Introduction to plant ecophysiology

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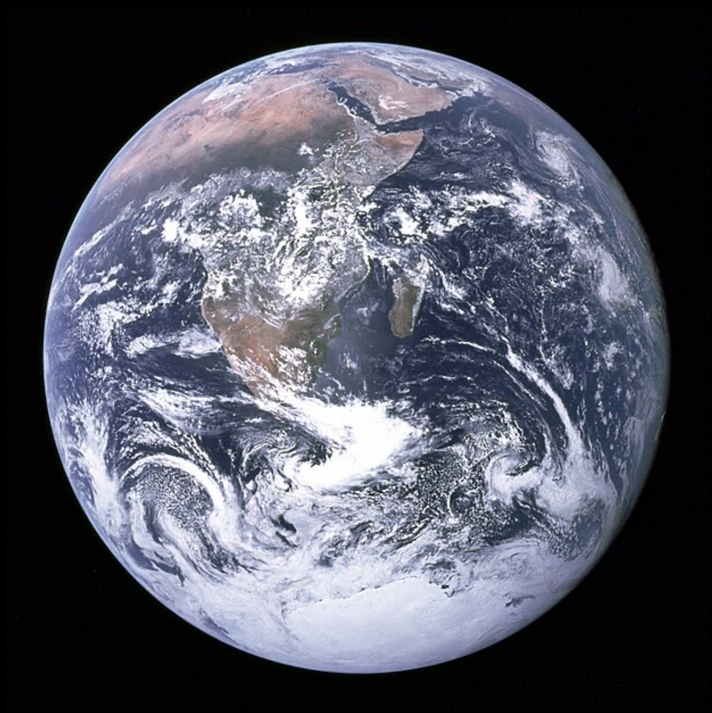
Photo: Alex Tunas, PERL

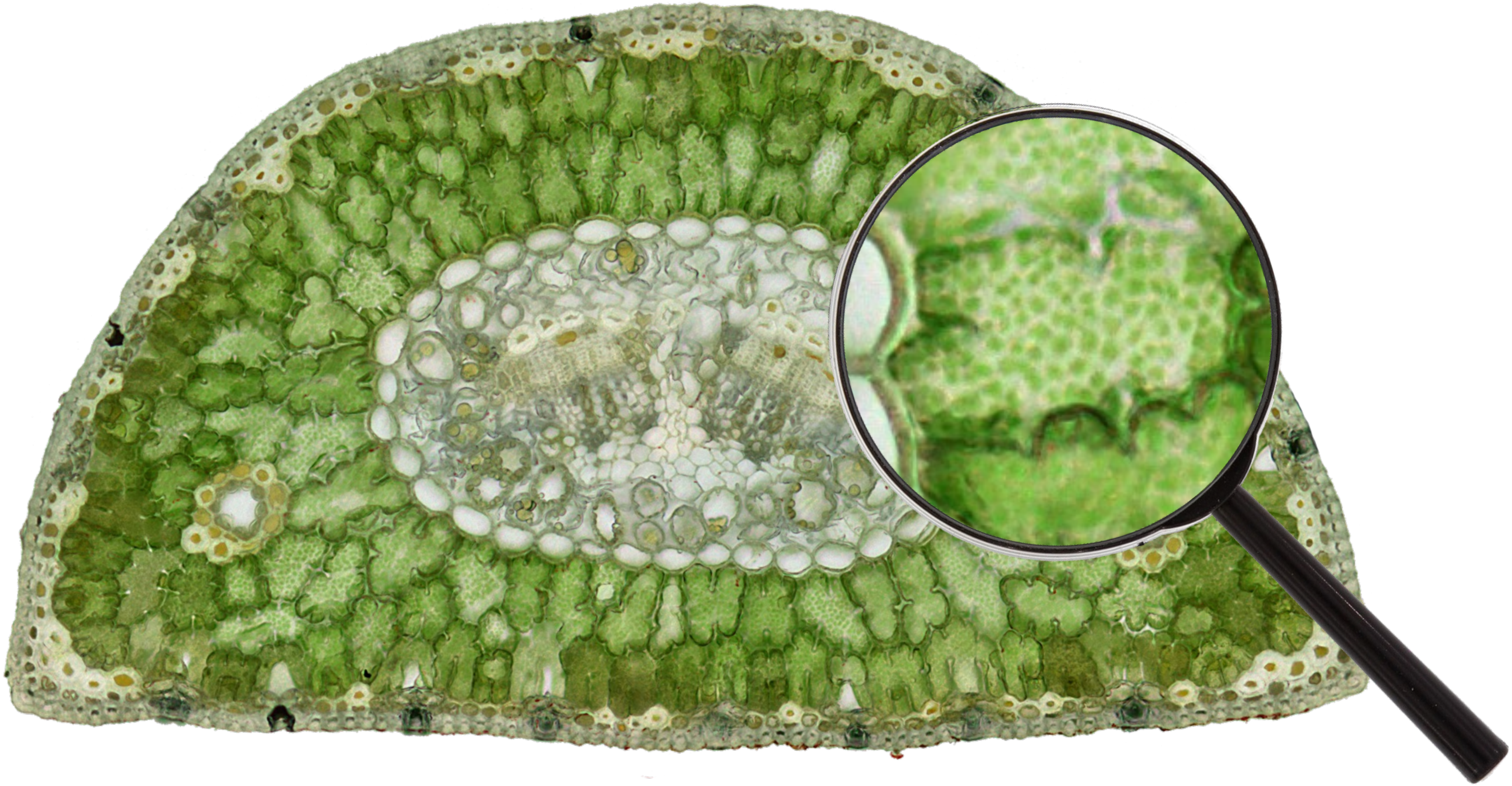
What has been the single most impactful event on this planet?



Oxygenic photosynthesis

Photo: Alex Tunas, PERL

Photosynthesis takes place in chloroplasts

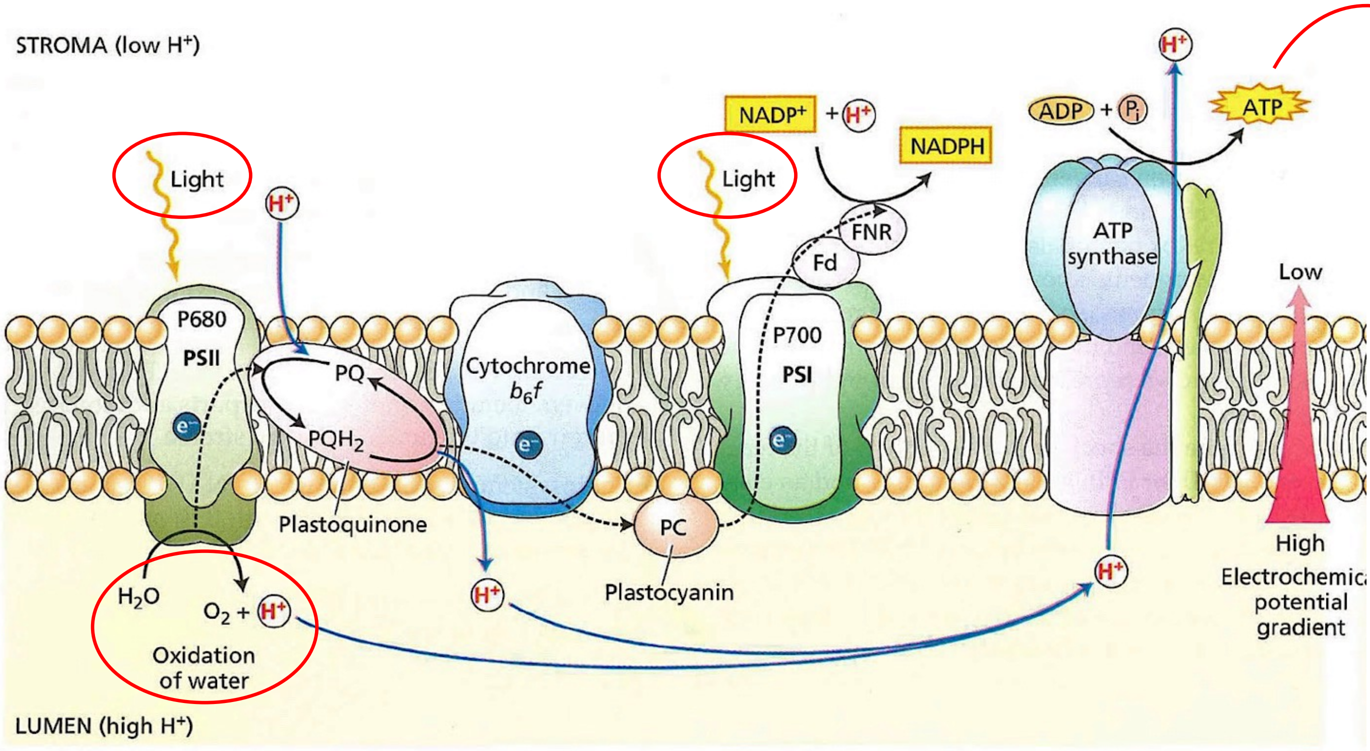


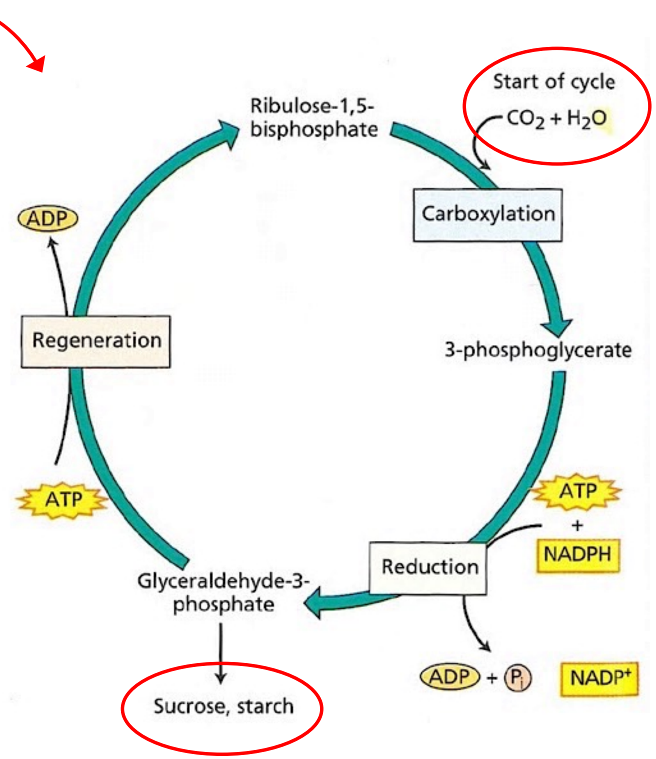
Photos: Mana Gharoun, Anouchka Perret-Gentil, Christoph Bachofen

Photosynthesis pathway

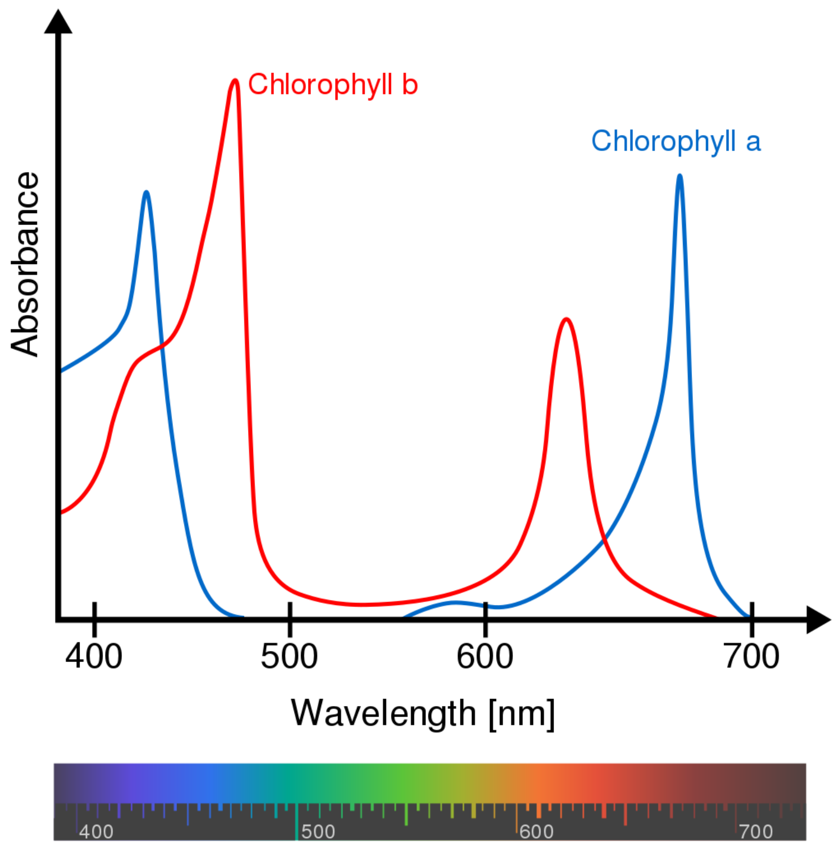
Light-dependent reaction:
photon uptake by chlorophyll

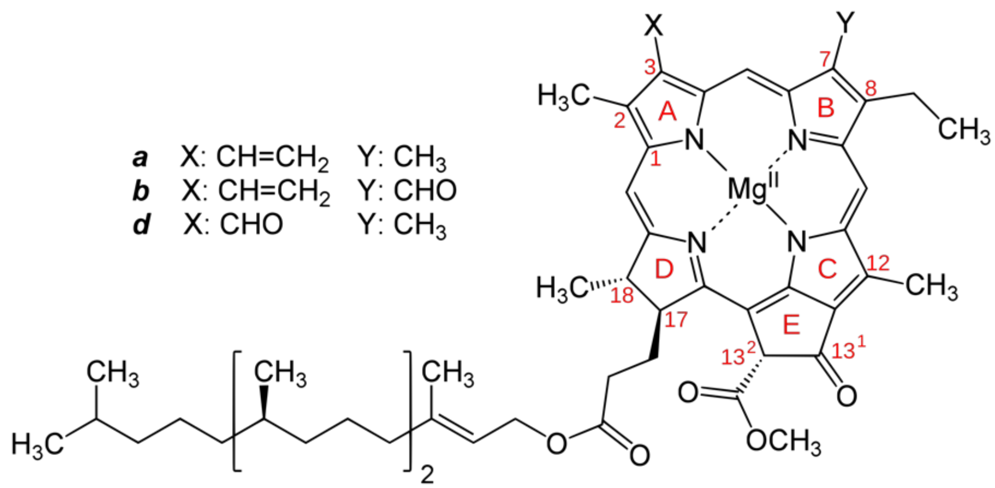
Light-independent reaction:
CO_2 fixation by RuBisCO





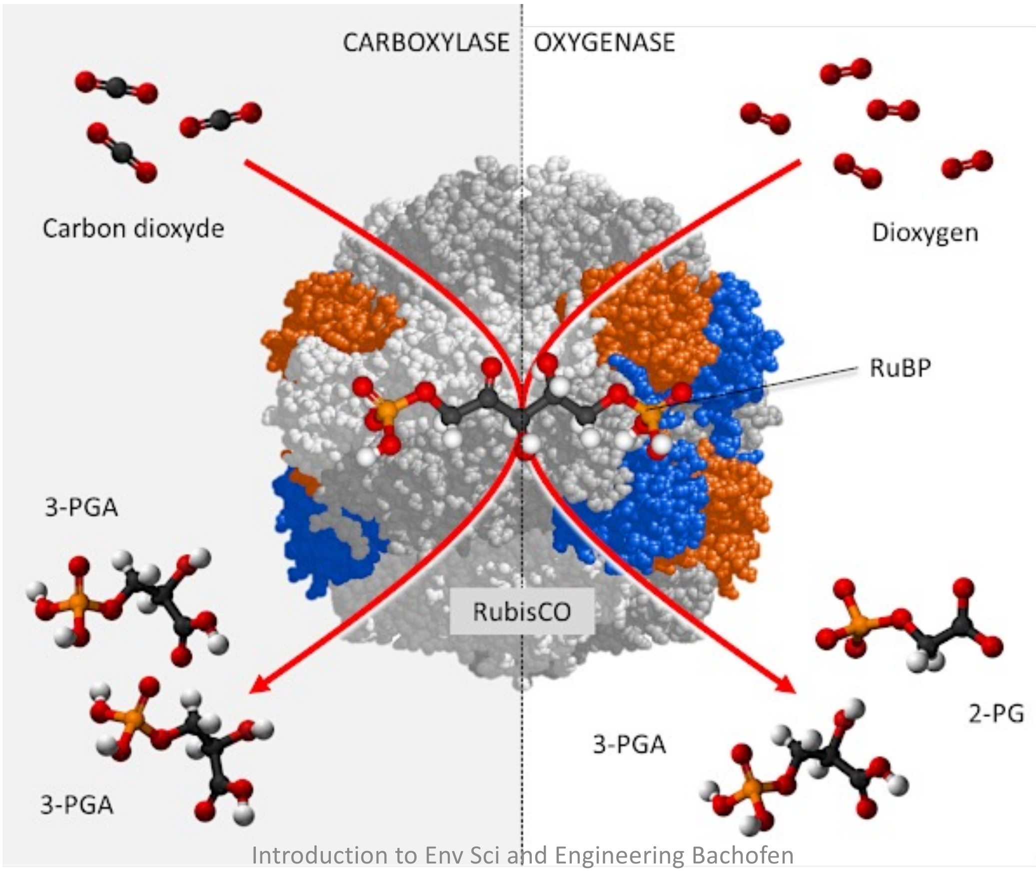
Light-dependent reaction with chlorophyll





Light-independent reaction with RuBisCO

RuBisCO is probably the most frequent protein on the planet

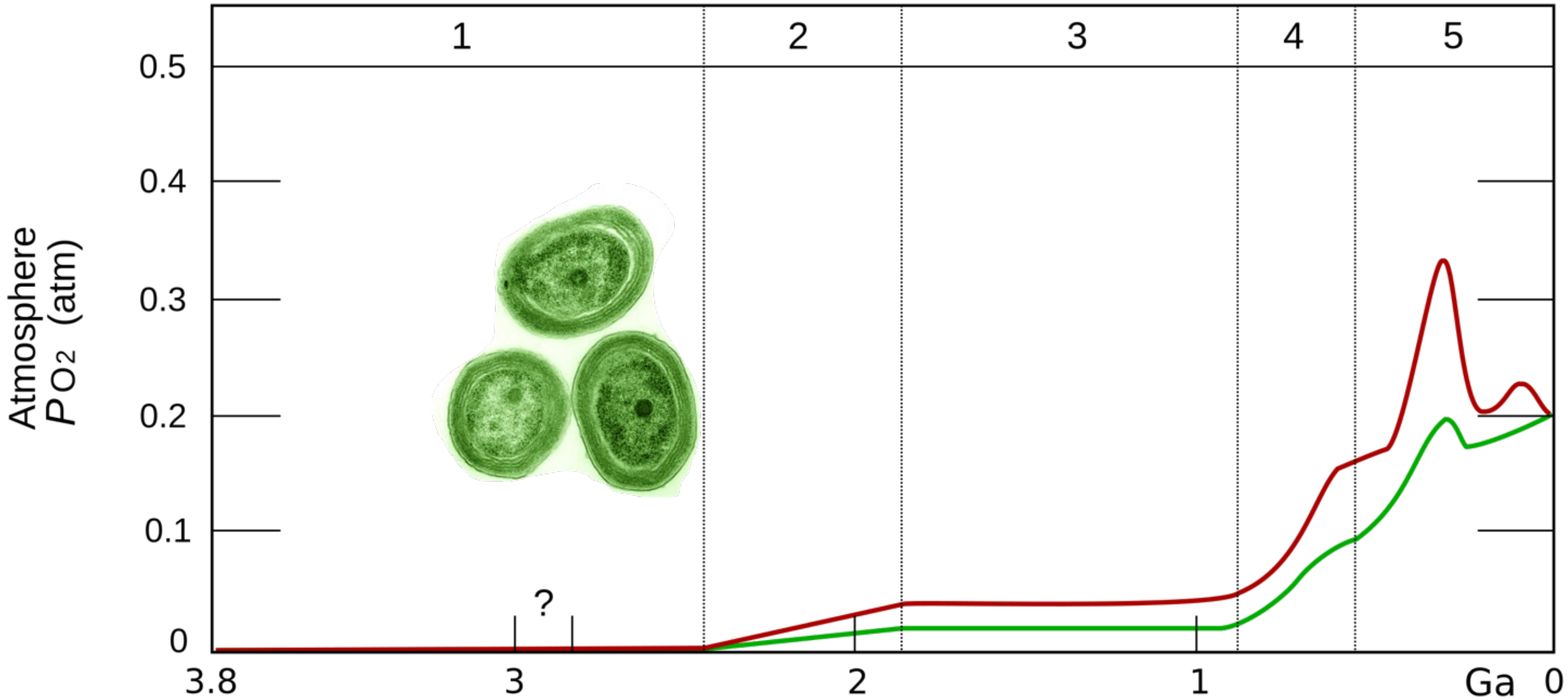


The great oxygenation event

Stromatolites at Shark Bay (Western Australia)

The great oxygenation event

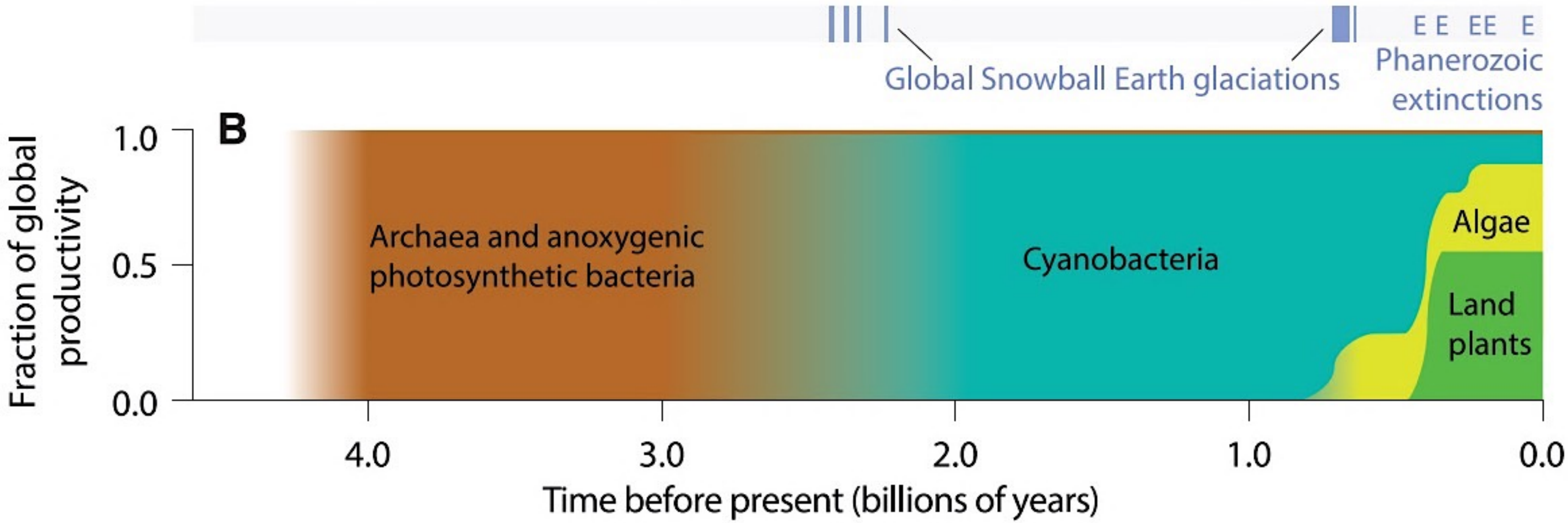
- ~ 2.4 billion years ago: O_2 in the atmosphere increases
- Reducing atmosphere → oxidizing atmosphere
- **~ 80 % of biosphere is extinct (most anaerobic bacteria)**



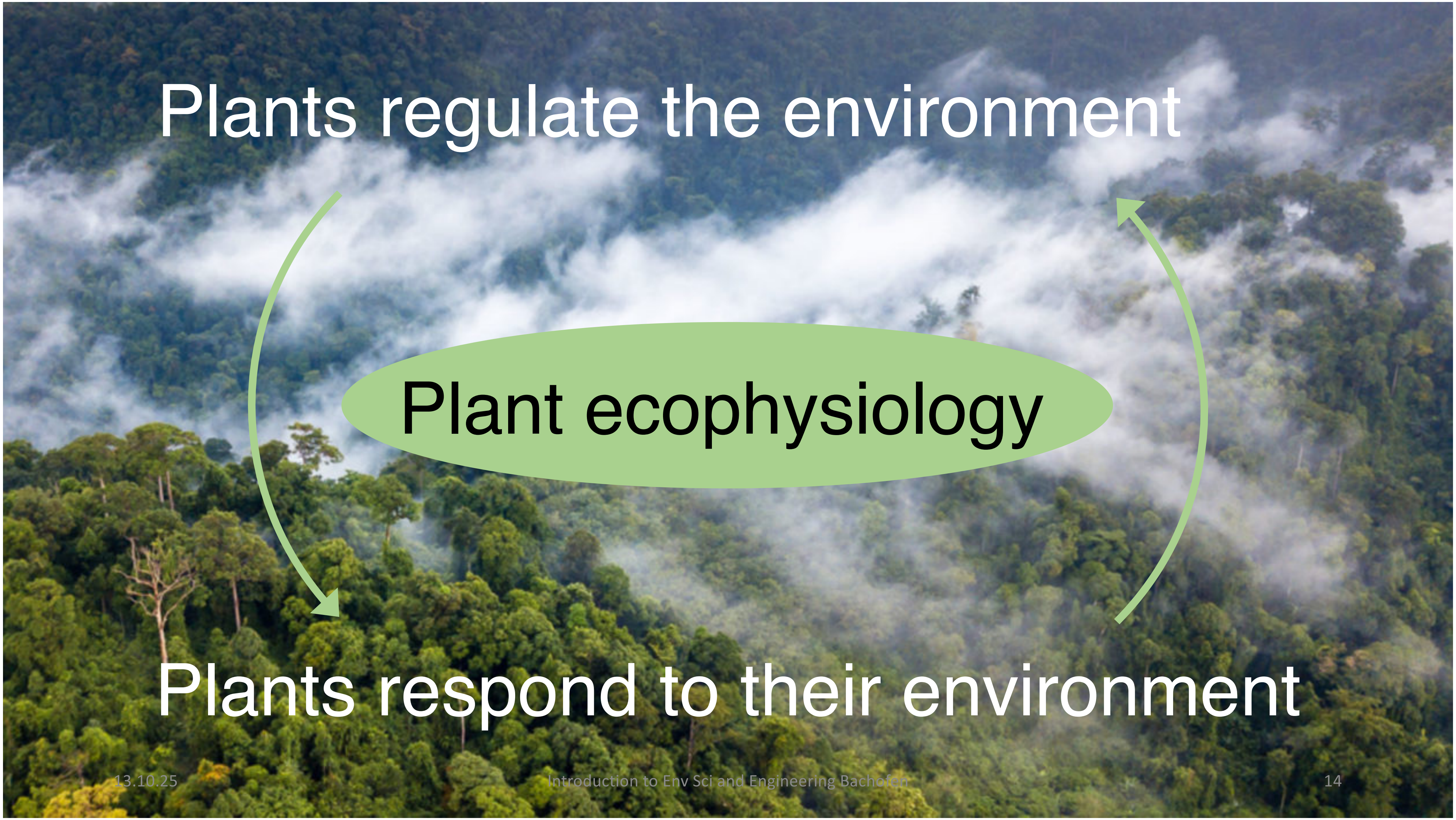
O_2 build-up in the atmosphere. Red and green lines represent the estimated range. Time is in billions of years (Ga).

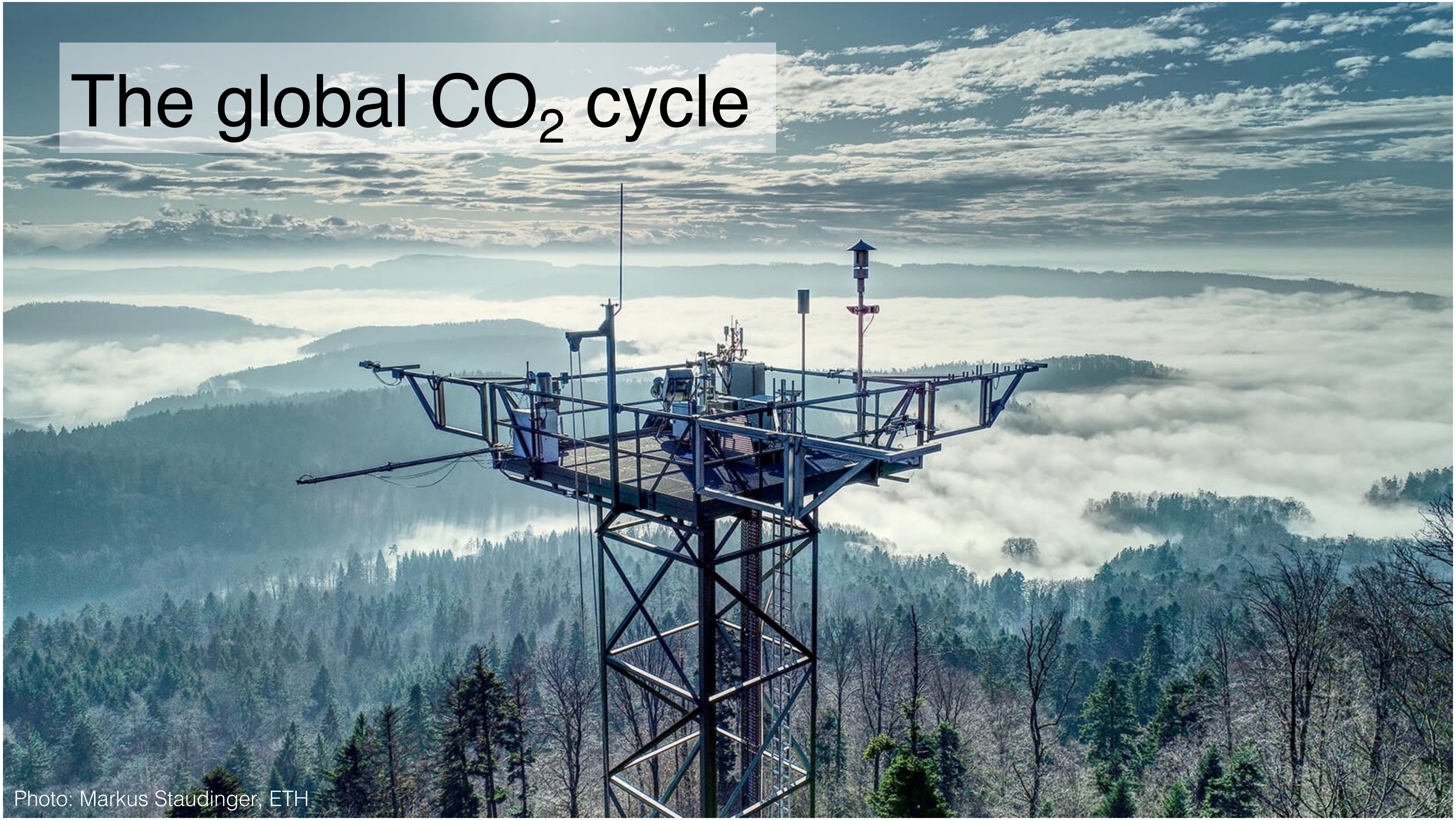
The great oxygenation event

Today, primary productivity is dominated by (1) terrestrial plants, (2) marine algae, (3) cyanobacteria.

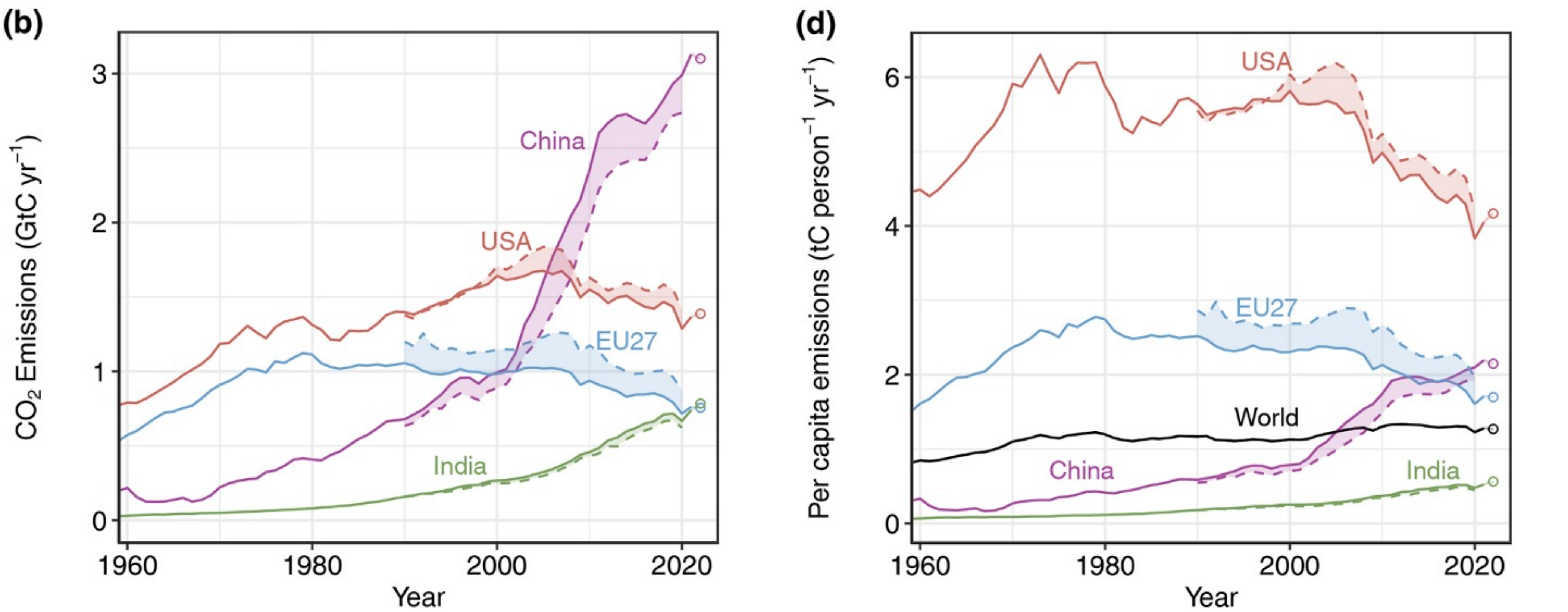


Crockford et al. 2023


Plants regulate the environment
Plant ecophysiology
Plants respond to their environment

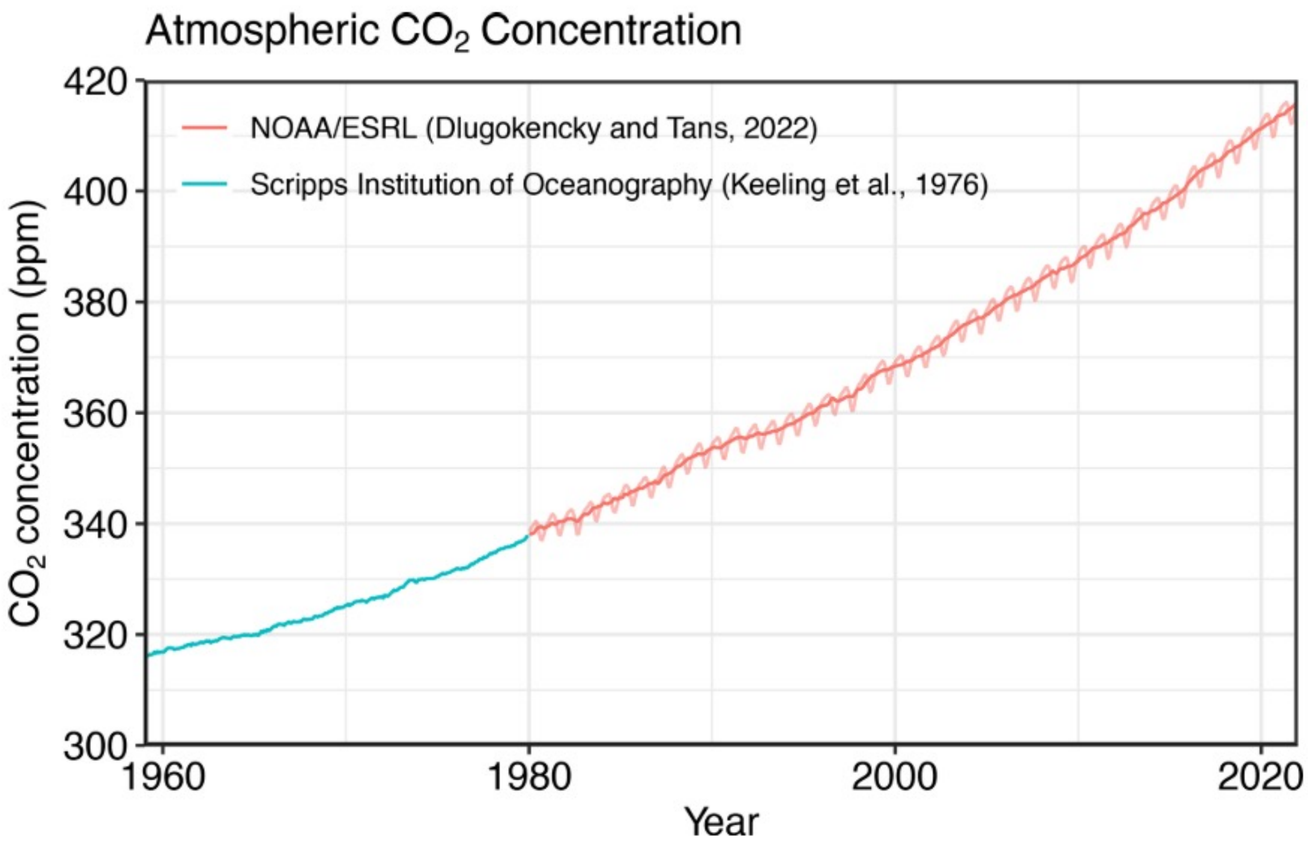

The global CO_2 cycle
Photo: Markus Staudinger, ETH

CO_2 emissions



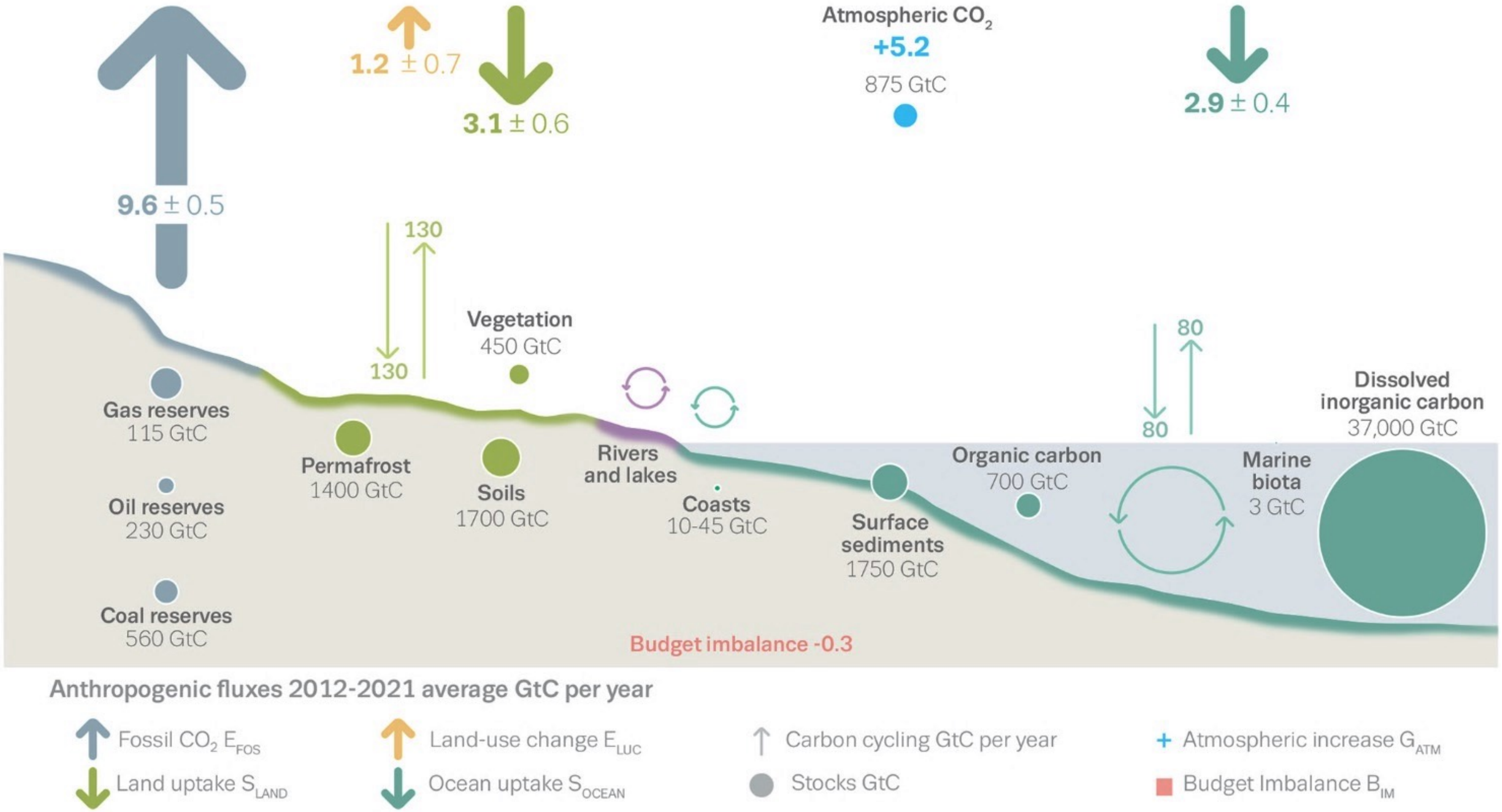
 Friedlingstein et al. 2022

CO_2 accumulation in the atmosphere



Friedlingstein et al. 2022

Global CO_2 cycle



Friedlingstein et al. 2022

Global carbon pools

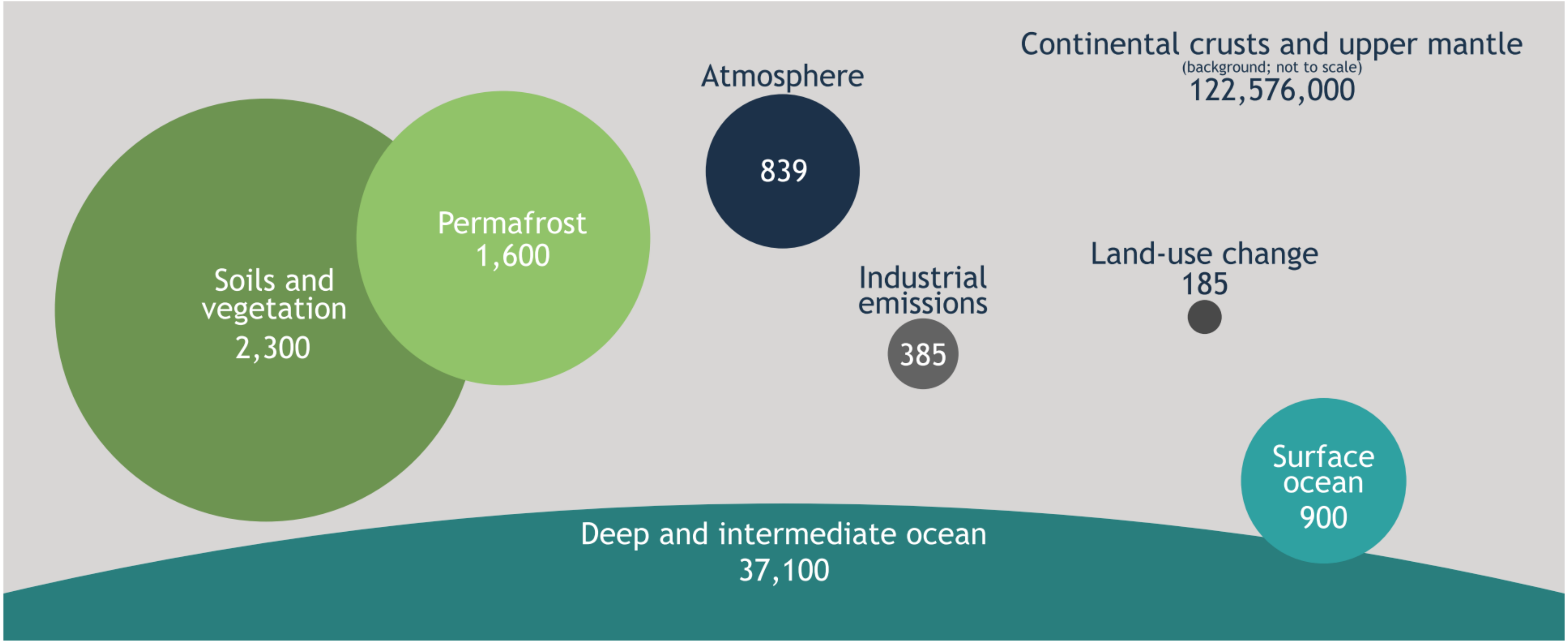


Figure 1. Global carbon stocks (carbon stored in pools), shown in gigatons.

Janowiak et al. 2017

Carbon pools in forests

Biome	Area (10^6 km^2)	Global Carbon Stocks (Gt C) Vegetation	Soils	Total	NPP (t C ha^{-1} yr^{-1})
Tropical forests	17.6	212	216	428	11.0 (5.0-17.5)
Temperate forests	10.4	59	100	159	6.3 (2.0-12.5)
Boreal forests	13.7	88	471	559	4.0 (1.0-7.5)
Tropical savannas	22.5	66	264	330	4.5 (1.0-10.0)
Temperate grasslands	12.5	9	295	304	3.0 (1.0-7.5)
Deserts & semideserts	30.0	8	191	199	0.05 (0.0-0.1)
Tundra	9.5	6	121	127	0.1 (0.0-0.4)
Wetlands	3.5	15	225	240	0.9 (0.1-3.9)
Croplands	16.0	3	128	131	1.6 (0.2-3.9)
Total	**135.6**	**466**	**2011**	**2477**	

	Forests	Rest of terrestrial biomes
Global terrestrial organic carbon stock (soil + vegetation)	46%	54%
Global terrestrial NPP*	65%	35%

*net primary production

Dixon et al. (1994) Science

Carbon pools in forests

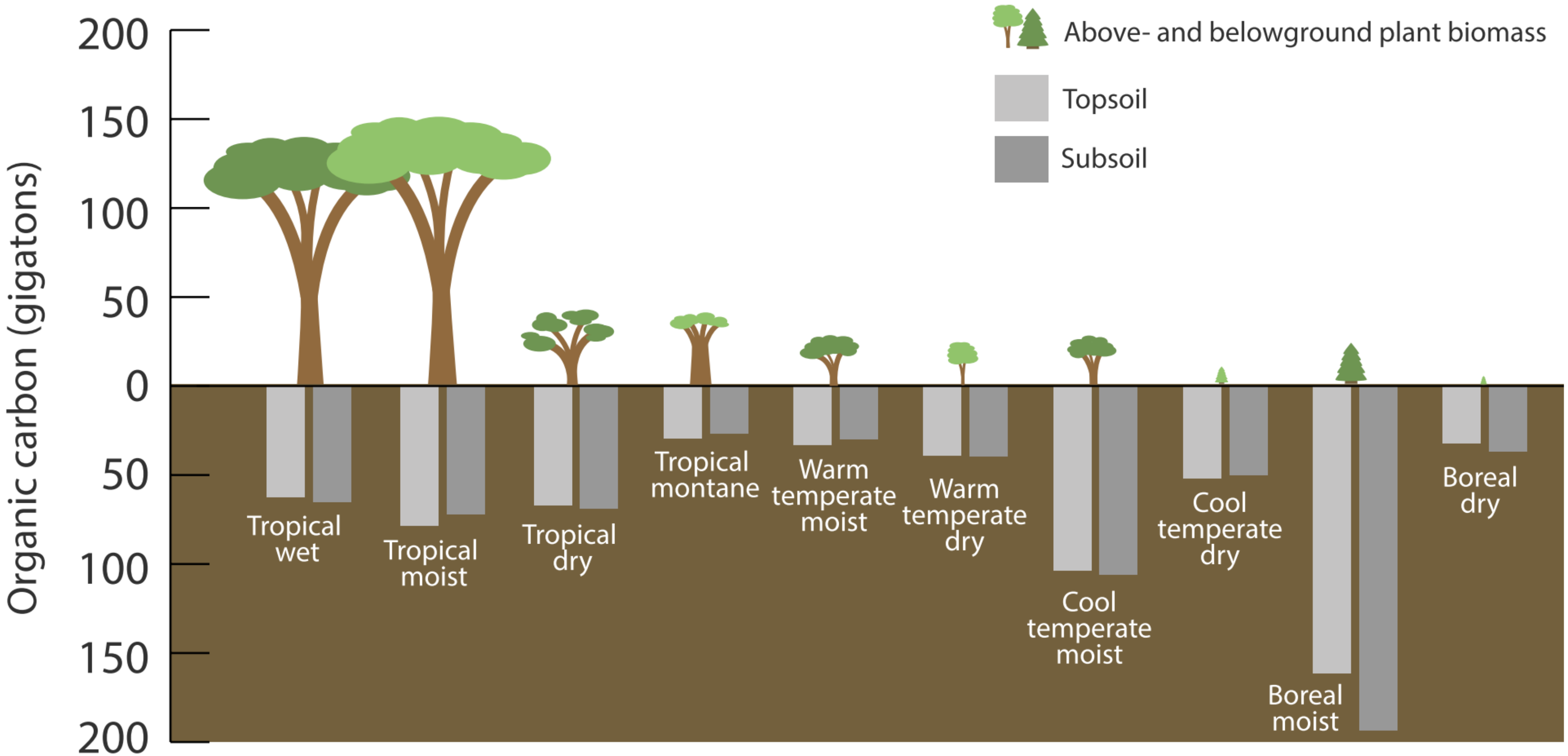


Figure 2. Carbon stored in ecosystems, shown in gigatons. Data from Scharlemann et al. (2014).

Janowiak et al. 2017

Global carbon fluxes

- CO_2 moves from the atmosphere to land through photosynthesis.
- CO_2 moves from land back to the atmosphere through plant and soil respiration, litter decomposition, and fires.
- Fluxes are typic[...] stocks
- Small shifts in global fluxes have a profound effect on the global carbon cycle (e.g. climate change)

Land ecosystems are absorbing ca. 25–30% of the annual anthropogenic CO_2 emissions

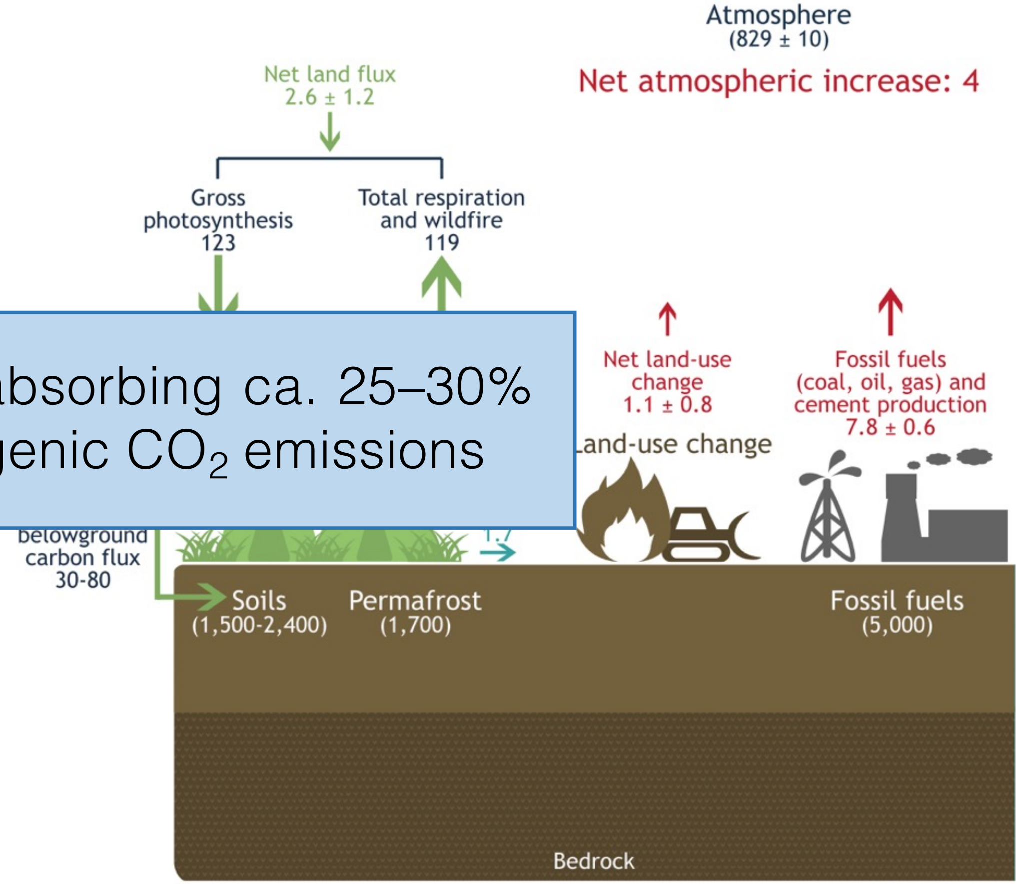


Figure 4. Global carbon cycle. Carbon (Gt C) stocks are denoted in parentheses and shown year) are associated with arrows and shown in gigatons per year.

Janowiak et al. 2017

Forest CO_2 cycle

Carbon uptake (net ecosystem production) by forests varies by forest type:

- Tropical forests have high uptake: 6.6 Mt C per hectare per year
- Temperate forests 4.4 Mt C per hectare per year
- Boreal forests 2.8 M

Difference in fluxes a

- Temperature and m
- Soil nutrient availability
- Forest age: young forests have low net CO_2 uptake, middle- stage stands have the highest net CO_2 uptake

Forests are major contributors to the terrestrial C sink and account for ca. 90% of the terrestrial biomass and about half of terrestrial net ecosystem production

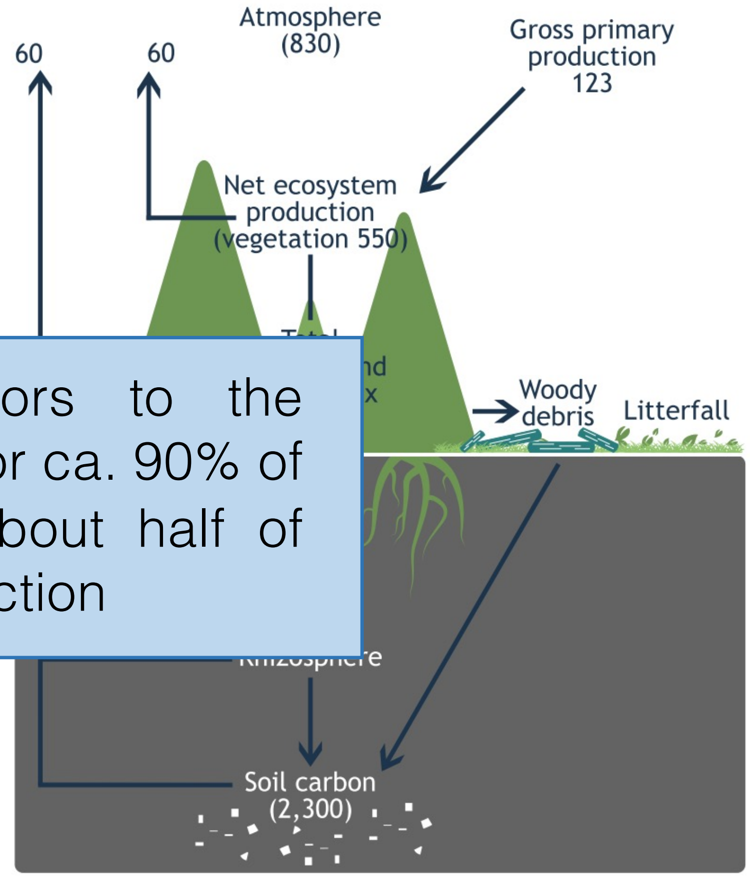


Figure 5. A depiction of the forest carbon cycle including both aboveground and belowground storage and flux terms. Carbon (Gt C) stocks are denoted in parentheses and shown in gigatons. Fluxes (Gt C per year) are associated with arrows and shown in gigatons per year.

Janowiak et al. 2017

Turnover rates of forest CO_2

- **Flux** = Amount of carbon that enters or leaves a stock
- **Turnover** = Rate at which carbon flows through a stock
- C turnover depends on climate, soil, vegetation type
- C turnover gives an idea of where it might be most vulnerable to be released as CO_2 to the atmosphere

- Tropical forests contain a lot of aboveground carbon, but it does not stay in the forest very long (turnover: 14 years) due to high decomposition rates and low soil carbon storage
- The biomes with extreme climates or those that are very dry have the longest turnover times (e.g., 66 years on average in tundra ecosystems)

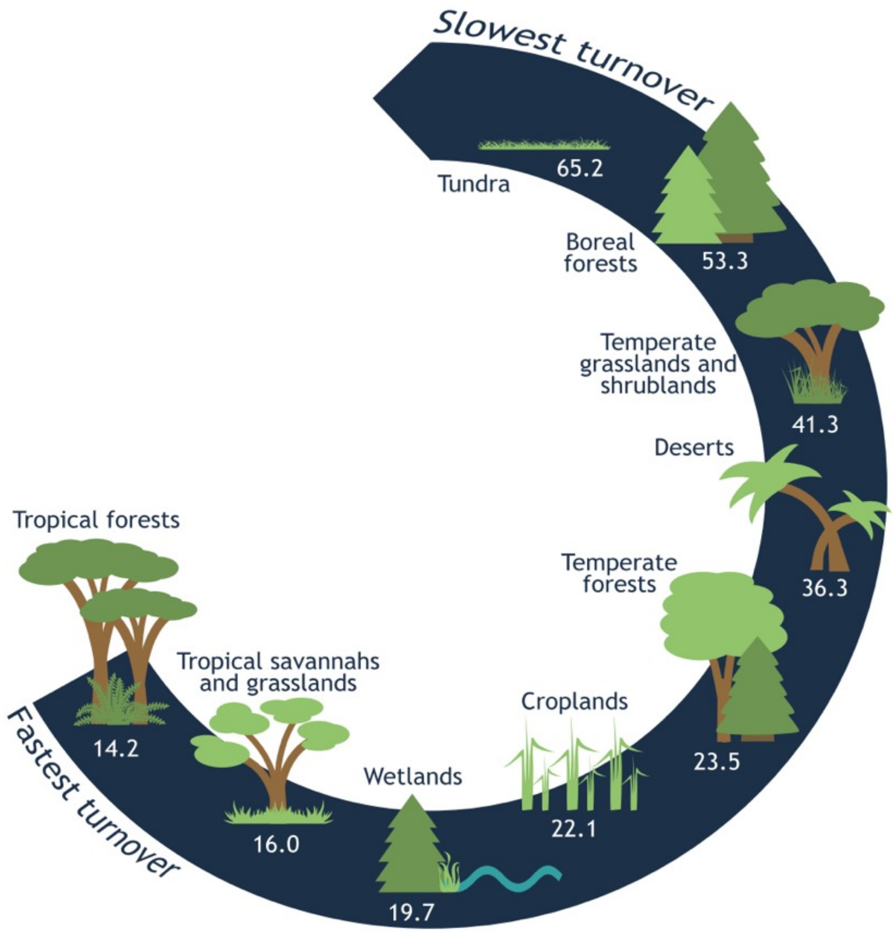
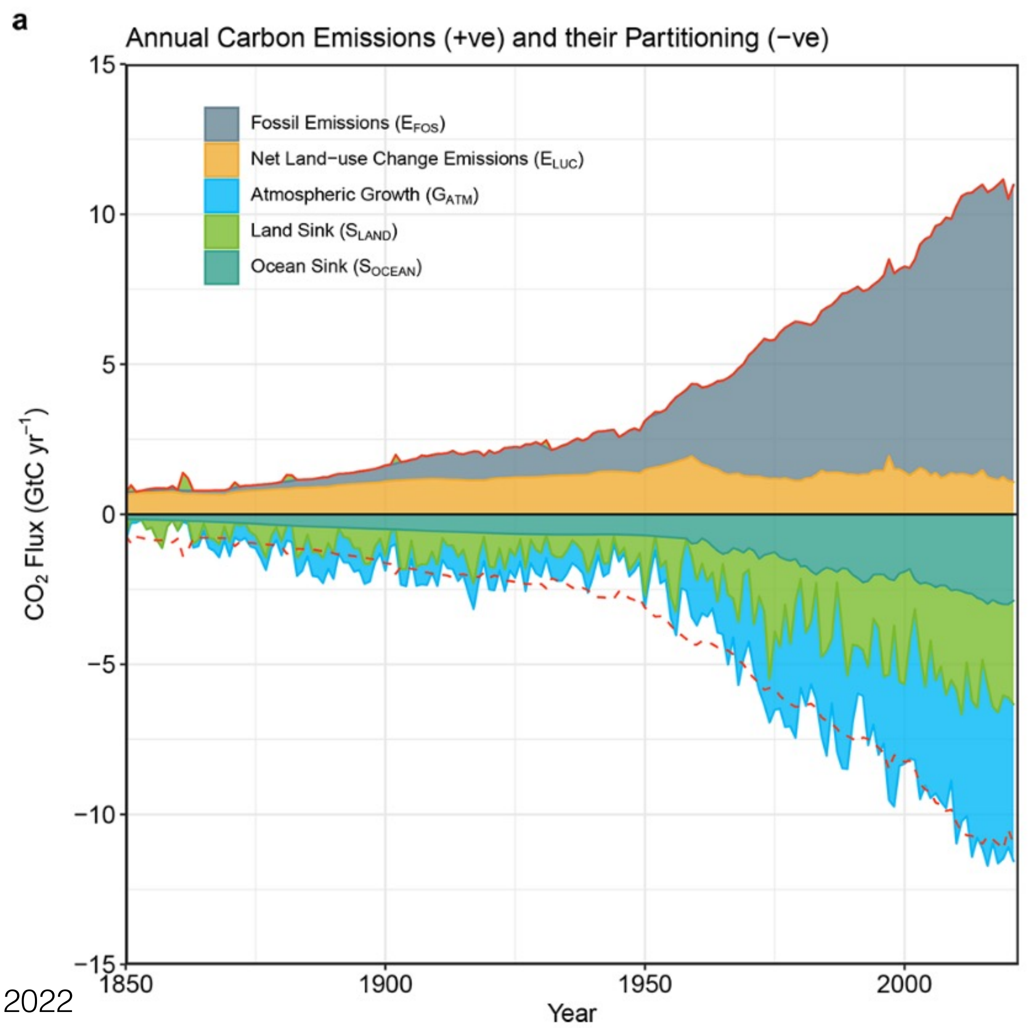


Figure 3. Average ecosystem turnover times (years) of different terrestrial carbon pools.

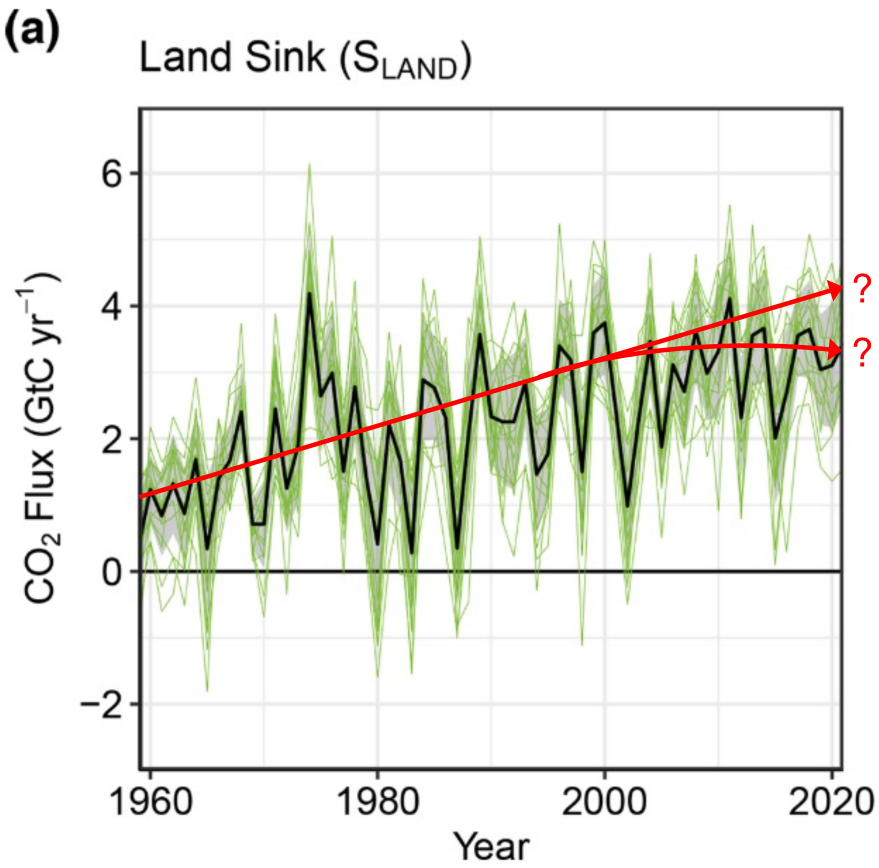
Janowiak et al. 2017

Global carbon fluxes



Friedlingstein et al. 2022

Land CO_2 sink



- Fertilization of plants by CO_2 and N inputs
- Lengthening of the growing season
- Global burned area has declined over the past decades (with local exceptions)
- The increase in land carbon sink has remained broadly constant over the last 6 decades

How do we measure CO_2 fluxes?

- Leaf gas exchange measurements: CO_2 and H_2O fluxes under controlled conditions in a cuvette
- Ecosystem gas exchange measurements: "eddy covariance" measurements of CO_2 and H_2O

Eddy covariance technique

Troposphere

Air masses
transporting CO_2

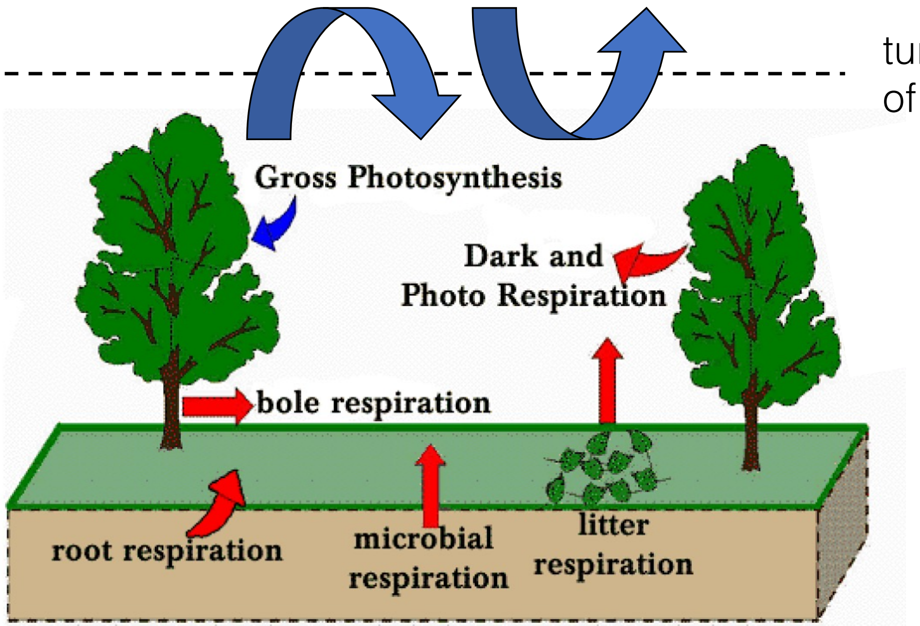
surface boundary layer

Mass transport

Wind direction
Windspeed

Concentration

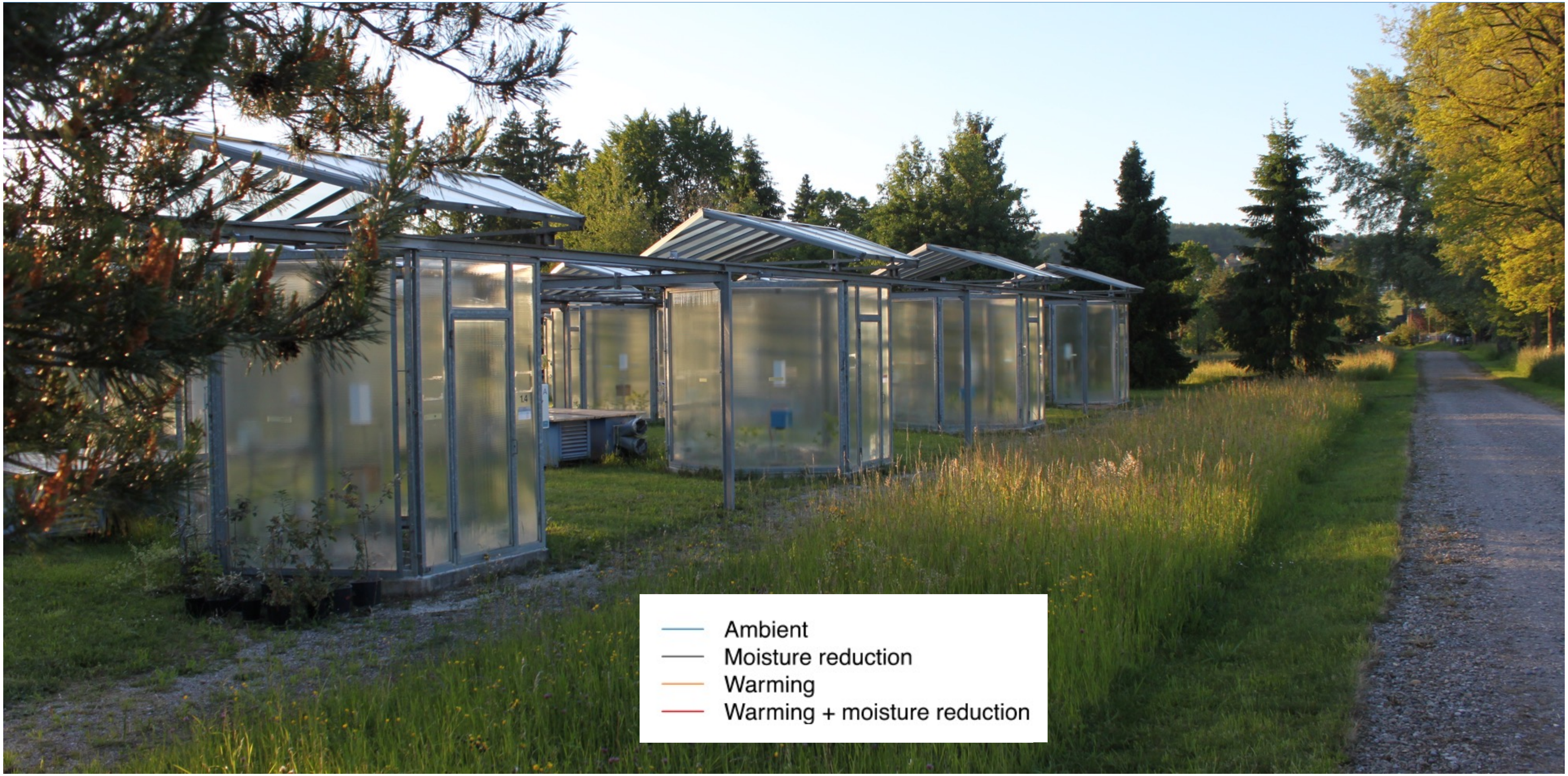
$[CO_2]$



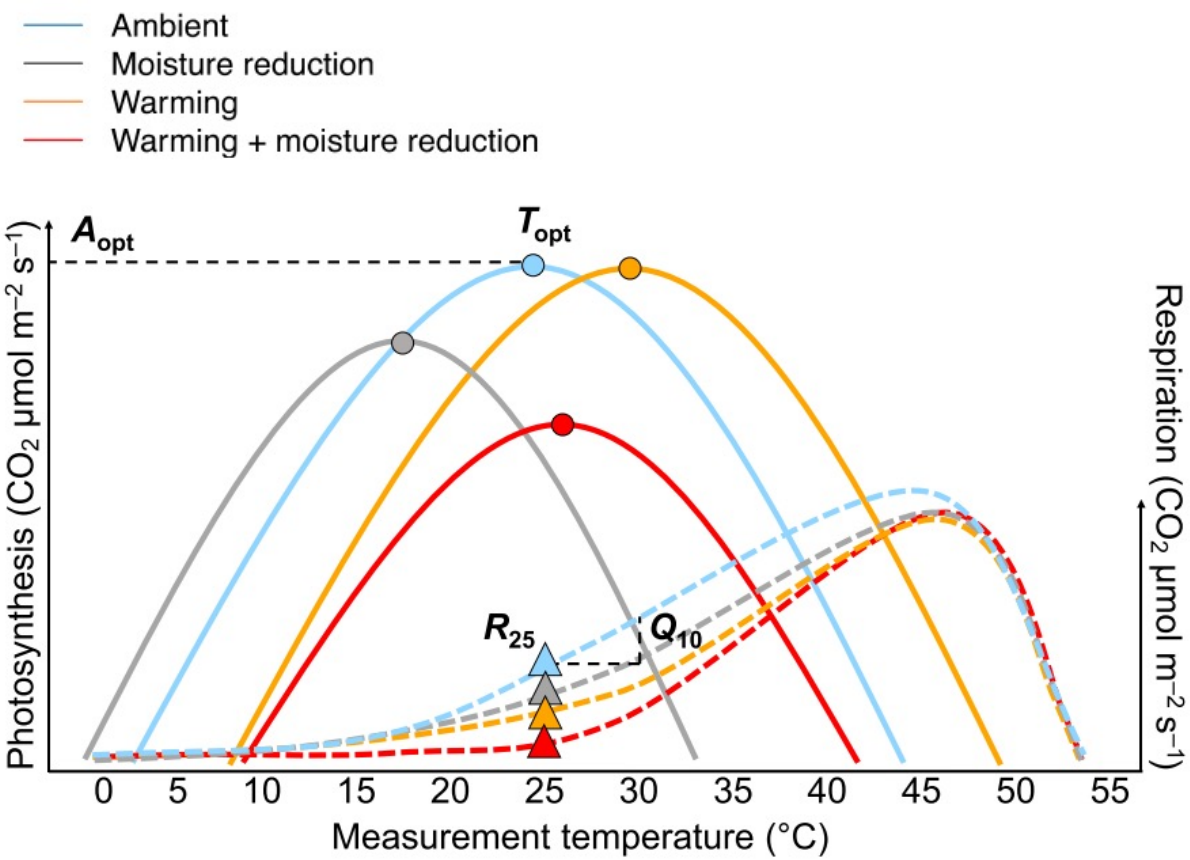
turbulent exchange
of air masses

Figure 6 Flows of Carbon dioxide in and out of an ecosystem

Controlled greenhouse experiments

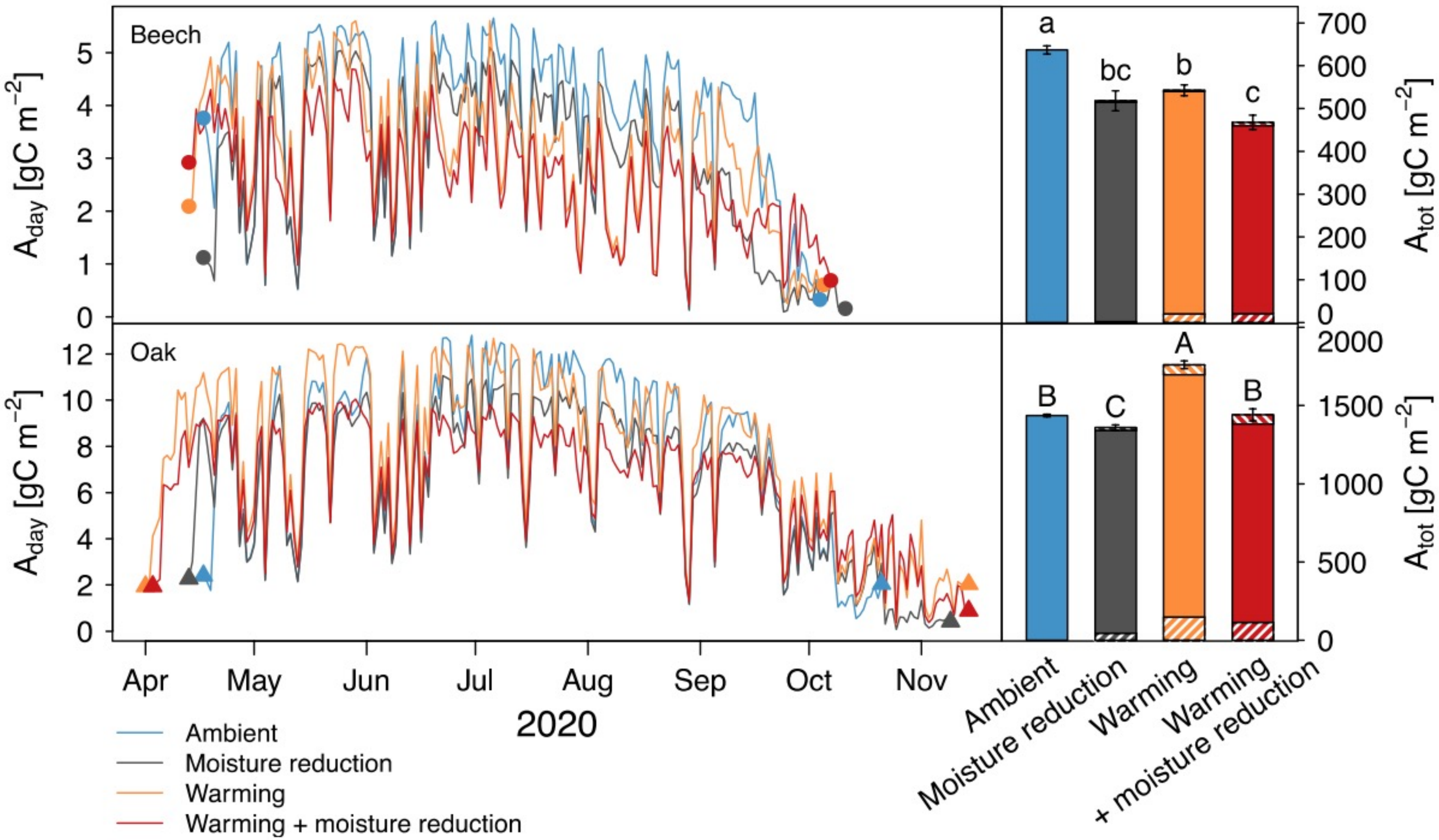


Leaf gas exchange measurements



Deluigi et al. 2025

Photosynthesis upscaling models

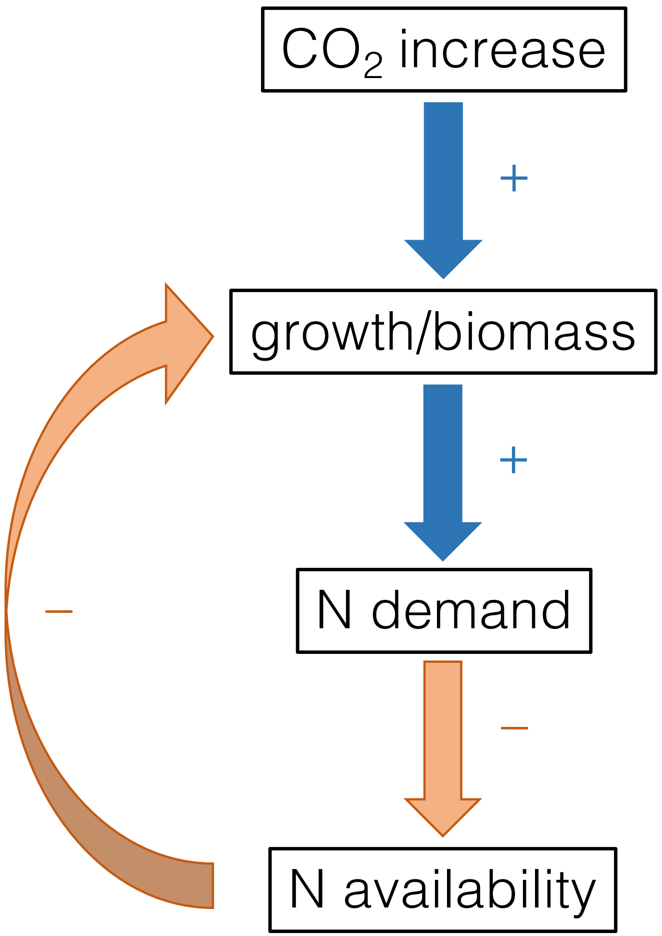


 Grossiord et al. 2022

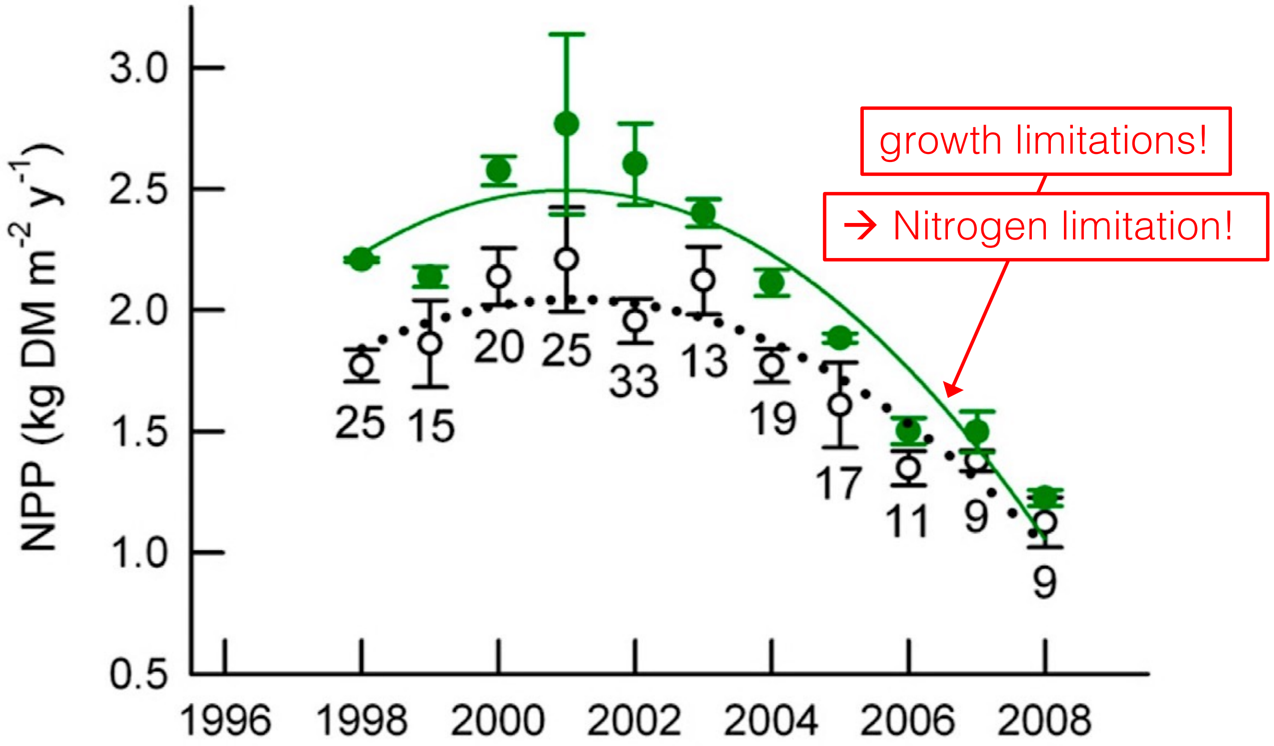
CO_2 fertilisation: FACE experiment

Free-Air CO_2 Enrichment (FACE): 550 ppm elevated CO_2

CO_2 fertilisation: FACE experiment



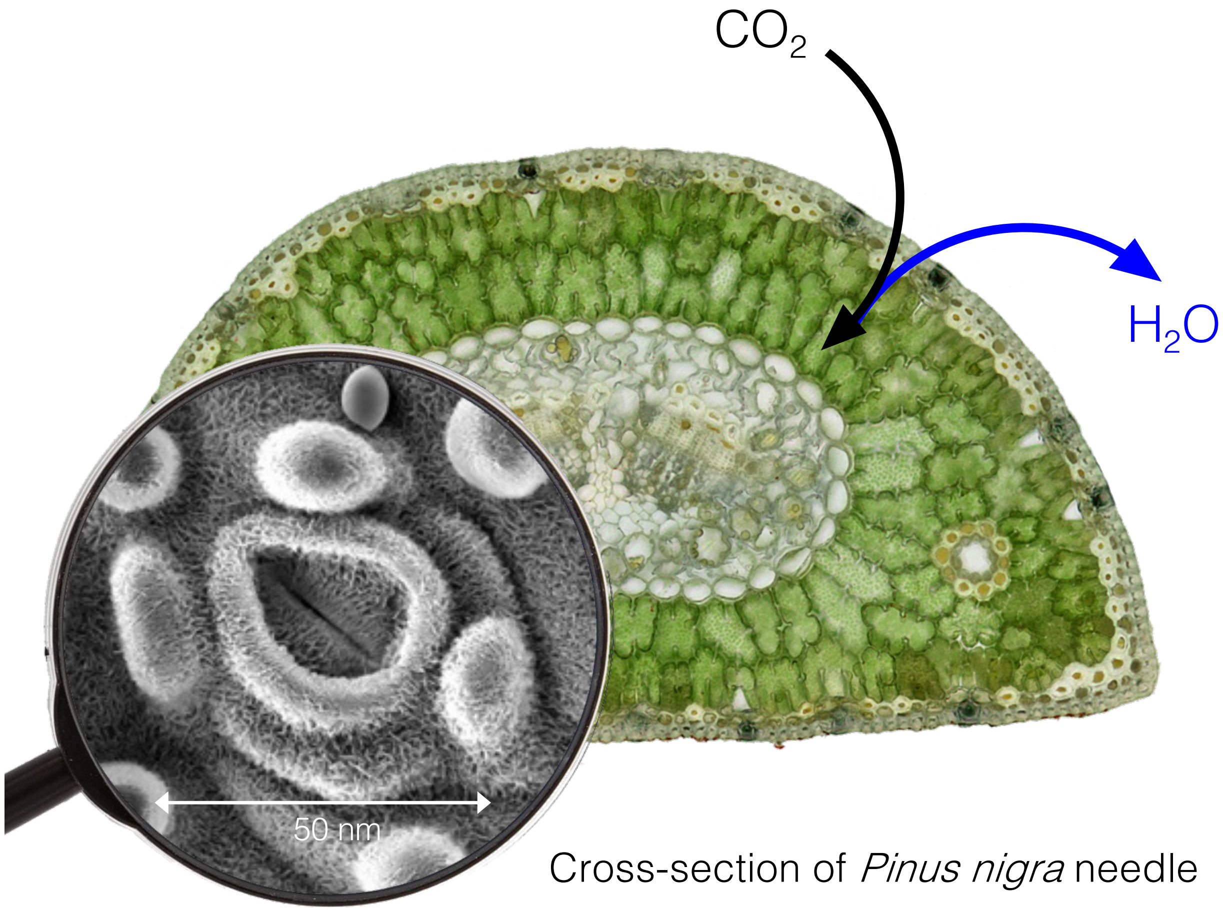
Free-Air CO_2 Enrichment (FACE): 550 ppm elevated CO_2



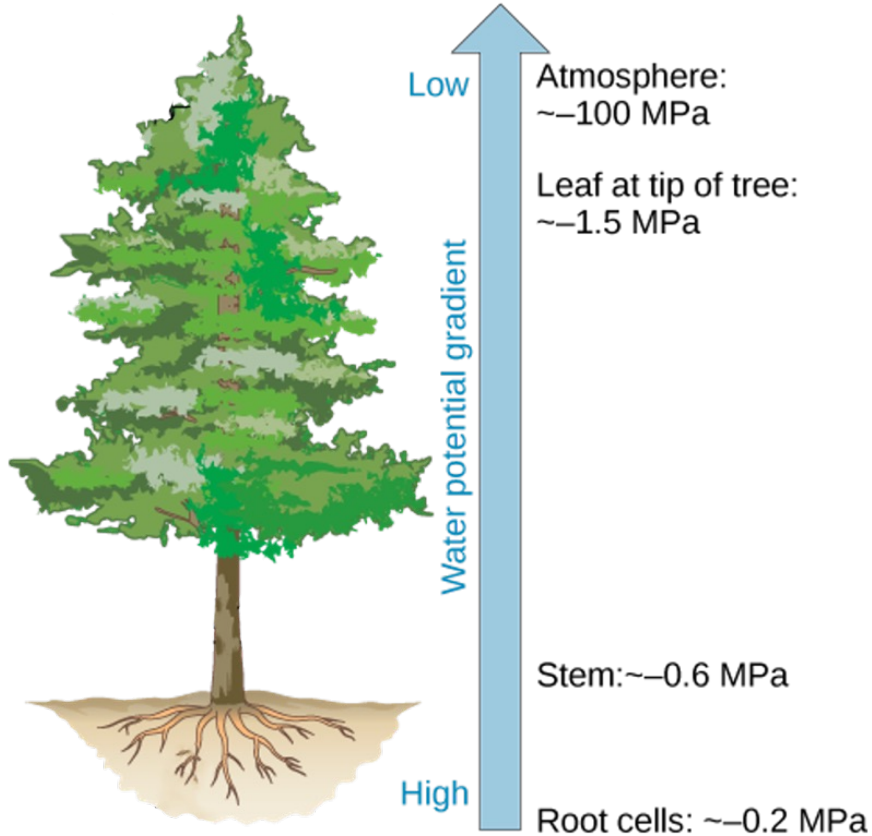
Norby et al. 2019 PNAS

Water use and transpiration

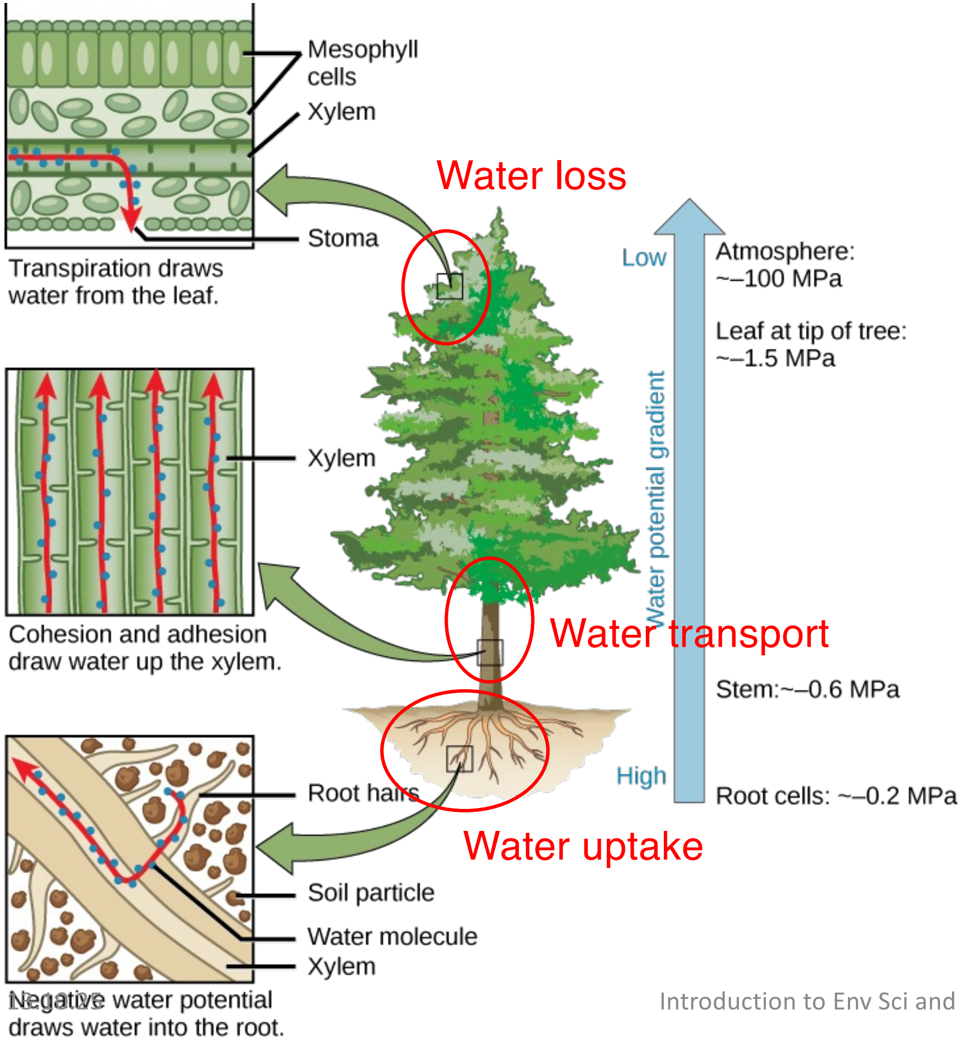
Tree water use



Cross-section of *Pinus nigra* needle



Photos: Mana Gharoun, Anouchka Perret-Gentil, Christoph Bachofen



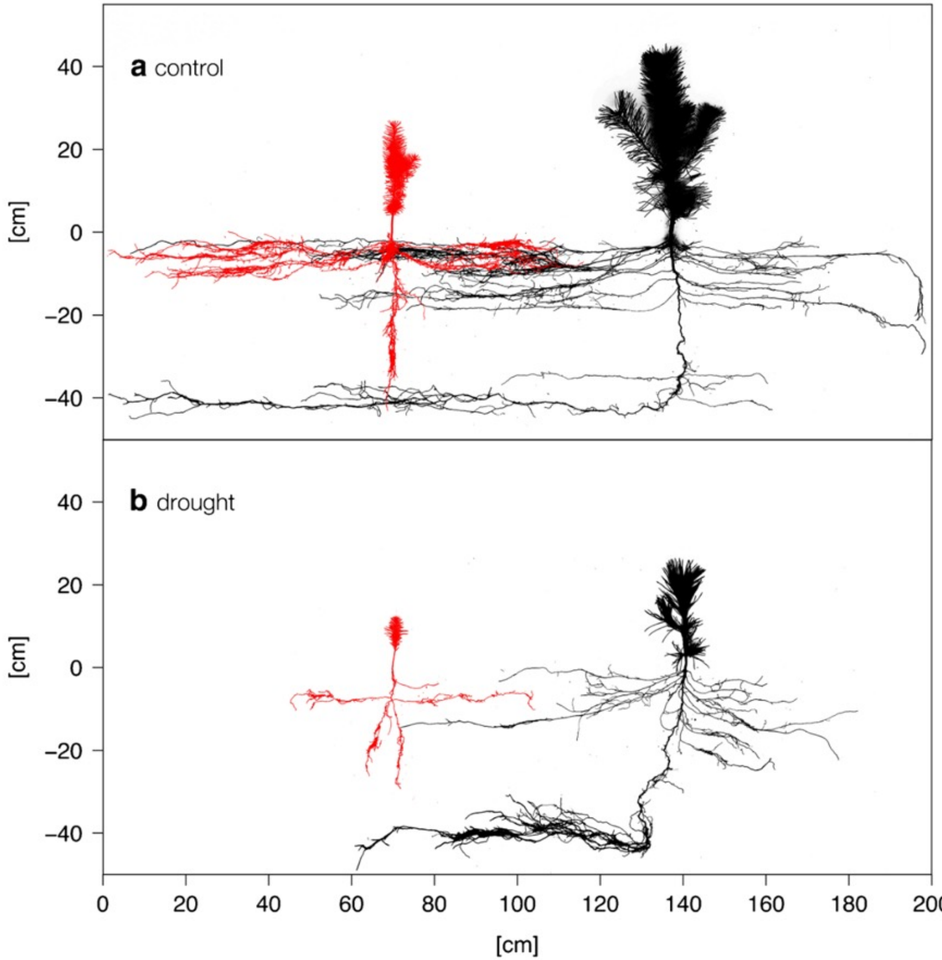
Cohesion-tension theory of water flow:

- Evaporation of water at the leaves creates a "negative pressure" (tension) in the plant's cells
- The tension propagates through the water conducting tissues (Xylem)
- At the roots the tension pulls the water out of the soil into the plant
- Dissolved nutrients in the soil (nitrate, ammonium, phosphates, etc.) are taken up with the water and transported to the cells that need them

Root research is hard!

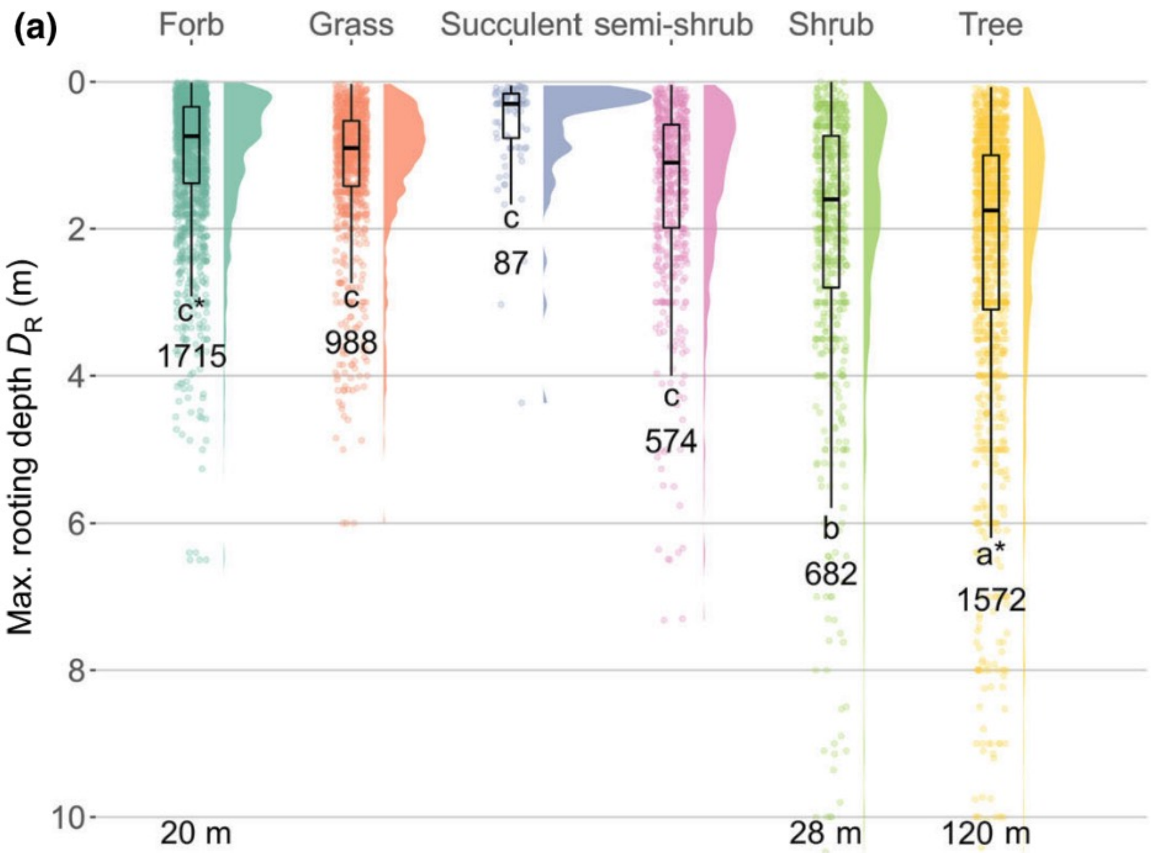
Dig out plants!

Bachofen et al. 2018



Moser et al. 2016

Tree water uptake: rooting depth

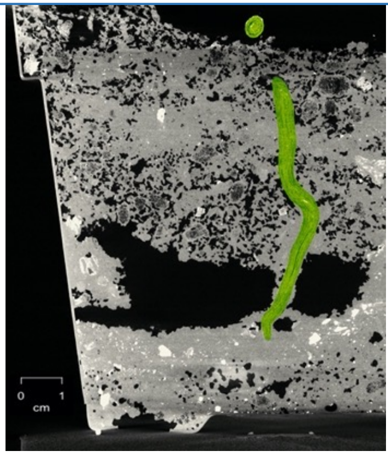


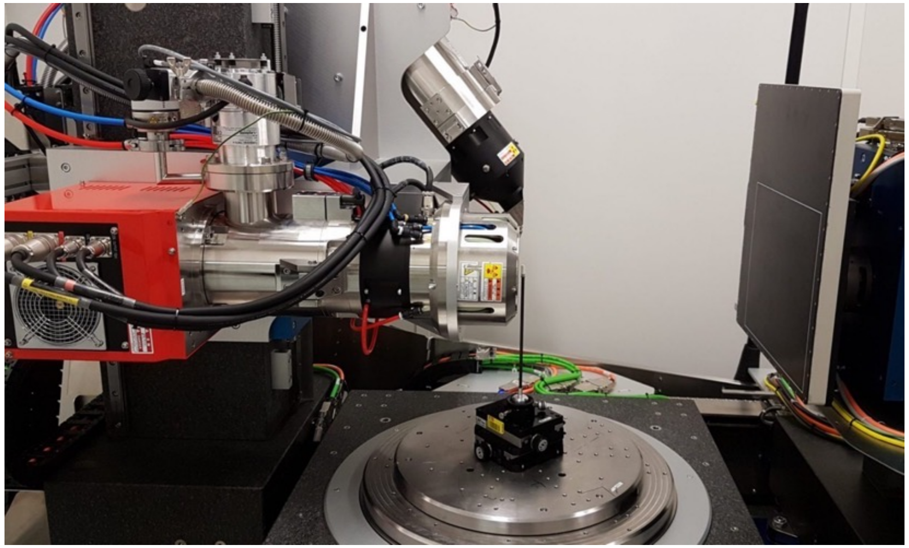
Root distribution is not tree water uptake, because:

- Not all roots found in the soil are physiologically active (take up water).
- Assigning roots to different species is almost impossible. Genetic analyses are very laborious and expensive.

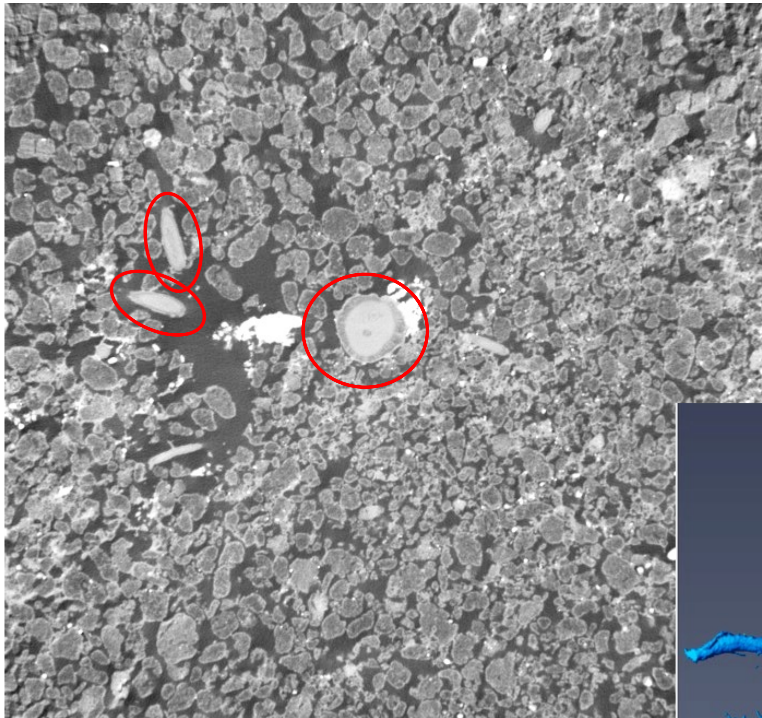
Tumber-Dávila et al. 2022

Root research is hard!

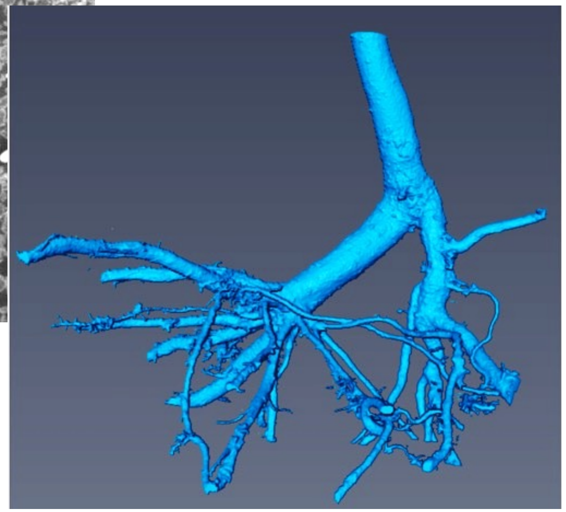




Micro-CT scan (X rays) of a spruce growing in perlite substrate

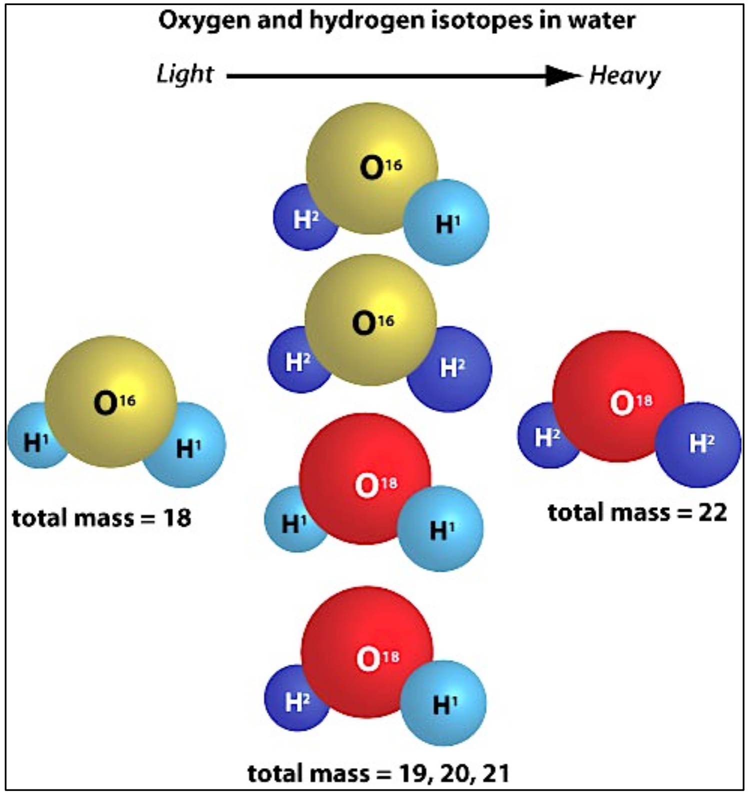


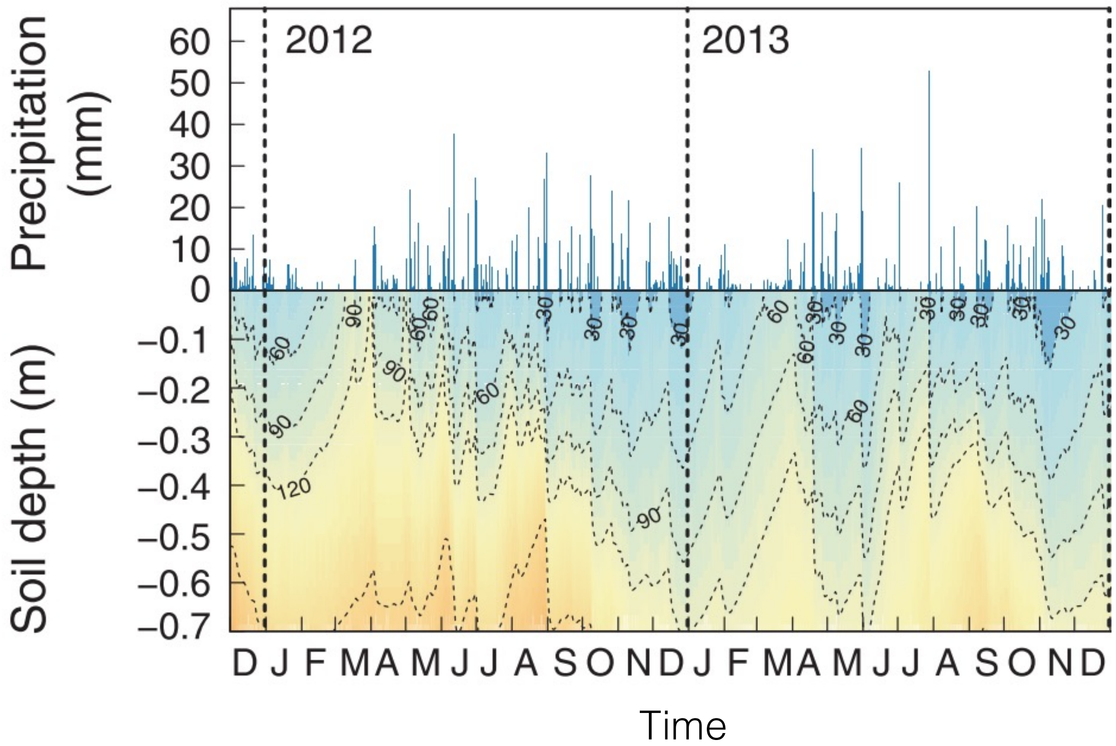
Van der Meer 2020



Root research is hard!

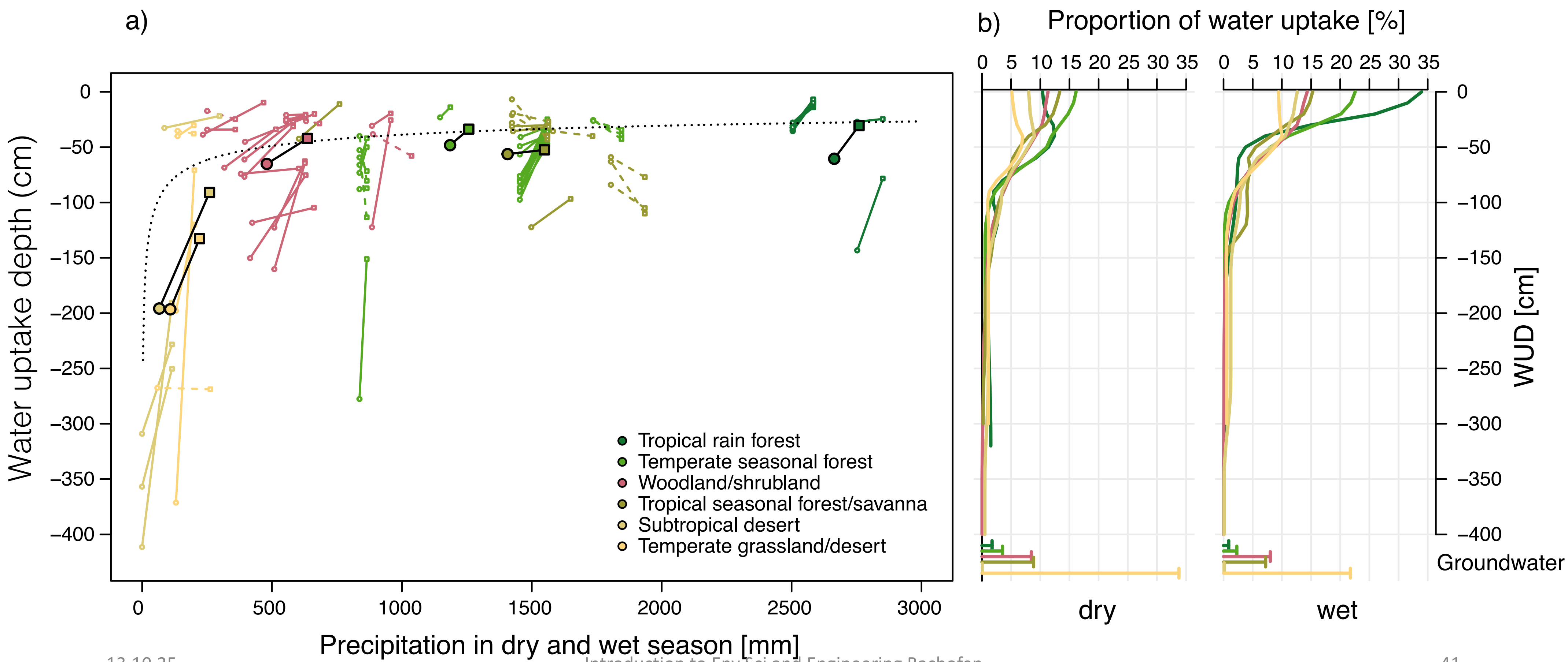
Soil and plant water isotopic composition





Global water uptake depth

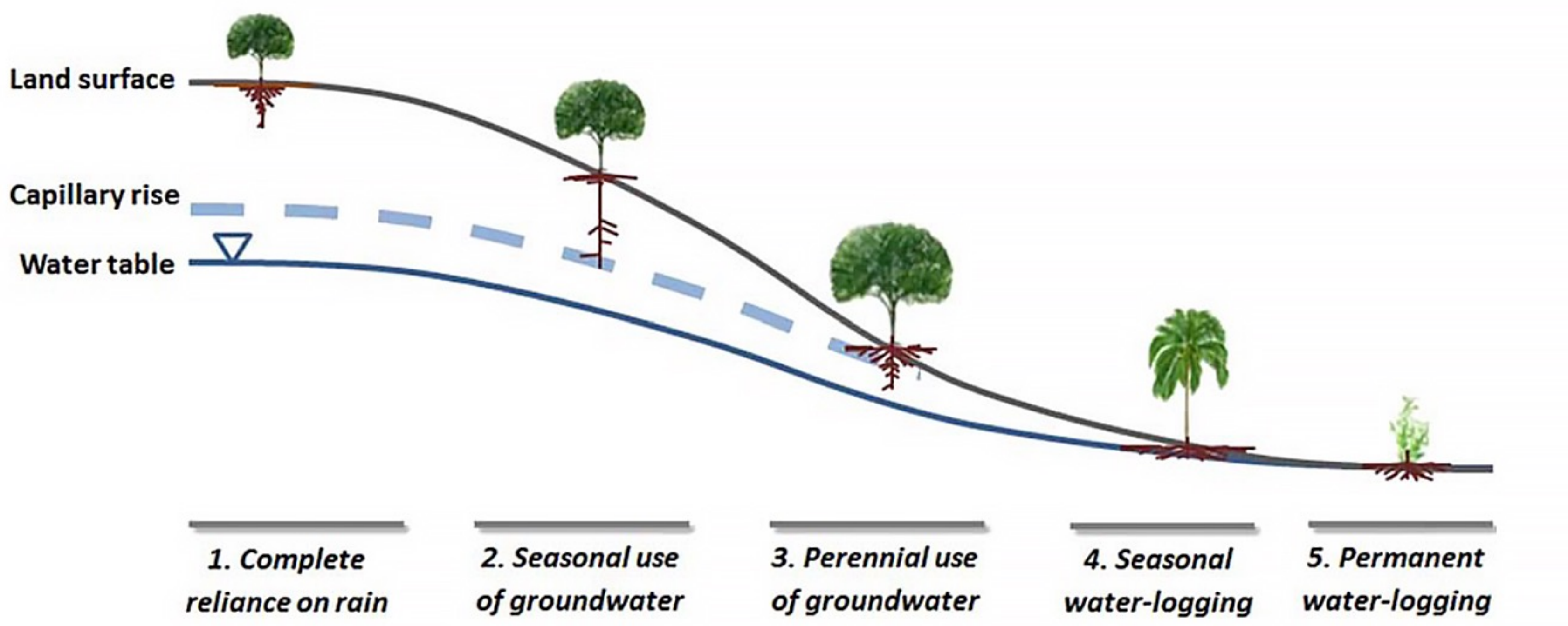
Trees can switch between shallow and deep-water sources depending on soil water availability



Bachofen et al. 2024

Water table and rooting depth

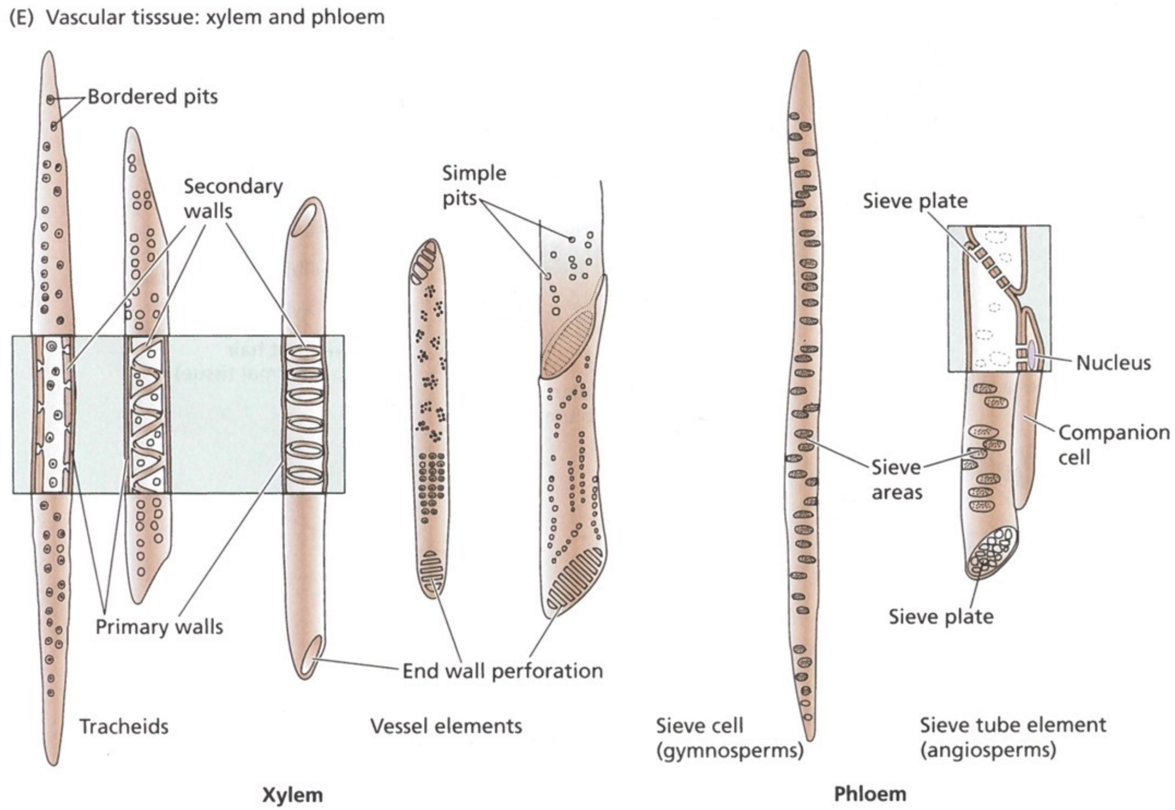
Maximum rooting depths follow the depth of the water table where/when the latter is accessible.



 Fan 2015, Water Resources Research

Water transport in the xylem

- Water transport takes place through specialised cells: xylem
- Increasing tensions in the xylem can lead to formation of **air embolism**, breaking the continuity of water transport



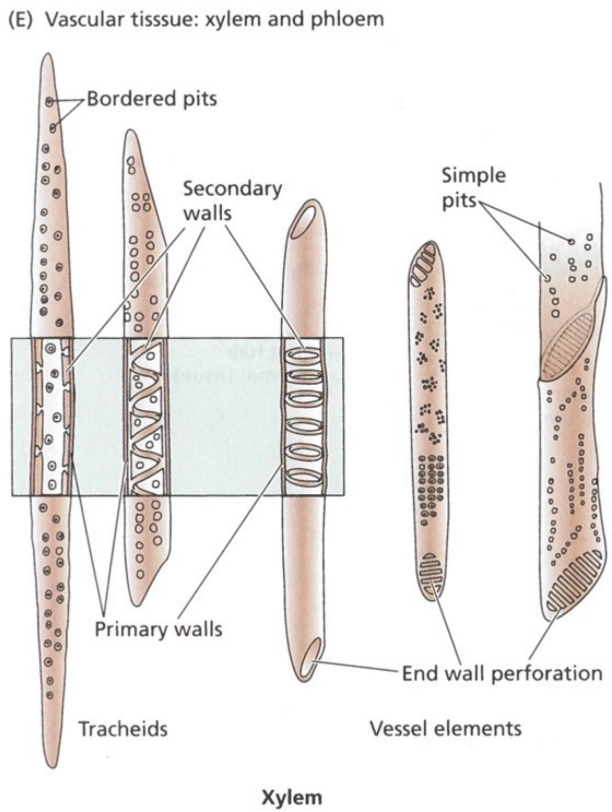
Water transport in the xylem

More drought tolerant

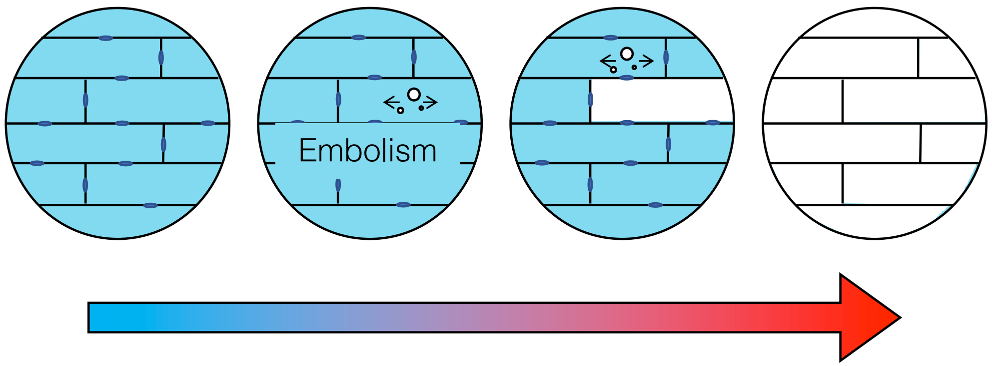
Downy oak

More drought sensitive

European beech

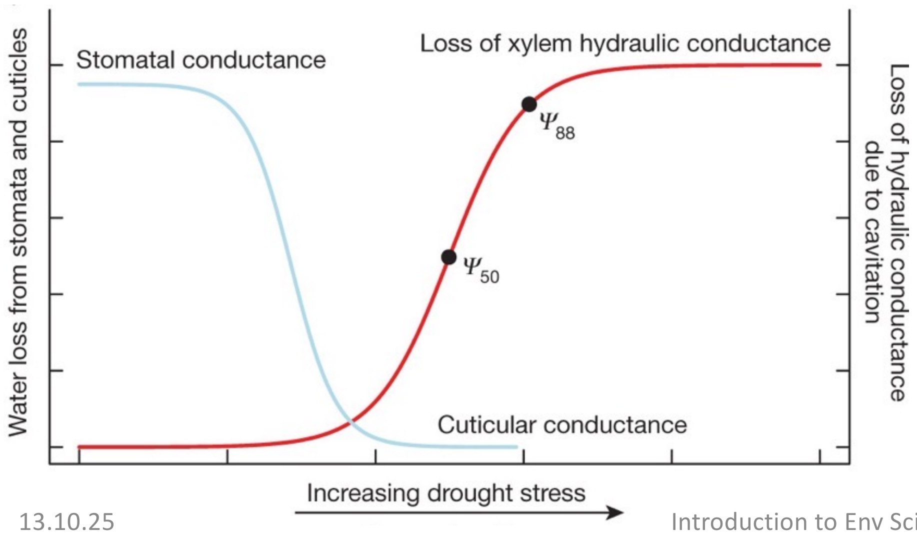


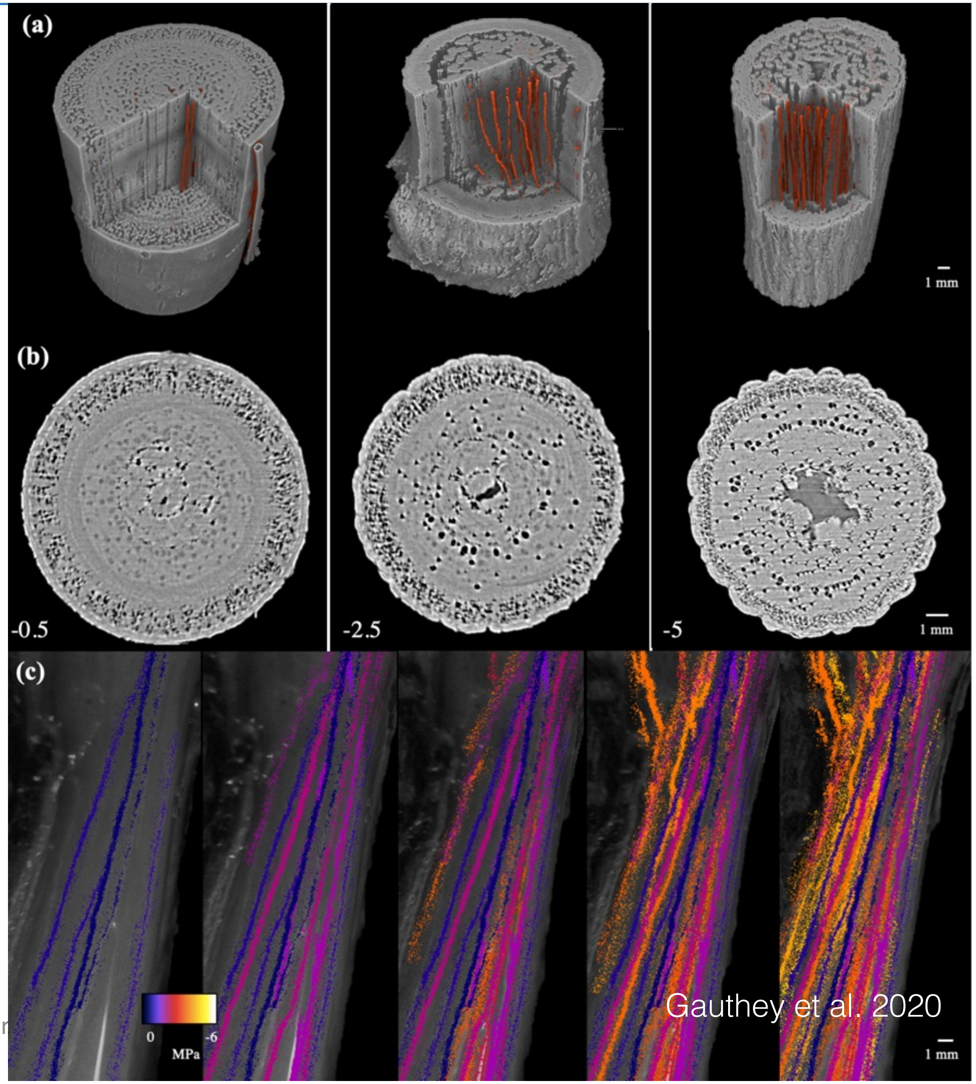
Air embolism in the xylem



Well watered

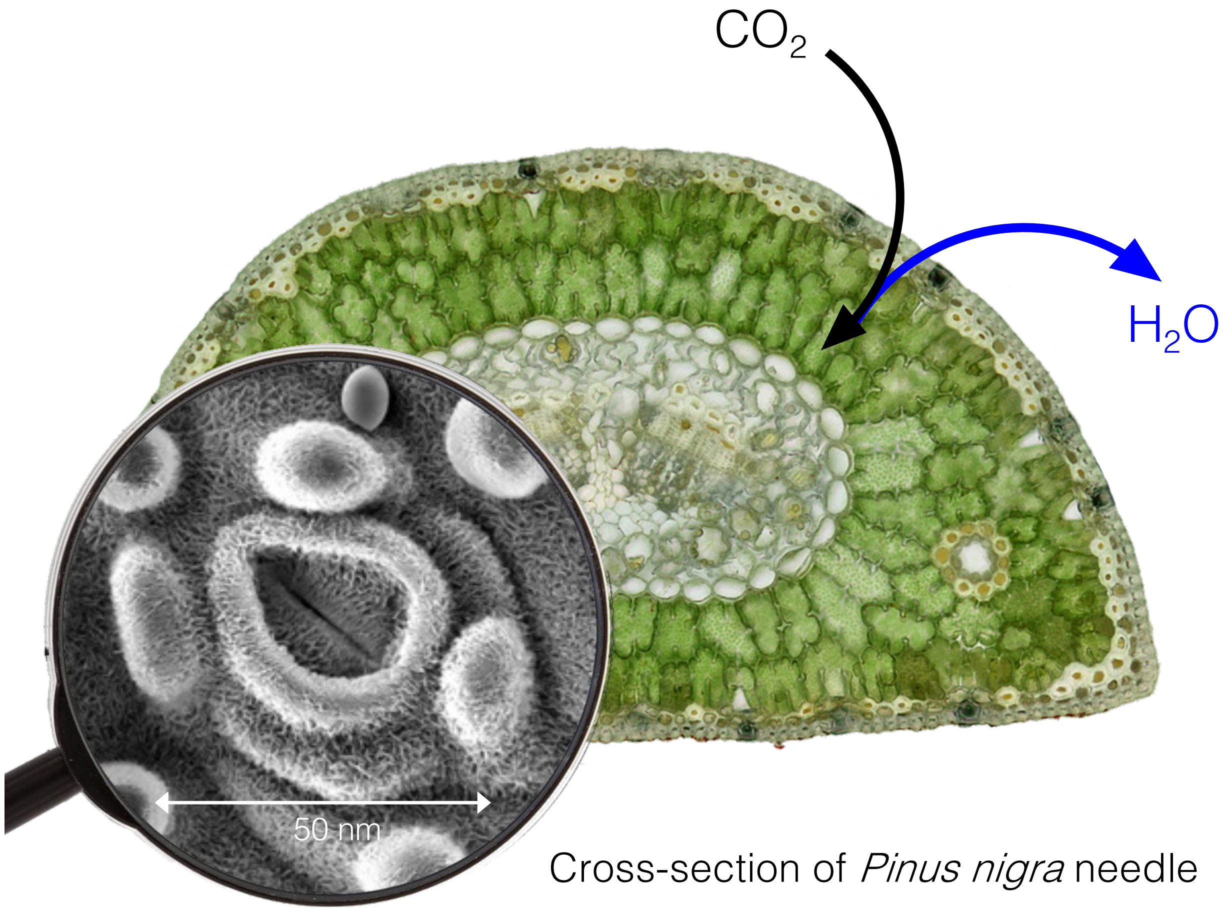
Water stressed






Platforme PIXE de l'EPFL

Evapotranspiration at stomata

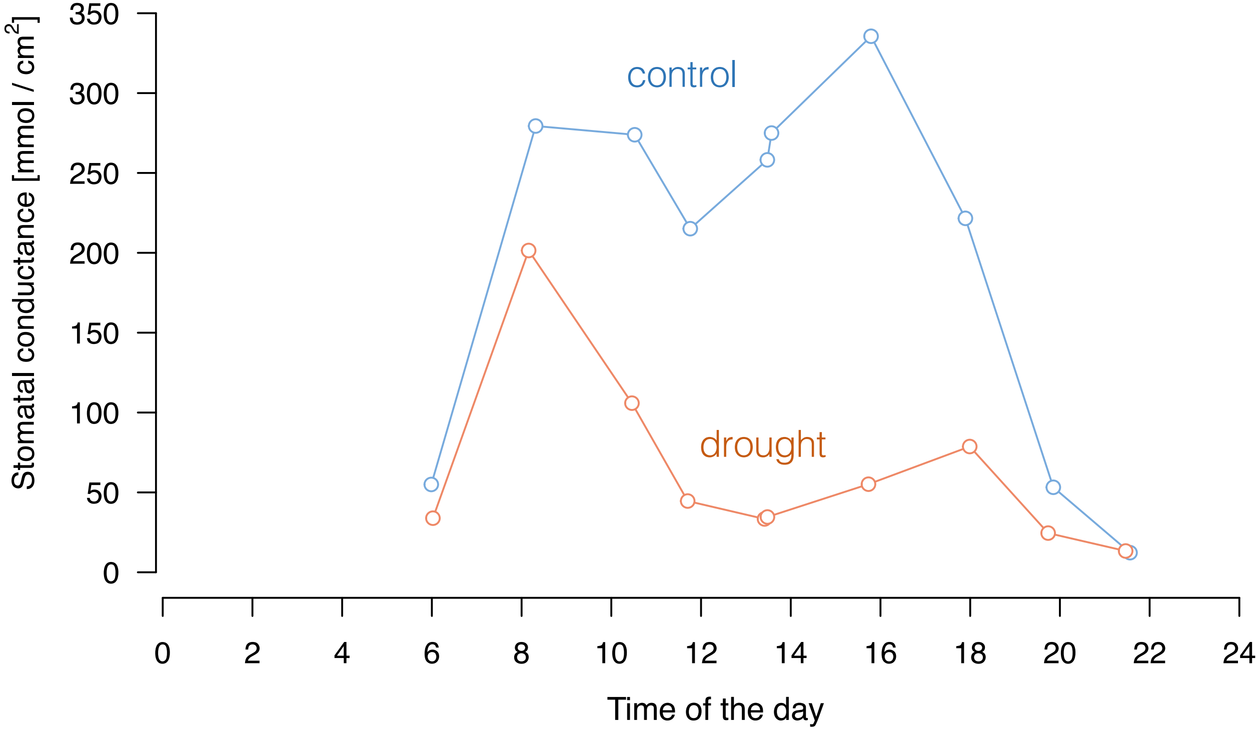


Cross-section of *Pinus nigra* needle

- CO_2 uptake through stomata (**stomatal conductance**)
- **Stomatal conductance** is regulated by environmental and biochemical factors (e.g. soil moisture, light availability, plant hormones, etc.)
- **Stomatal conductance** is driven by atmospheric water demand (atmos-pheric vapour pressure)

Photos: Mana Gharoun, Anouchka Perret-Gentil, Christoph Bachofen

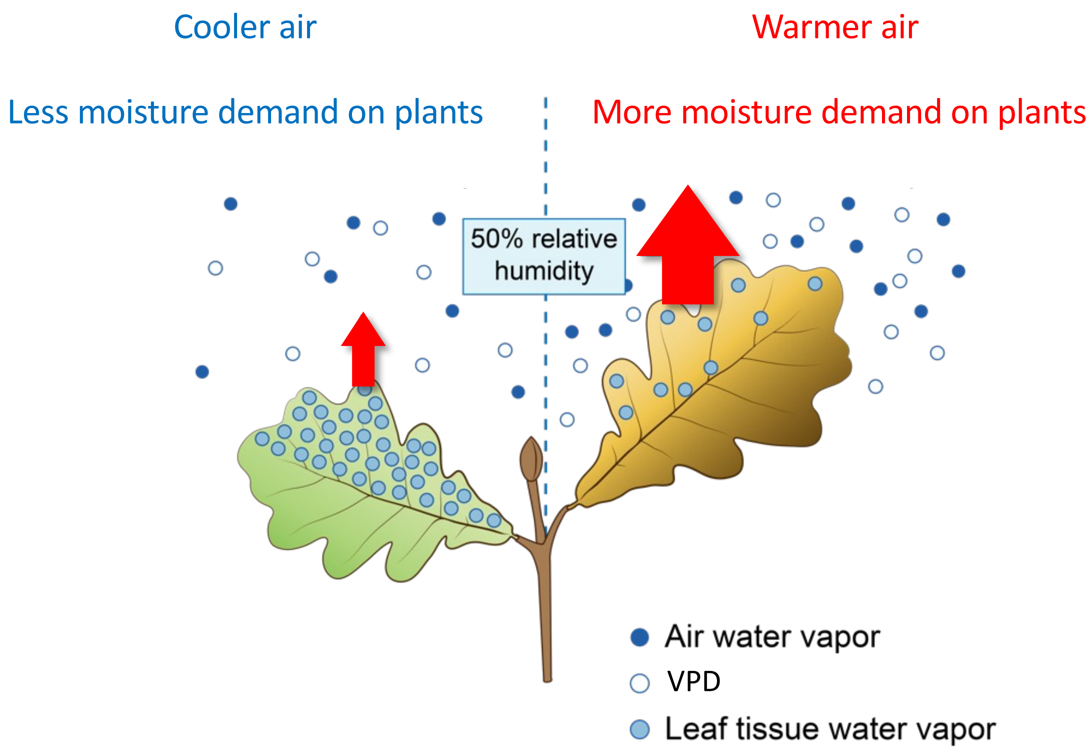
Tree transpiration is sensitive to soil drought



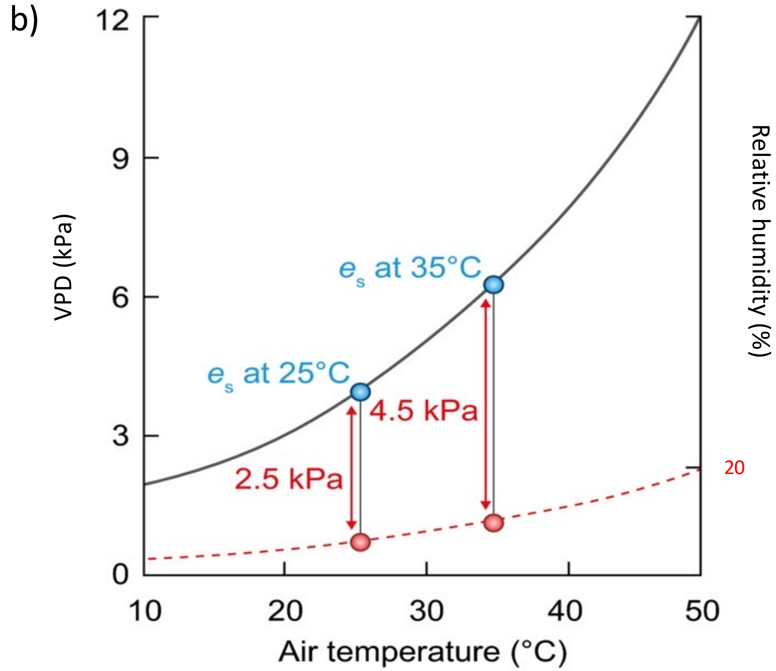
Bachofen et al. 2017

Transpiration responses to VPD

VPD = $e_s - e_a$ = (611exp (17.27 x **T** / 237.3 + **T**)) – (**RH** x e_s/100)

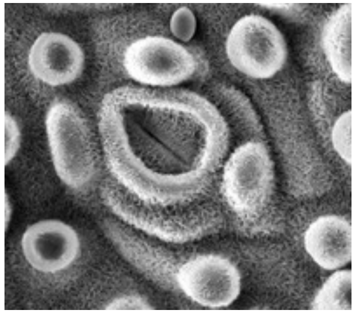


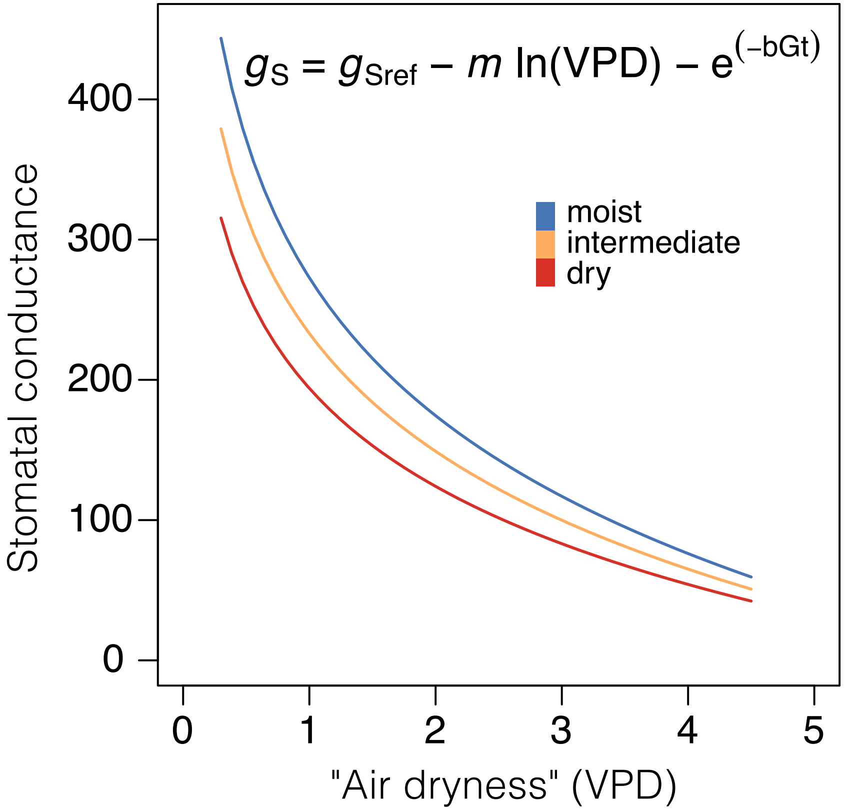
USGCRP, 2018



Grossiord et al. (2020) New Phytologist

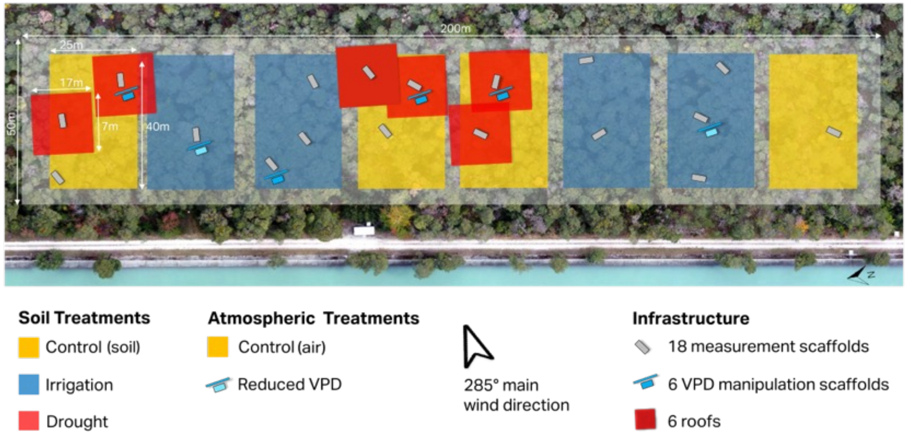
Transpiration responses to VPD and soil water



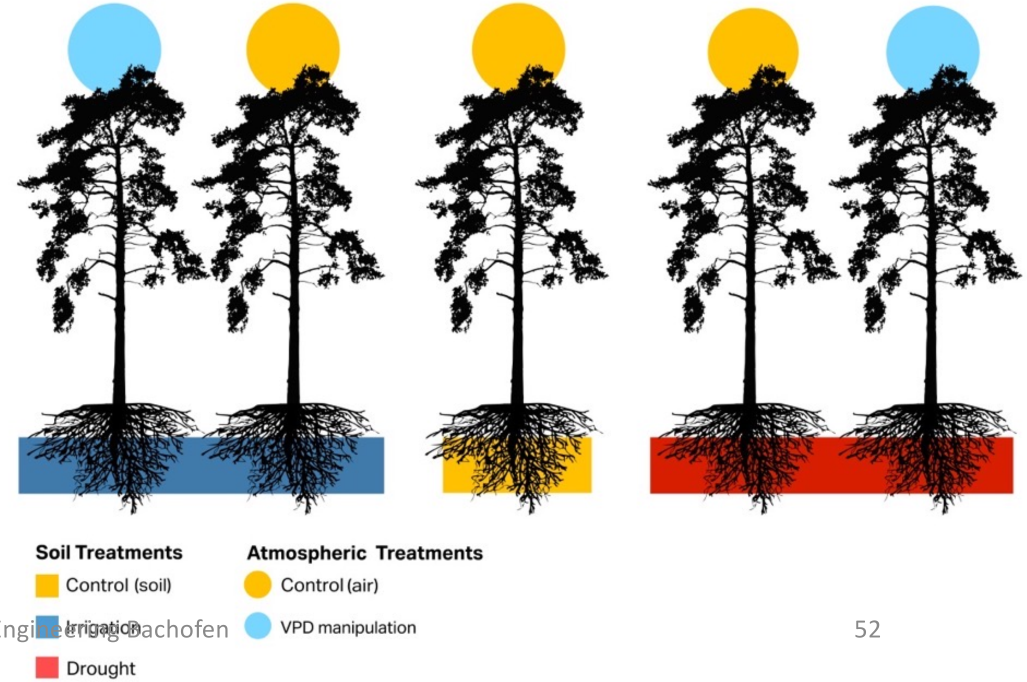


- Dry air leads to water loss in the leaves
- To preserve water in the leaves, plants close their stomata
- Water loss to the air is lowered
- Soil drought increases these responses and leads to faster closure of stomata

Bachofen et al. 2023

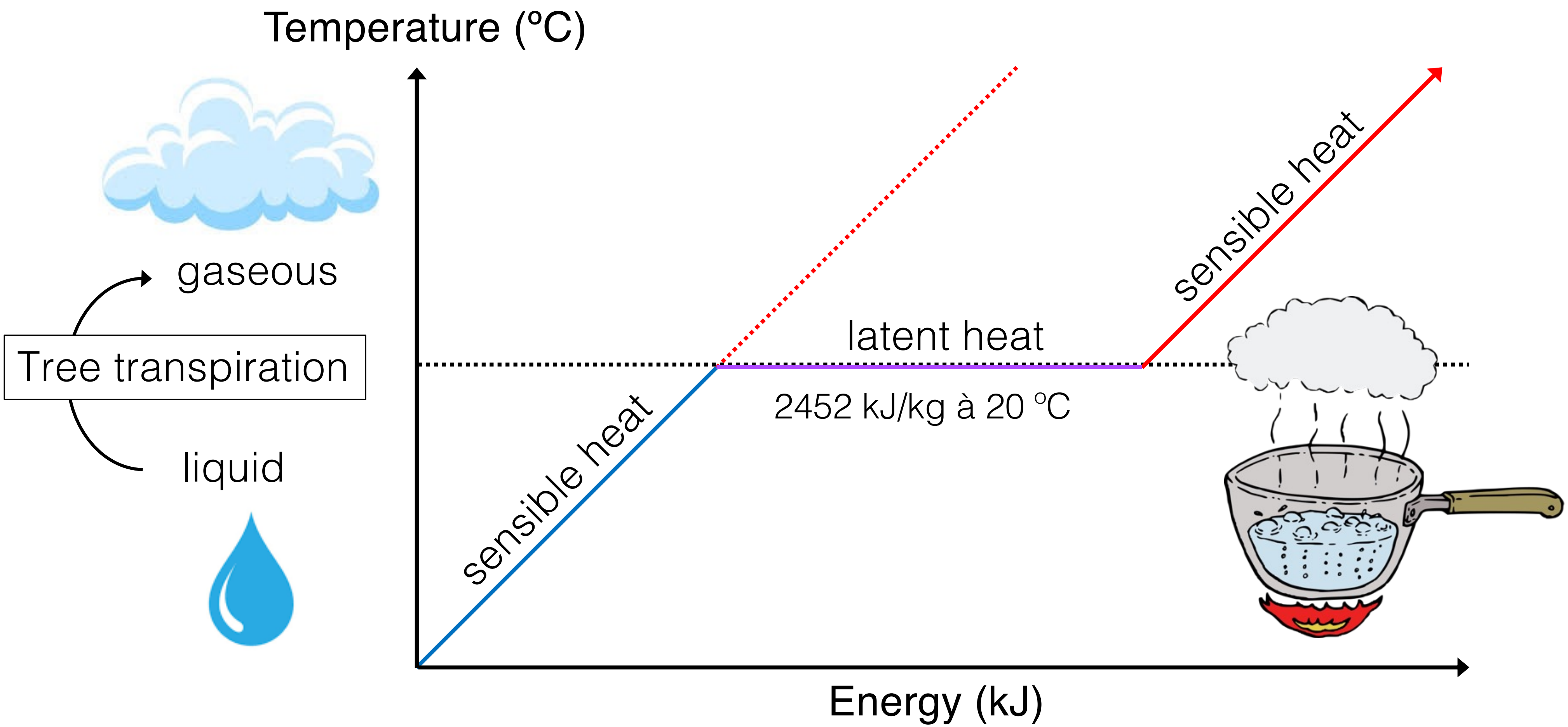


200m
25m
17m
7m
40m
50m
Soil Treatments
Control (soil)
Irrigation
Drought
Atmospheric Treatments
Control (air)
Reduced VPD
285° main wind direction
Infrastructure
18 measurement scaffolds
6 VPD manipulation scaffolds
6 roofs

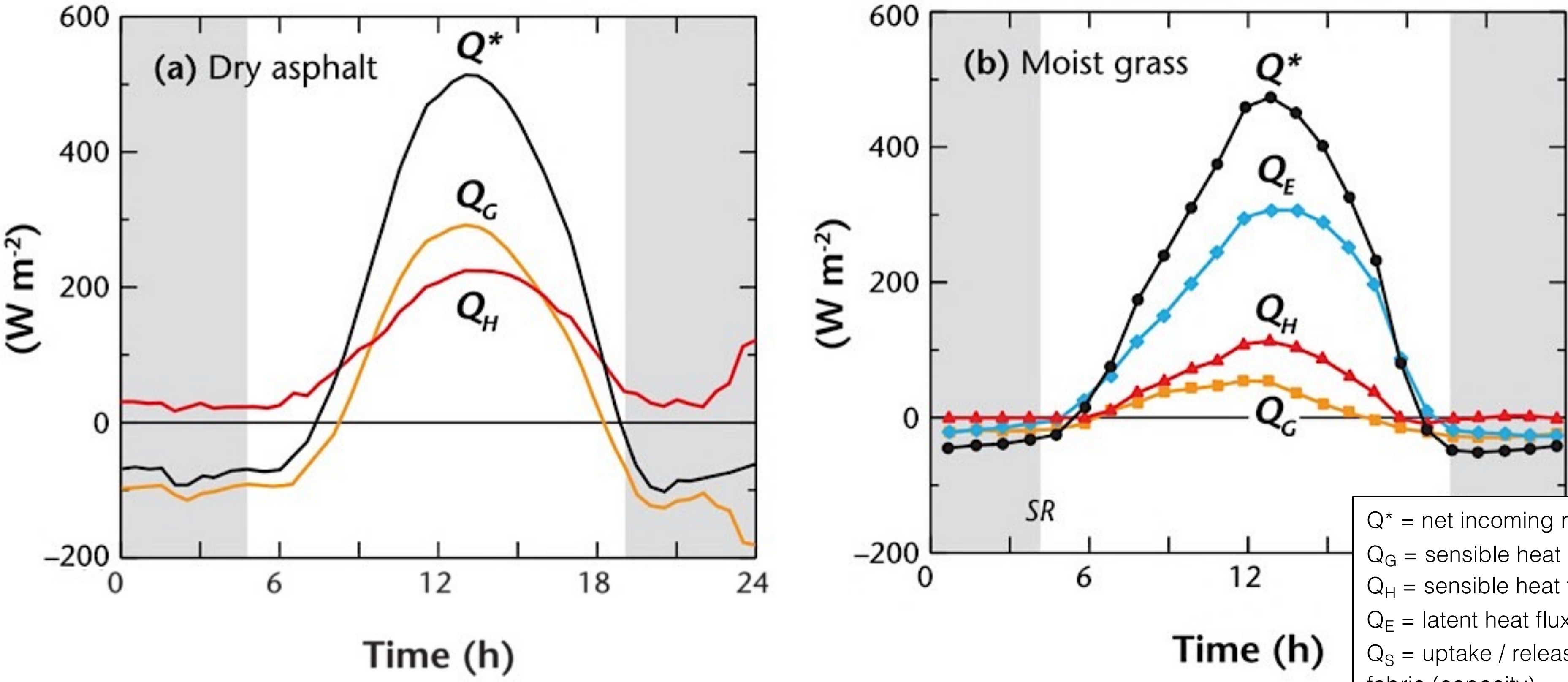


Soil Treatments
Control (soil)
Irrigation
Drought
Atmospheric Treatments
Control (air)
VPD manipulation

Cooling by transpiration: latent heat flux

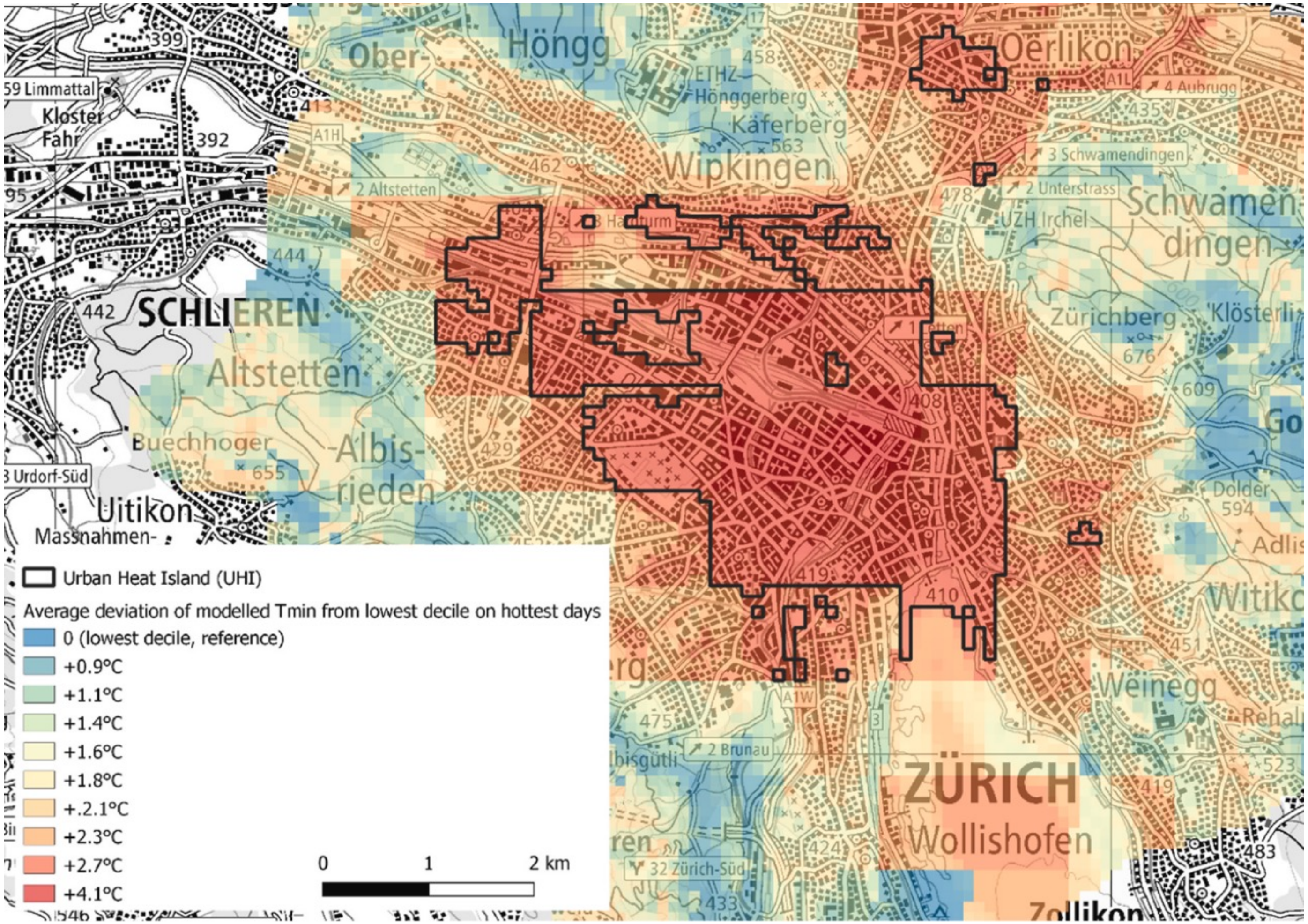


Example SEBs of unobstructed urban facets: (a) dry asphalt road near Vienna, Austria. (b) slightly moist grassed site in an urban park in Vancouver, Canada. (Oke et al. 2017)



Q* = net incoming radiation
Q_G = sensible heat conducted to the soil
Q_H = sensible heat flux to the air
Q_E = latent heat flux to the air
Q_S = uptake / release of heat from urban fabric (capacity)
SR and SS = sunrise and sunset

The urban heat island

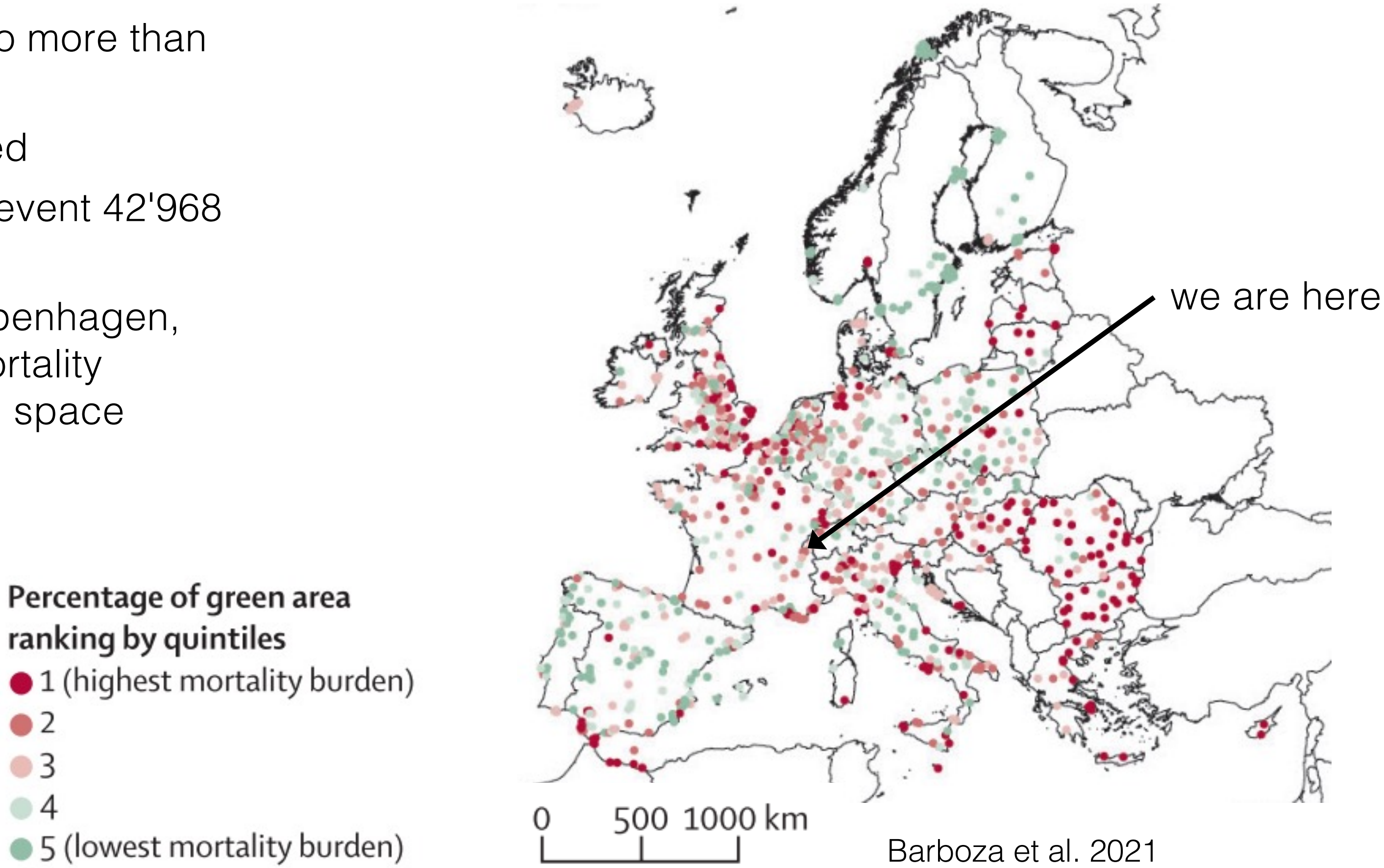


"In 2018, only 15 stations out of 576 were located in inner cities"

Wicki *et al.* 2024
Flückiger *et al.* 2022

Heat-induced deaths

- 2003 heat wave in Europe lead to more than 70'000 additional deaths
- Big cities were especially affected
- Access to green space could prevent 42'968 deaths annually
- Athens, Brussels, Budapest, Copenhagen, and Riga showed the highest mortality burdens due to the lack of green space

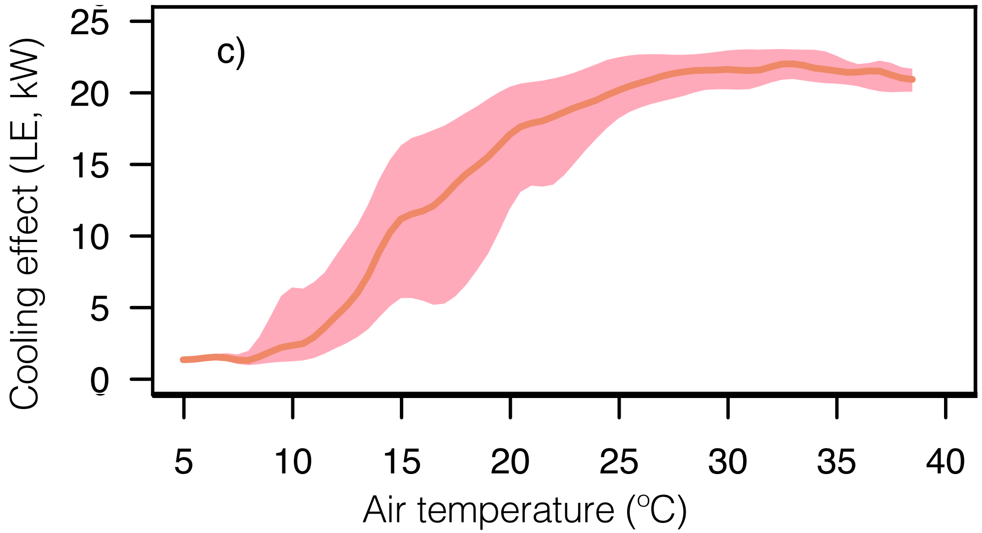


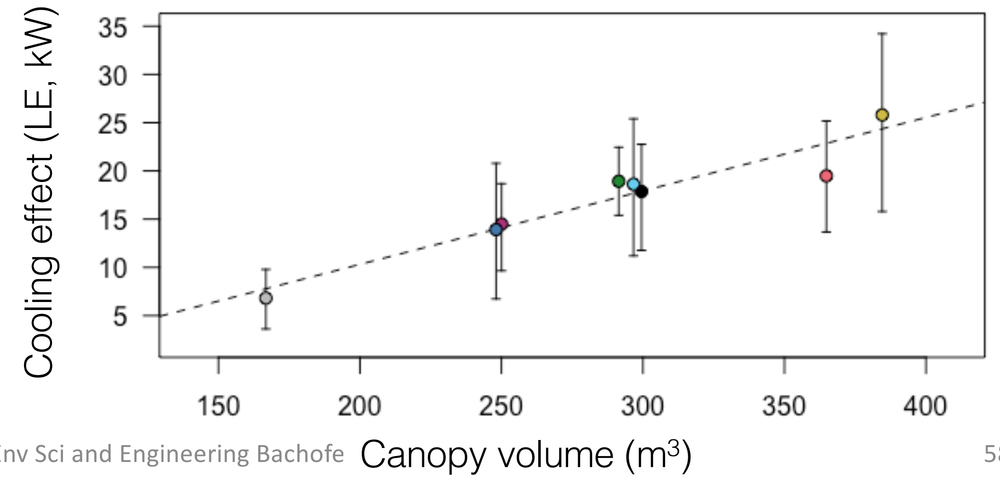
Barboza et al. 2021

Can trees mitigate the urban heat island?

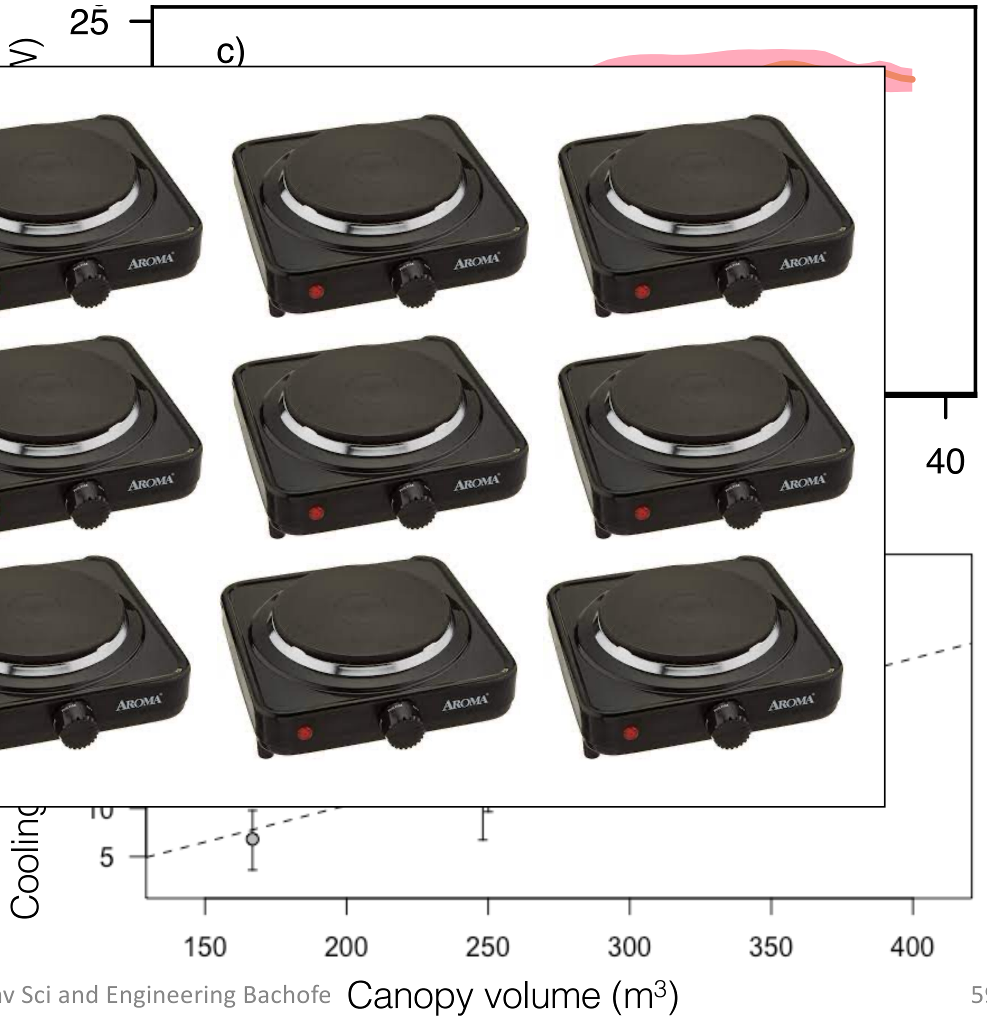
Transpiration cooling of trees

→ Up to 500 liters of water is transpired by the platanus trees per day





Transpiration cooling of trees



→ Up to 500 liters of water is transpired by the platanus trees per day

Take home

- Land plants are a major component of the global CO_2 cycle through photosynthesis, growth and respiration.
- Plant CO_2 uptake, water uptake, and transpiration respond to changes in environmental conditions, such as soil drought, VPD, temperature, and more.
- To understand how plants regulate the environment, we need to understand their responses to environmental change (feedbacks).
- This will allow to effectively manage forest ecosystems to alleviate antropogenic damages on the environment.