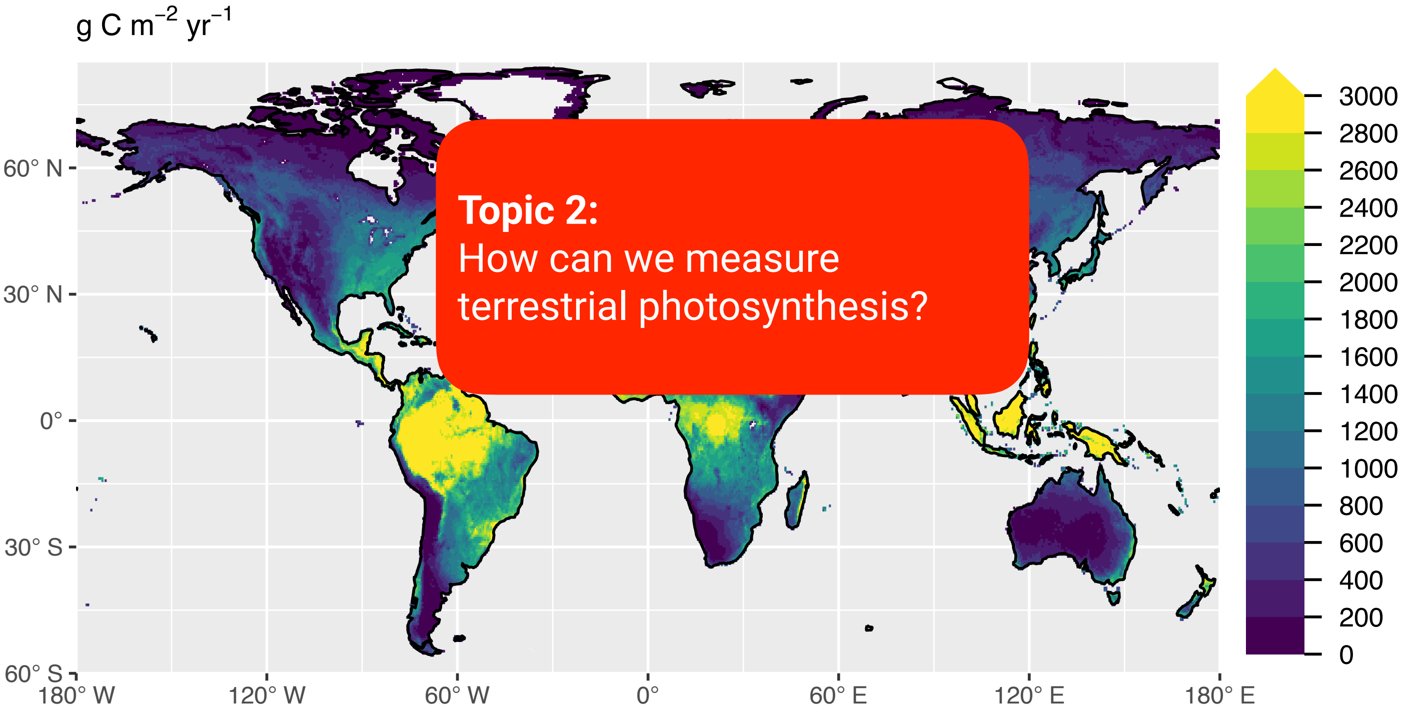
O



Simple 1-box model predicts:

- **Increasing I ➔ increasing C**
- **ΔC ~ residence time**

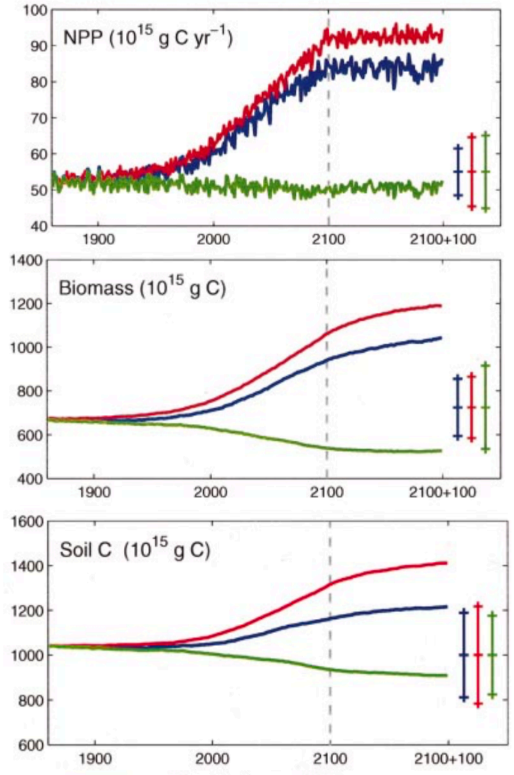
Terrestrial photosynthesis

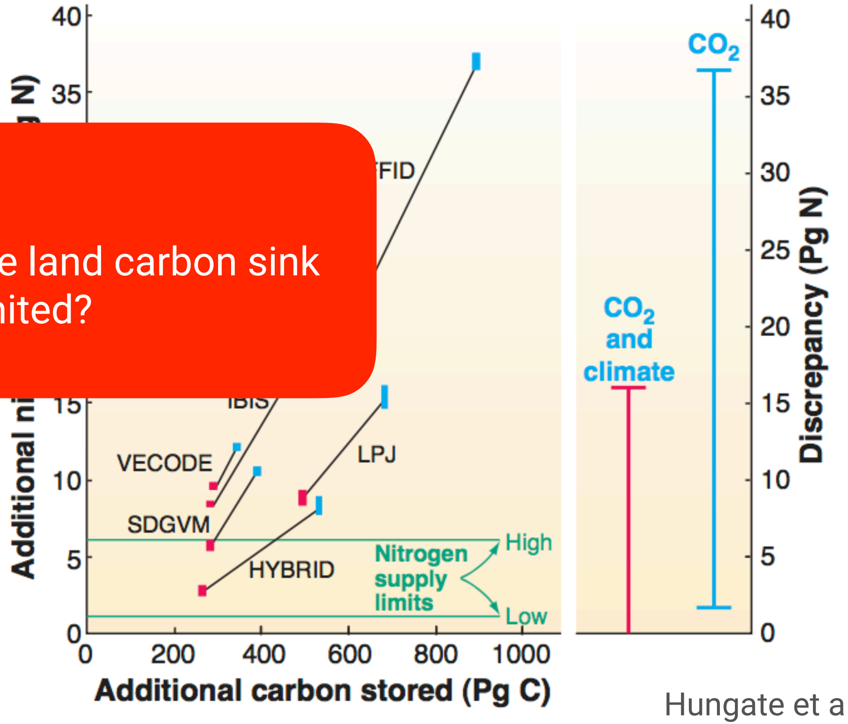


Topic 2:
How can we measure terrestrial photosynthesis?

Nutrient limitation?

Cramer et al., 2001 *GCB*





Topic 3:
Is the future land carbon sink nutrient-limited?

Hungate et al., 2003

Carbon - water coupling

- Diffusion across the leaf surface (through stomata)
  Fick's Law

- **g_s determines both CO_2 assimilation and transpiration**

$$A = g_s\,(c_a - c_i) = g_s\,c_a(1 - \chi)$$

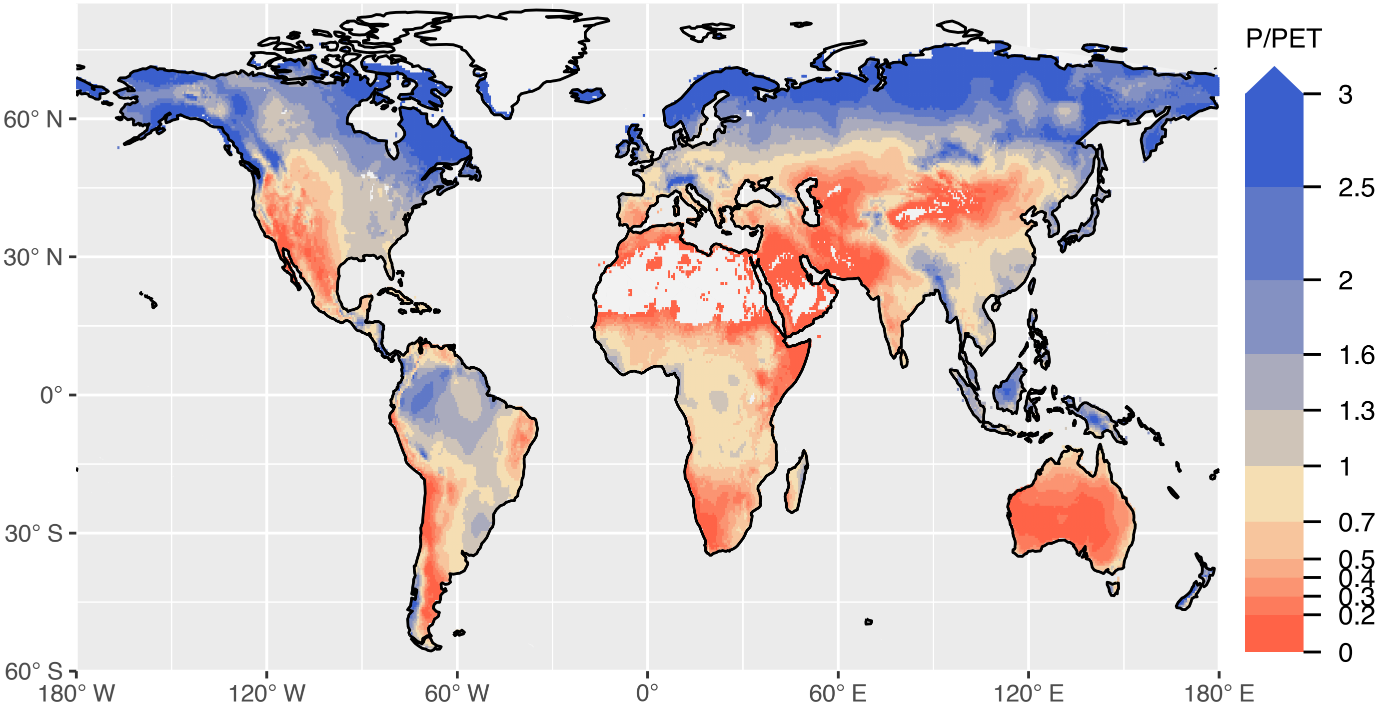
$$E = 1.6\,g_s\,\underbrace{(e_a - e_i)}_{D}$$

$$\mathrm{WUE} = A/E = \frac{c_a\,(1 - \chi)}{1.6\,D}$$

- A: CO_2 assimilation (mol CO_2 m^{-2} s^{-1})
- g_s: stomatal conductance to CO_2 (mol CO_2 m^{-2} s^{-1} Pa^{-1})
- c_a: ambient CO_2 partial pressure (Pa)
- c_i: leaf-internal CO_2 partial pressure (Pa)

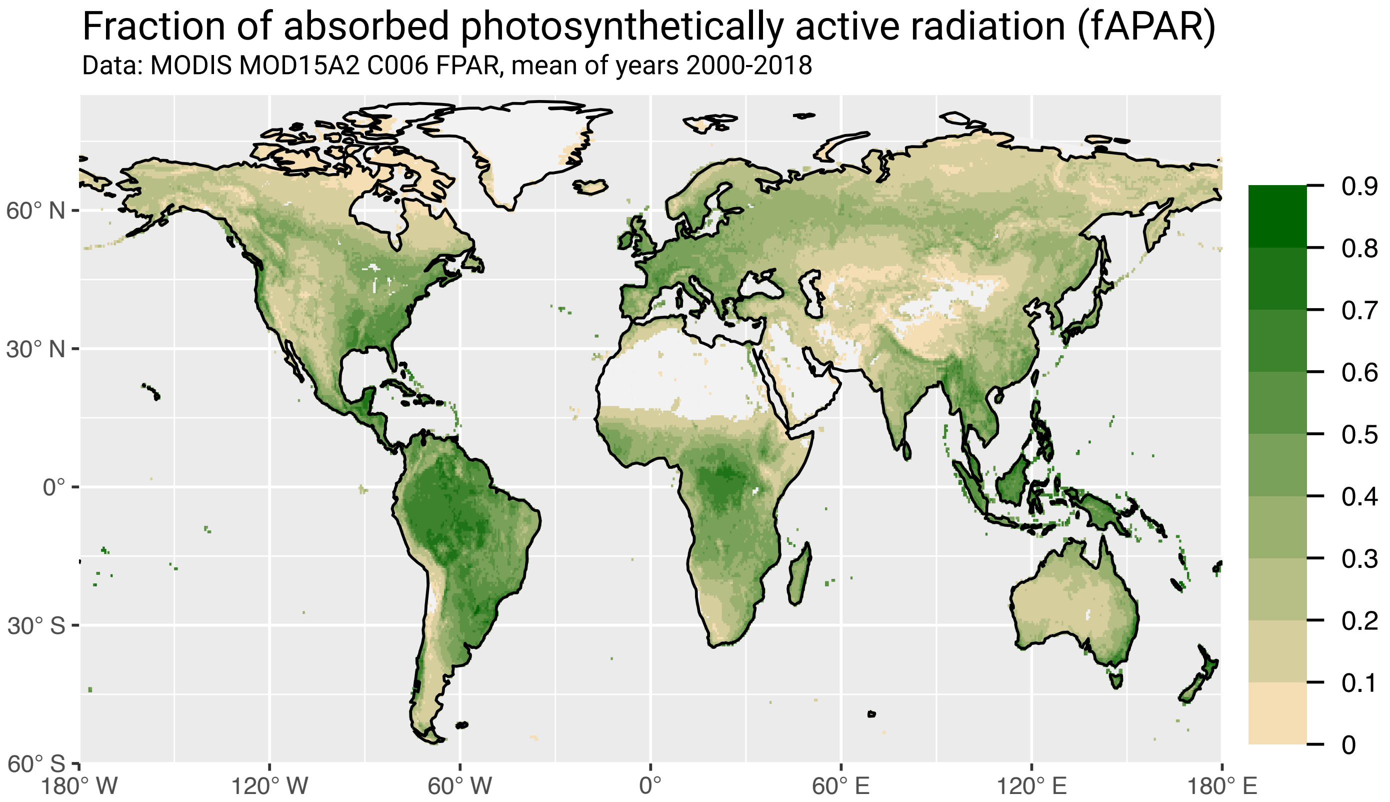
- E: Transpiration (mol H_2O m^{-2} s^{-1})
- e_a: water vapour pressure at leaf surface (Pa)
- e_i: leaf-internal water vapour pressure (Pa)
- D: vapour pressure deficit (Pa)

Precipitation over potential evapotranspiration



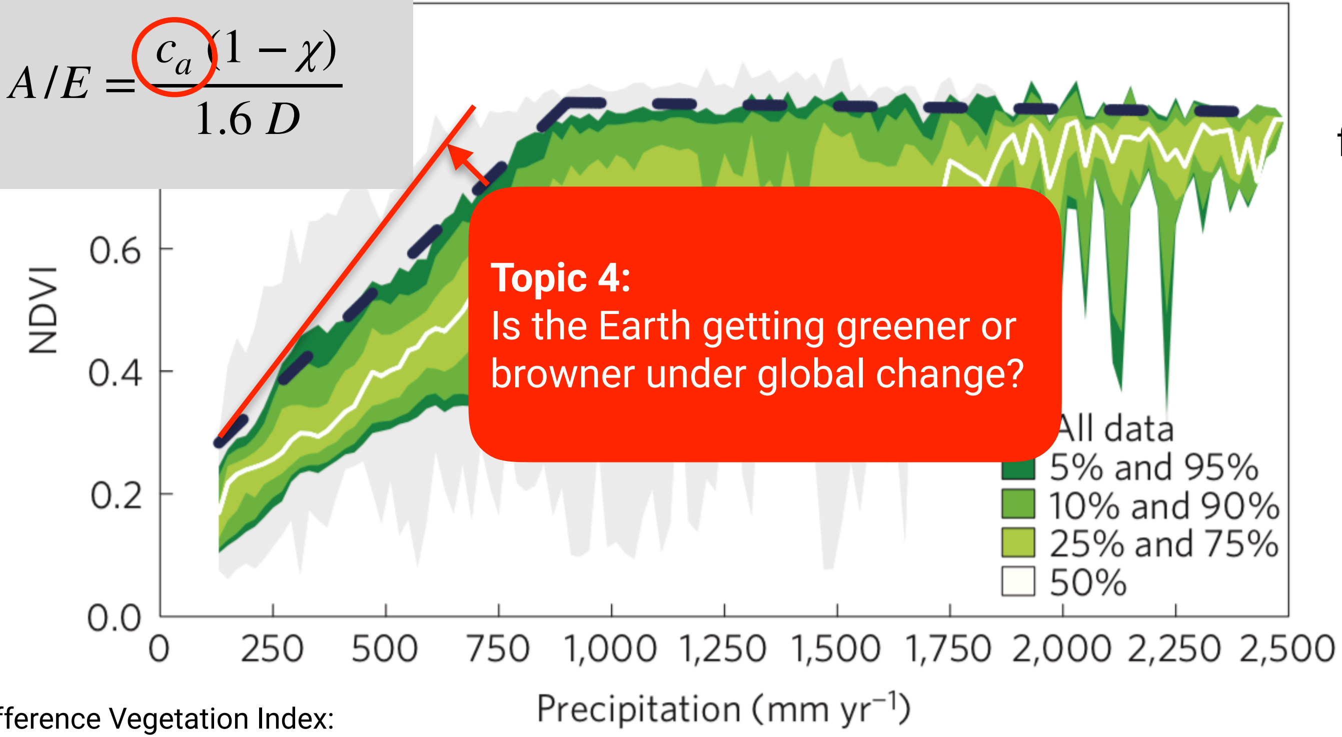
Data: Greve et al., 2014

Vegetation cover



Vegetation cover

$$\text{WUE} = A/E = \frac{c_a(1-\chi)}{1.6\,D}$$



Topic 4:
Is the Earth getting greener or browner under global change?

NDVI ≈ fAPAR

$\text{fAPAR} \approx 1 - e^{-kL}$

L: Leaf area index (LAI)
k: light extinction coefficient (≅0.5)

Normalized Difference Vegetation Index:
NDVI = $(R_{IR} - R_R)/(R_{IR} + R_R)$
R_{IR} = near infrared reflectance
R_R = red reflectance (Chl absorption)

Ukkola et al., 2015

Now it’s your turn…

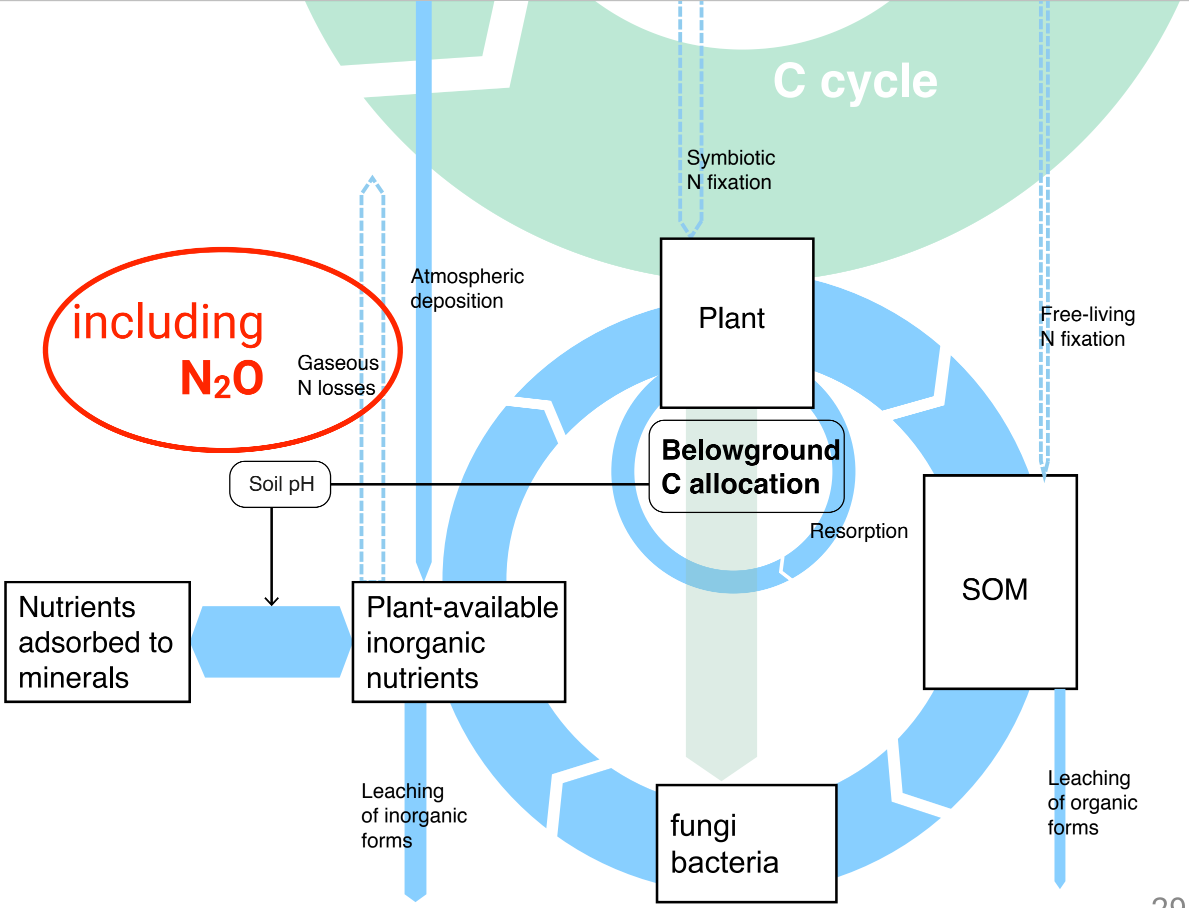
The nutrient constraint

Macro nutrients:

- Nitrogen (N)
- Phosphorous (P)

- Nutrients are required for biomass synthesis.
- Relatively small variations in stoichiometric relationships in different plant pools, soil organic matter, and microbial biomass.

$$r_{N:C}\,\mathrm{NPP} = N_{uptake}$$



Carbon - water coupling: Canopy scale

- GPP reaches asymptote with increasing *L*.
- E_c is 70-90% of ET globally
- Linear scaling of canopy transpiration with *L*.

$$\text{GPP} \sim (1 - e^{-kL})$$

- *L*: Leaf area index (LAI)

$$\text{ET} = E_s + E_c + E_i$$

$$E_c = 1.6\, g_c L$$

- ET: Evapotranspiration
- E_s: Soil evaporation
- E_c: Canopy transpiration
- E_i: Evaporation from intercepted precipitation

Carbon - water coupling: Canopy scale

- GPP reaches asymptote with increasing *L*.
- E_c is 70-90% of ET globally
- Linear scaling of canopy transpiration with *L*.

$$\text{GPP} = \text{LUE} \cdot \text{PAR} \cdot \text{fAPAR}$$

$$\text{GPP} \sim (1 - e^{-kL})$$

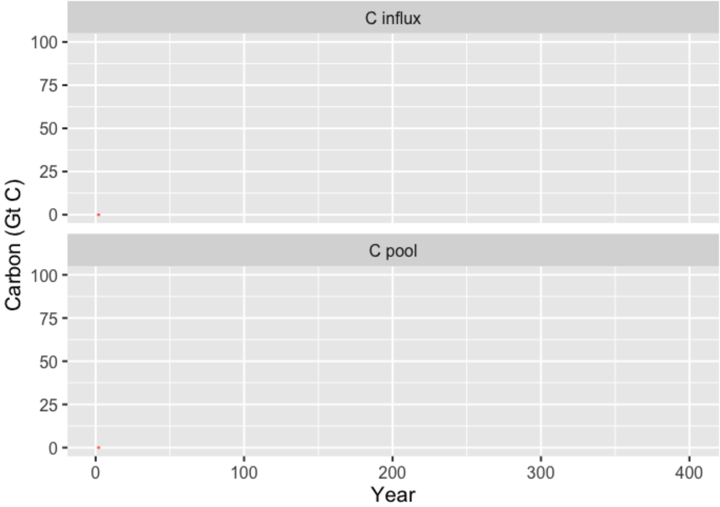
$$\text{ET} = E_s + E_c + E_i$$

$$E_c = 1.6\, g_c L$$

- PAR: Photosynthetically active radiation
- fAPAR: Fraction of absorbed PAR
- LUE: Light use efficiency
- *L*: Leaf area index (LAI)

- ET: Evapotranspiration
- E_s: Soil evaporation
- E_c: Canopy transpiration
- E_i: Evaporation from intercepted precipitation

Pulse - decay

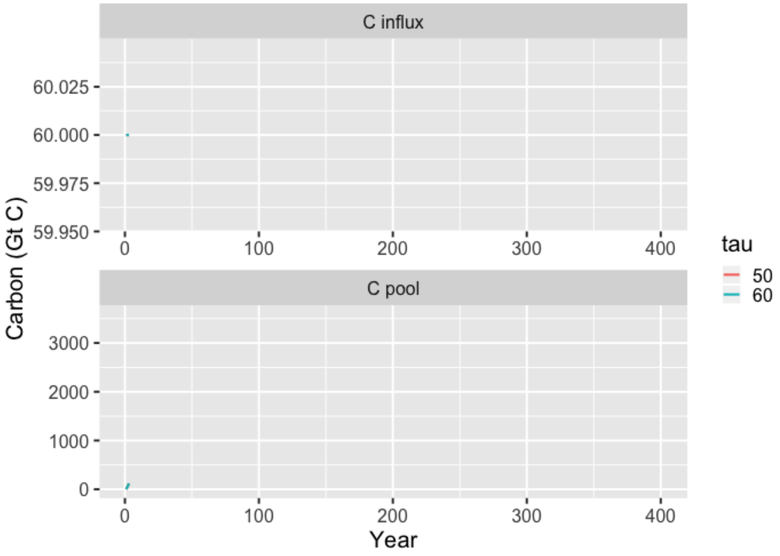


- **Exponential decay of the pulse ➔ *atmospheric fraction* depends on time scale.**

$$\frac{dC}{dt} = -kC(t)$$

$$\Rightarrow C(t) = C_0\, e^{-kt}$$

“Spin-up” to “equilibrium”



- **Asymptotically reaching steady state.**
- **The steady-state pool size scales with τ.**

$$C^* = \tau I$$

"Spin-up" to "equilibrium"

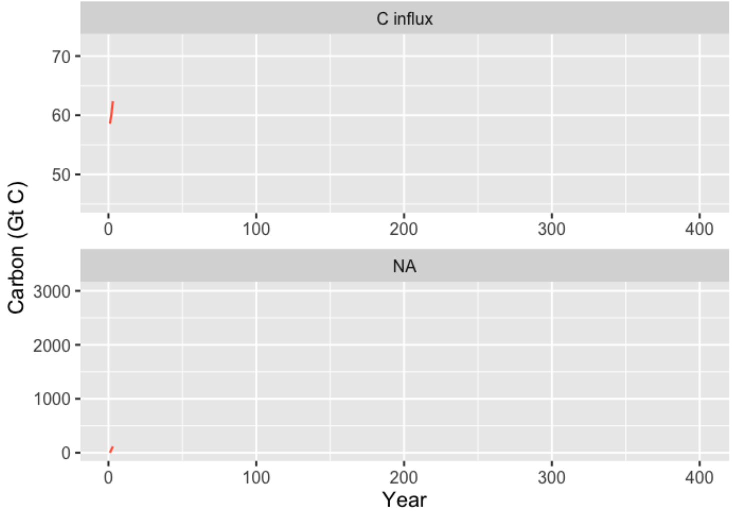
I = 60 + σ Gt C yr^{-1}

Terrestrial C storage

O

- 'Equilibrium' or 'steady state' is a concept used to describe a state where inputs and outputs, averaged over a time scale of characteristic length, tend to be equal.
- Trees don't grow into the sky and neither does the soil.

$$\lim_{t \to \infty} \frac{x(t) - x(t=0)}{t} = 0$$



Carbon cycle "elements" that don't reach equilibrium at a millennial time scale

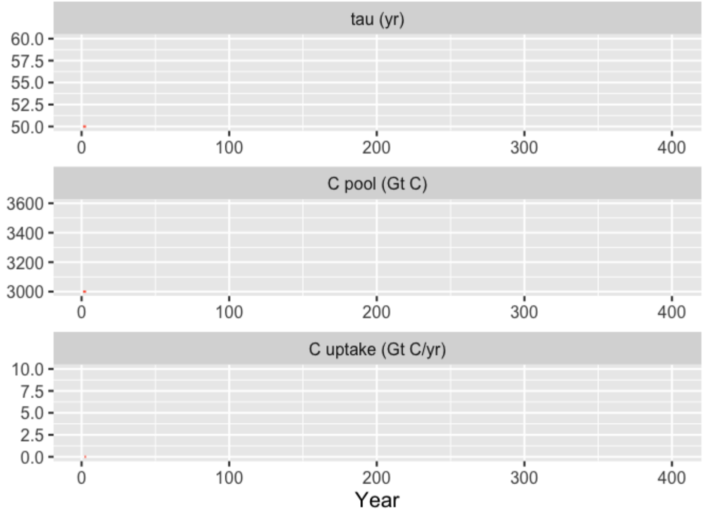
- Carbon stored in peat soils
- Permafrost
- Yedoma
- Sediments in aquatic systems

Step increase of residence time

I

Terrestrial C storage
τ increasing from 50 yr to 60 yr

O



- **Planting trees induces a temporary sink.**
- **Deforestation has the opposite effect.**

Controls on GPP

- Diffusion across the leaf surface (through stomata)
  Fick's Law

$$A = g_s(c_a - c_i)$$

- g_s: stomatal conductance to CO_2
- c_a: ambient CO_2 concentration
- c_i: leaf-internal CO_2 concentration

- Biochemical rates
  Farquhar et al., 1980

$$A = \min(A_J, A_C)$$

$$A_J = \varphi I_0 \frac{c_i - \Gamma^*}{c_i + 2\Gamma^*}$$

$$A_C = V_{cmax} \frac{c_i - \Gamma^*}{c_i + K}$$

- A_C is the Rubisco-limited rate; V_{cmax} is the activity of the carbon-fixing enzyme, Rubisco
- A_J is the electron transport-limited rate; depending on absorbed photosynthetically active radiation (PAR, here I_0) and the intrinsic quantum efficiency of photosynthesis (≈ 0.093)
- Γ^* is the compensation point (increases with temperature)
- K is the effective Michaelis-Menten coefficient (depends on O_2, also increases with temperature)