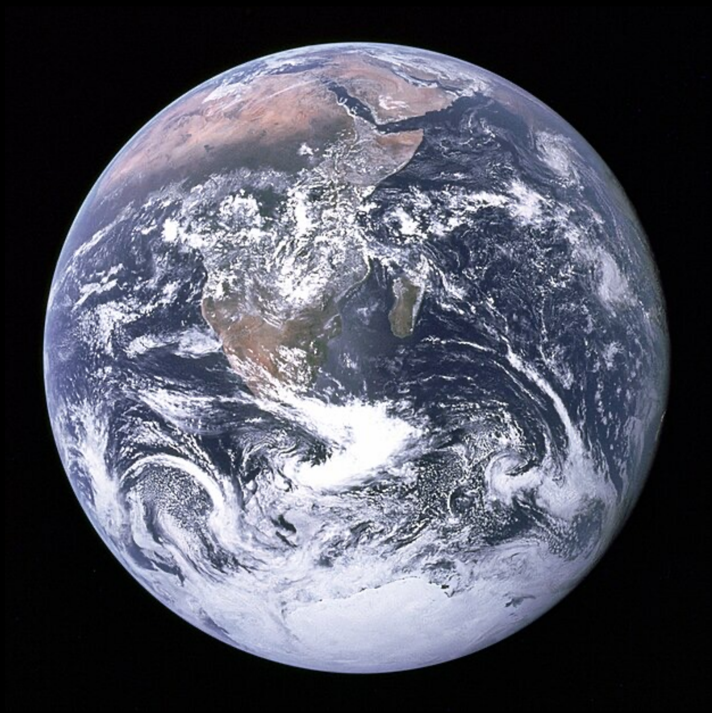
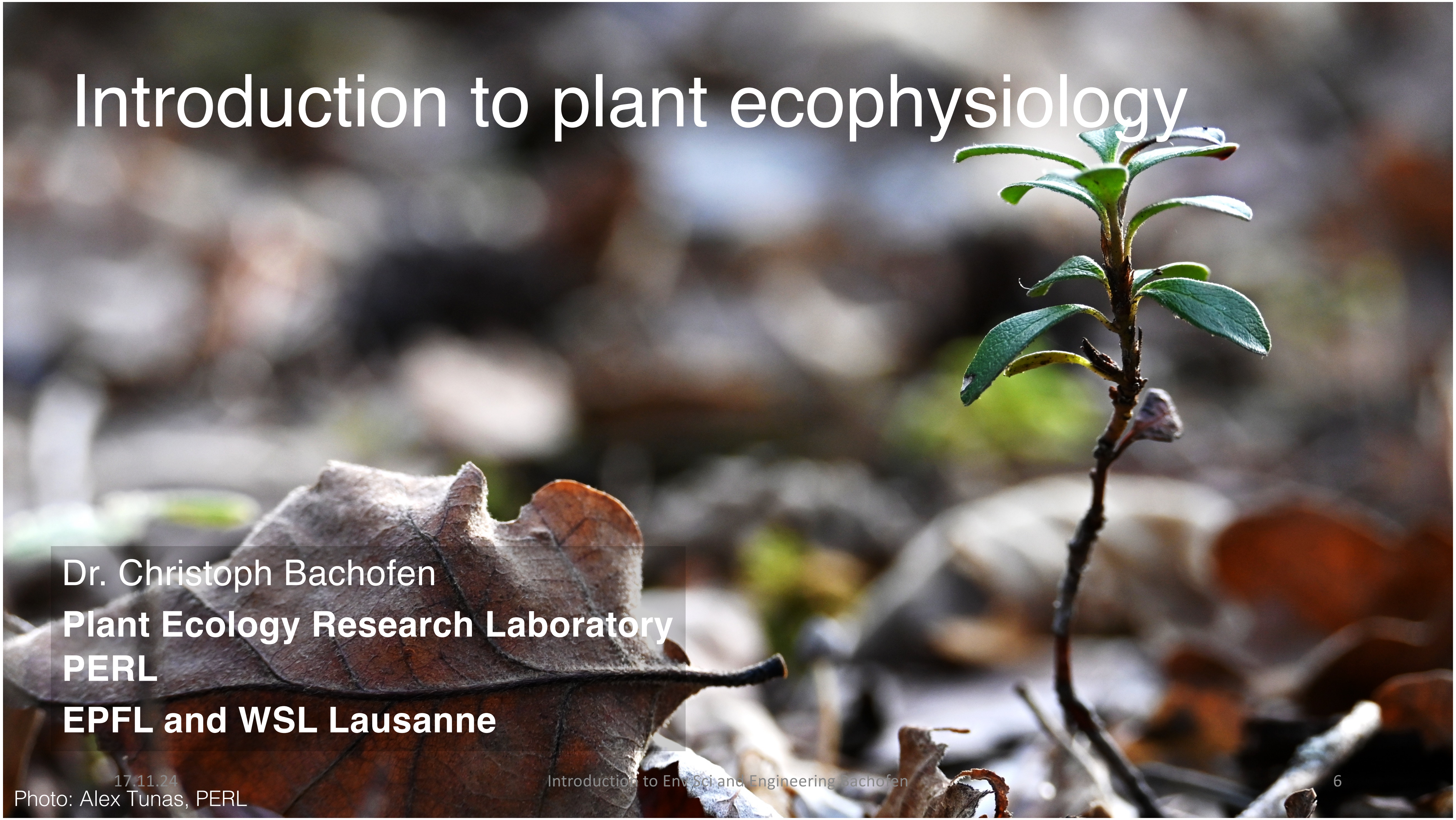
[redacted]

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



Oxygenic photosynthesis

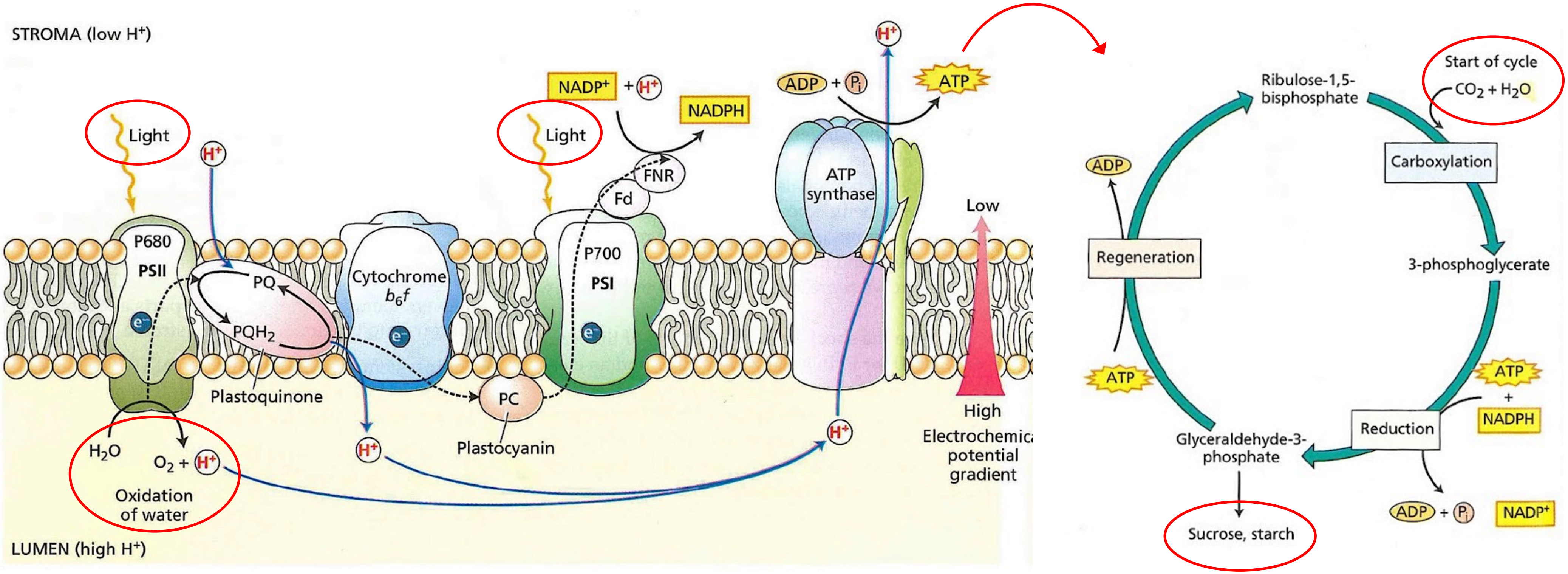
Photo: Alex Tunas, PERL


Introduction to plant ecophysiology
Dr. Christoph Bachofen
Plant Ecology Research Laboratory
PERL
EPFL and WSL Lausanne
17.11.24
Introduction to Env Engineering Bachofen
6
Photo: Alex Tunas, PERL

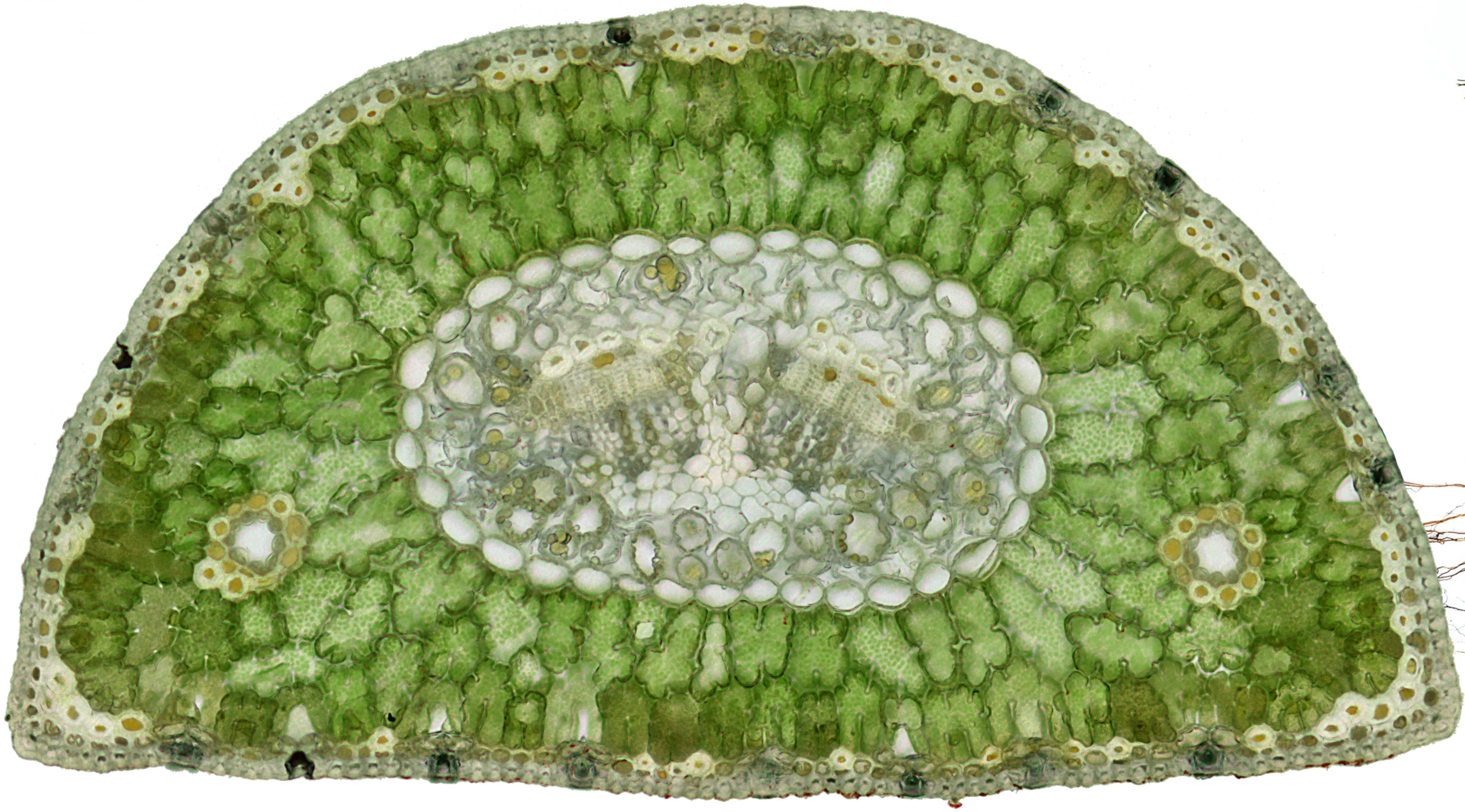
Oxygenic photosynthesis

Light-dependent reaction: photon uptake by chlorophyll and electron transport chain

Light-independent reaction: CO_2 fixation by RuBisCO



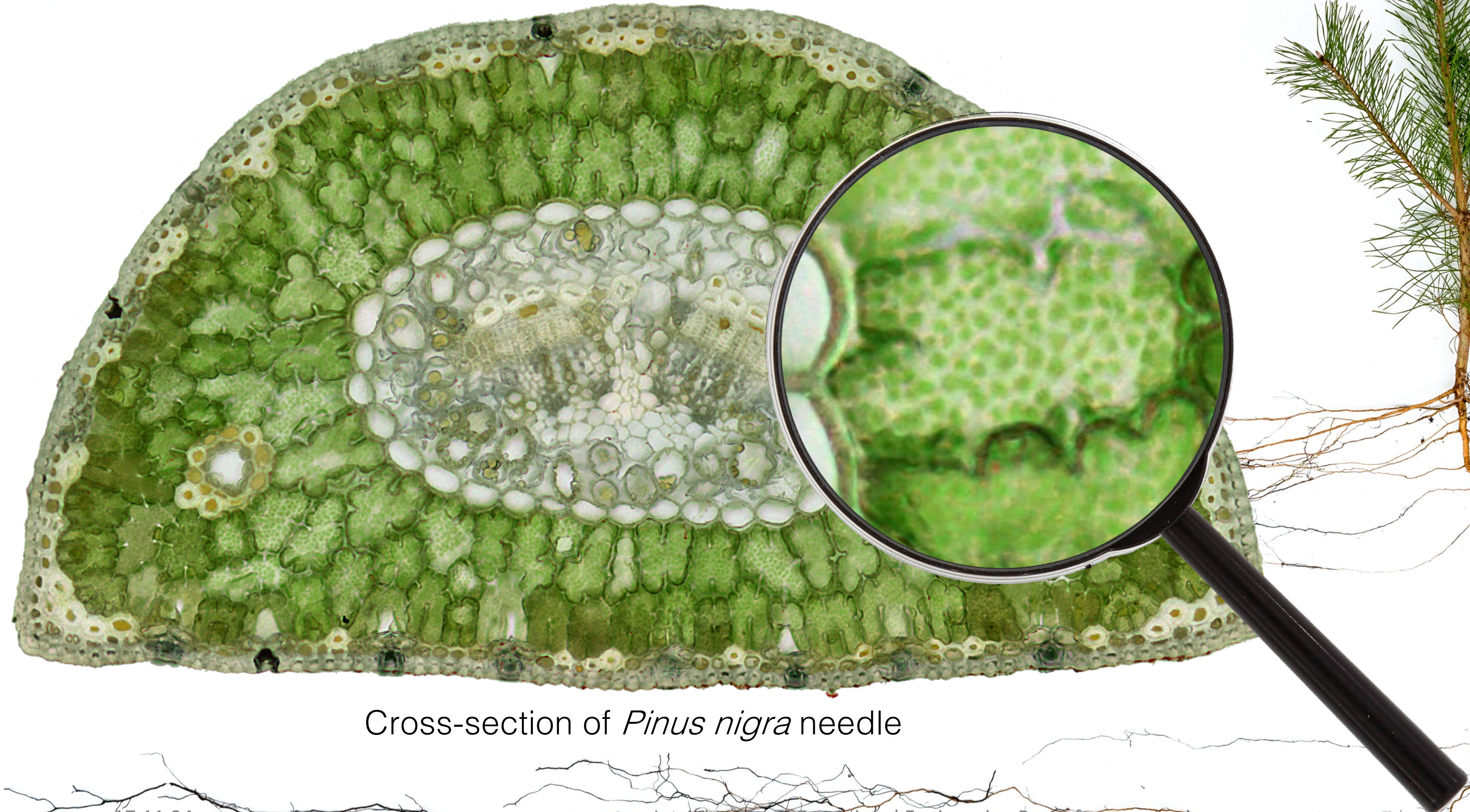
Photosynthesis takes place in chloroplasts



Cross-section of *Pinus nigra* needle

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

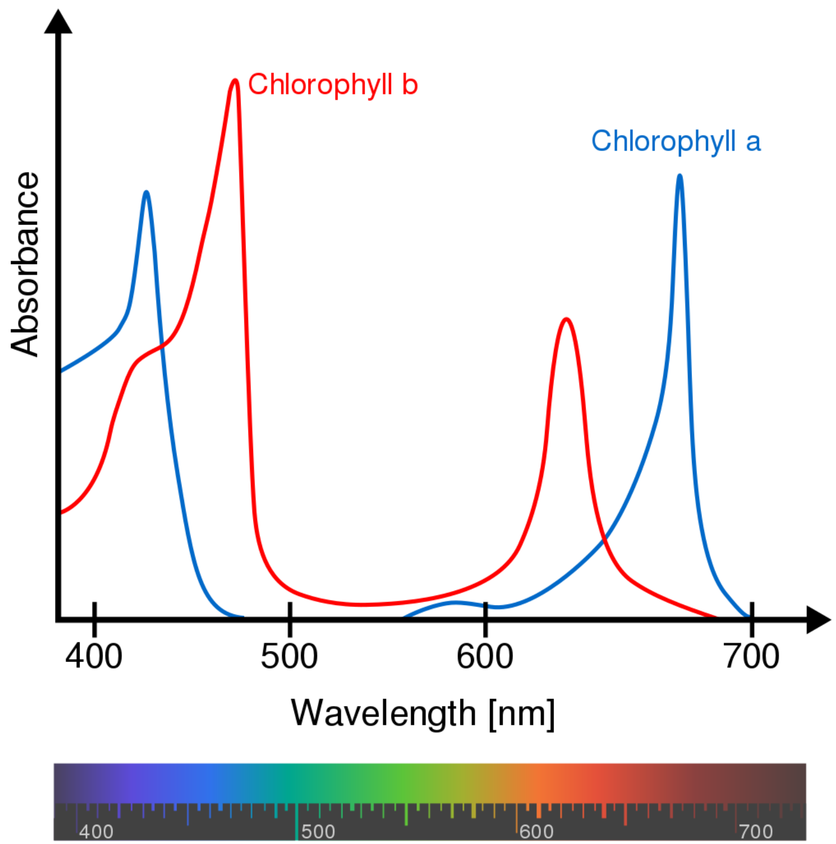
Photosynthesis takes place in chloroplasts

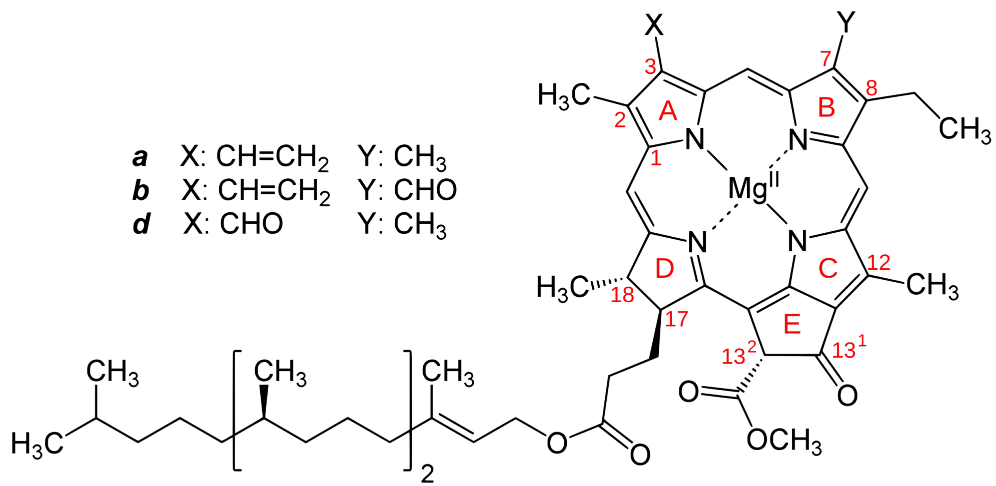


Cross-section of *Pinus nigra* needle

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

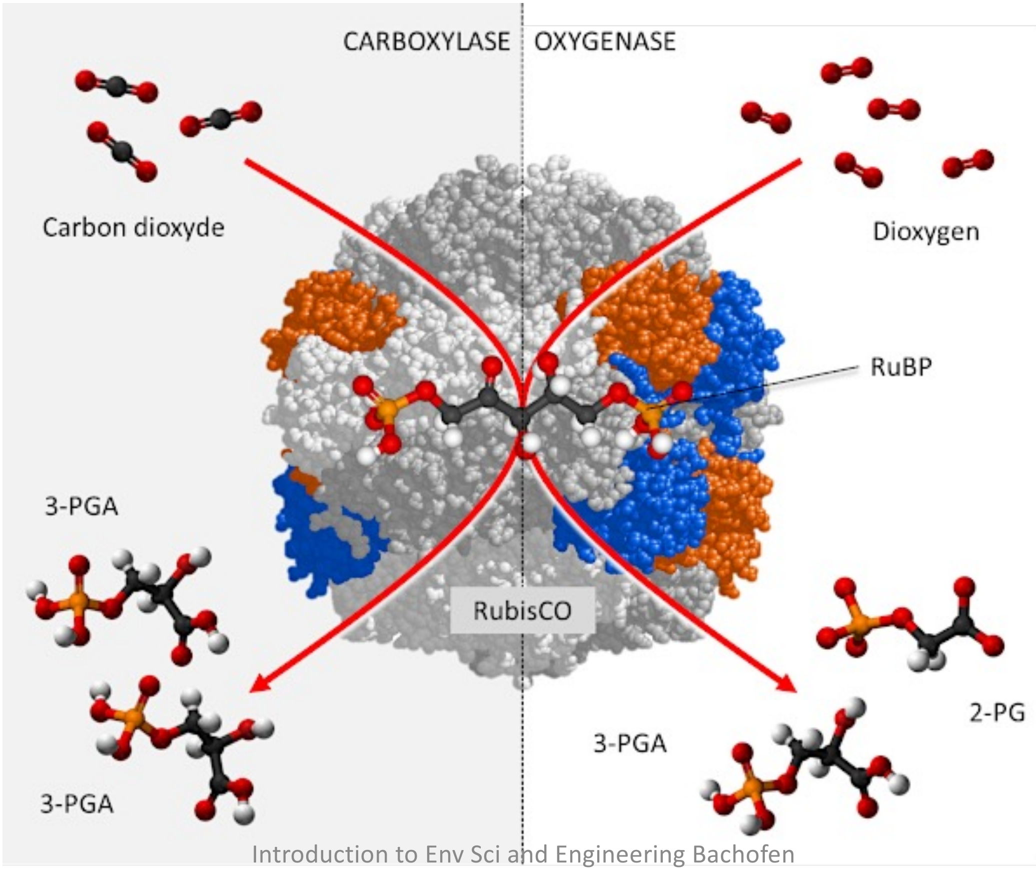
Light-dependent reaction with chlorophyll





Light-independent reaction with RuBisCO

RuBisCO is probably the most frequent protein on the planet

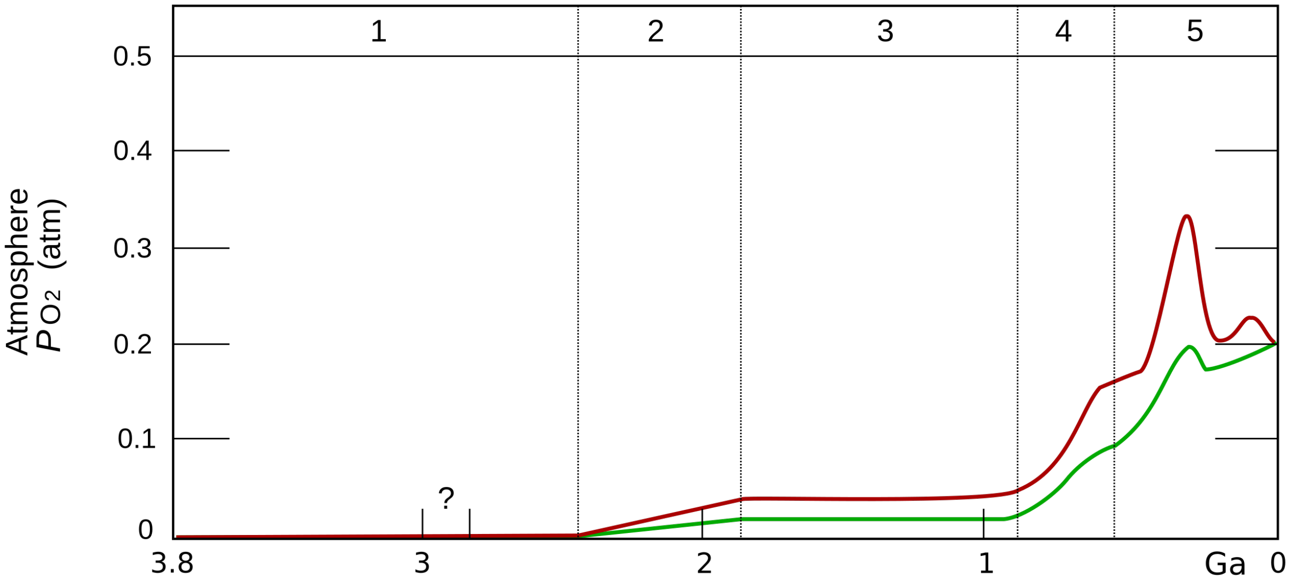


The great oxygenation event

Stromatolites at Shark Bay (Western Australia)

The great oxygenation event

- Rise in the concentration of free oxygen in the earth's atmosphere ~ 2.4 billion years ago
- Reducing atmosphere → oxidizing atmosphere
- ~ 80 % of biosphere extinct (most anaerobic bacteria)



O_2 build-up in the Earth's atmosphere. Red and green lines represent the range of the estimates while time is measured in billions of years ago (Ga).

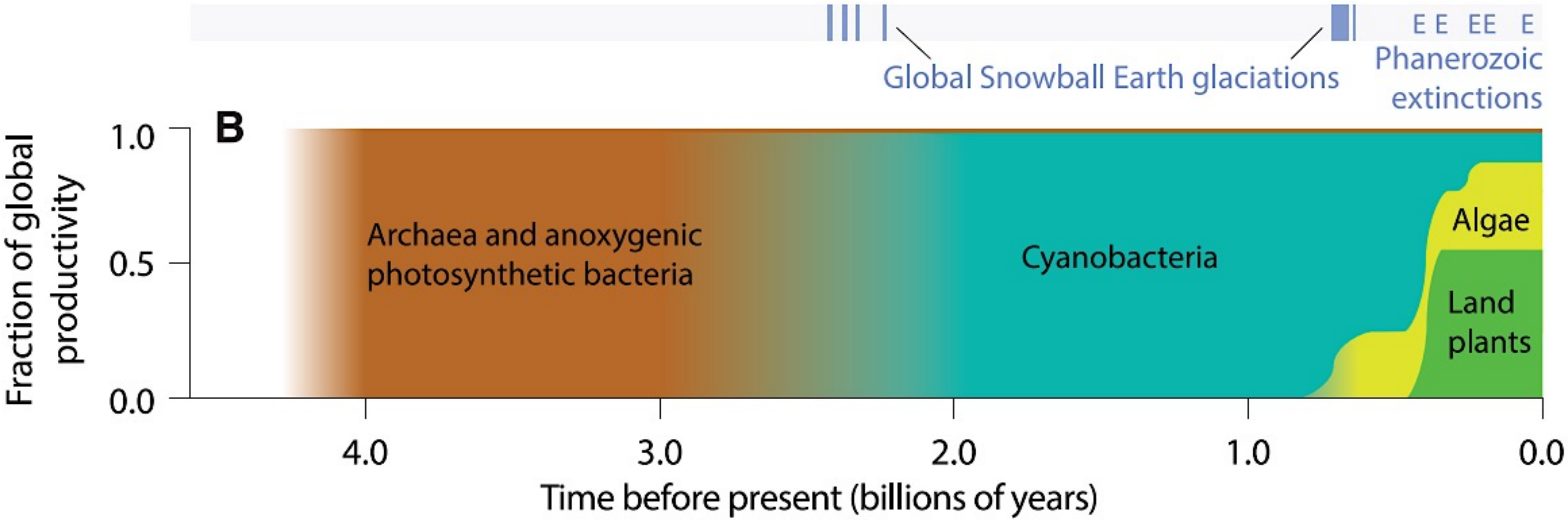
3.85–2.45 Ga: Practically no O_2 in the atmosphere. The oceans were also largely anoxic.

2.45–1.85 Ga: O_2 produced, rising to values of 0.02 and 0.04 atm, but absorbed in oceans and seabed rock.

1.85–0.85 Ga: O_2 starts to gas out of the oceans, but is absorbed by land surfaces. No significant change in oxygen level.

0.85 Ga – present: Other O_2 reservoirs filled; gas accumulates in atmosphere.

The great oxygenation event



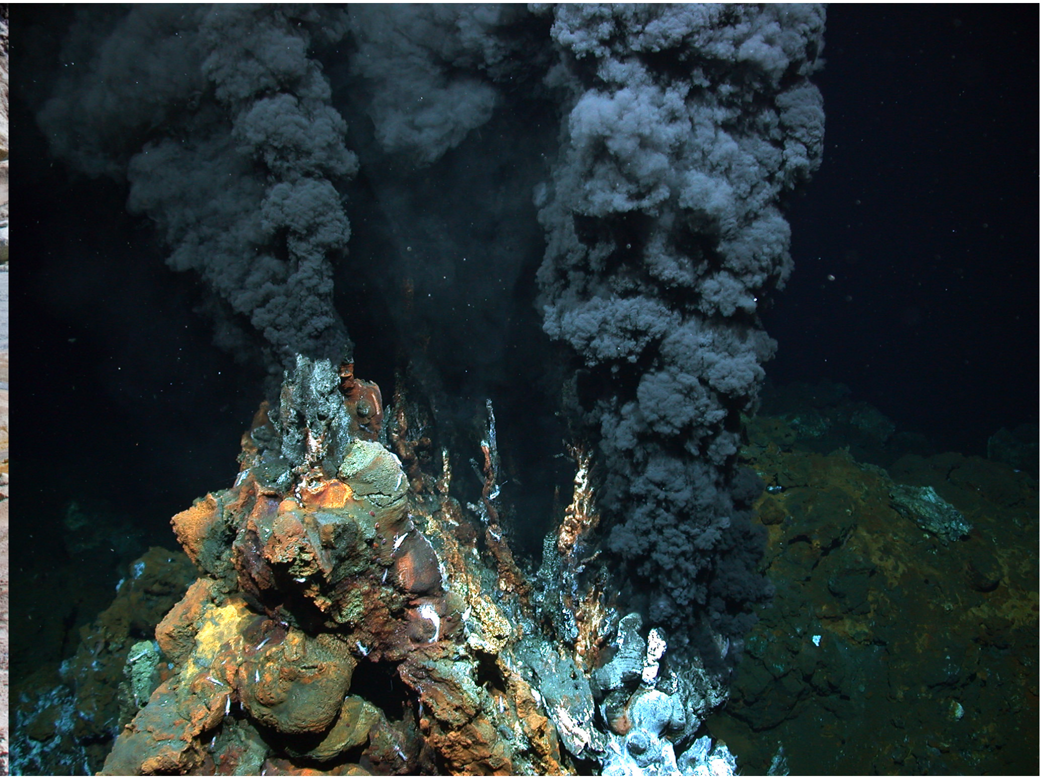
Today, primary productivity is dominated by terrestrial plants, followed by marine algae, followed by cyanobacteria.

 Crockford et al. 2023

Life before oxygen

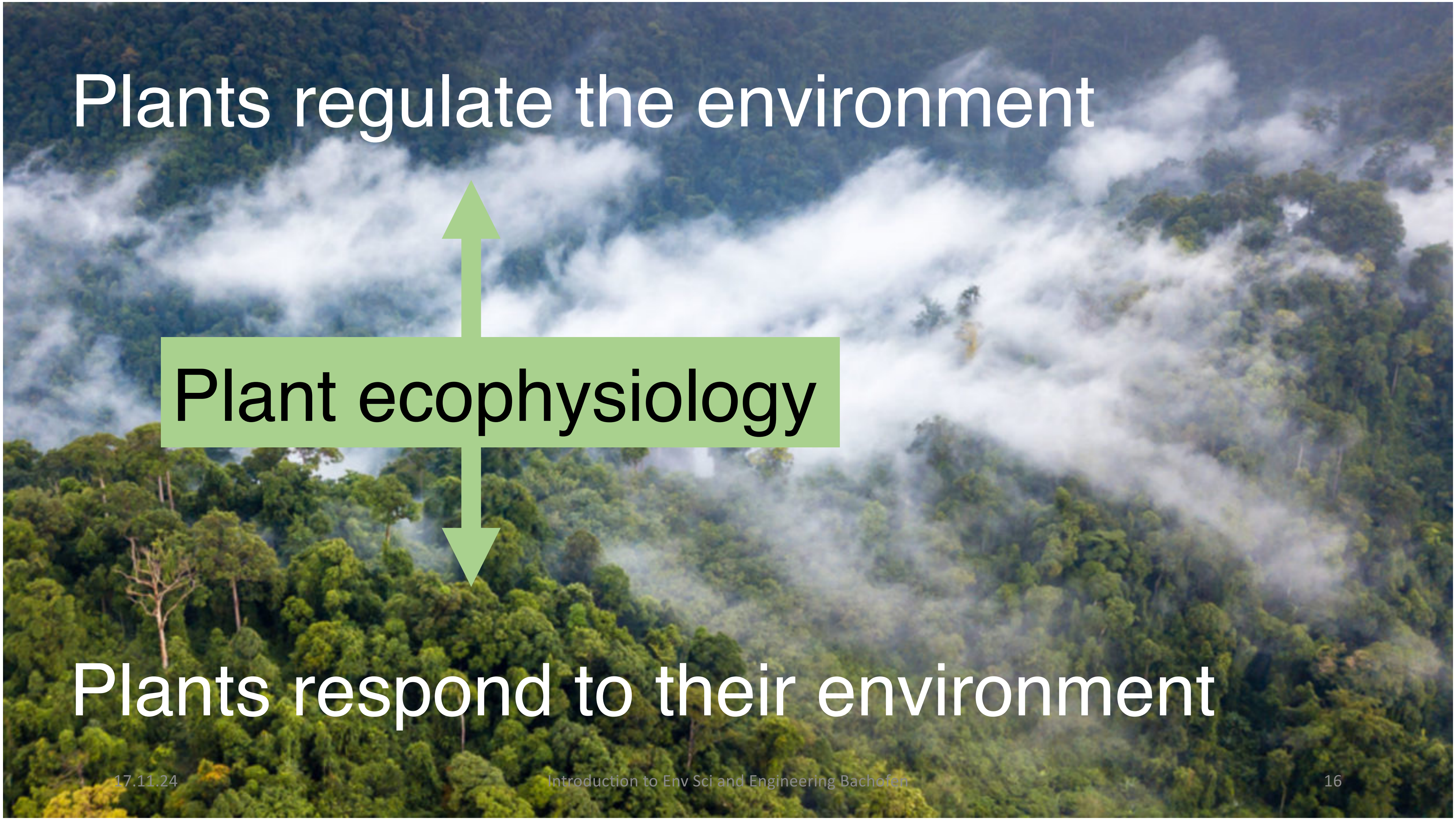
The earliest atmosphere is likely to have been dominated by H_2, H_2O, CO, and CO_2

Sulfur bacteria, Lassen National Park US



Hydrothermal vents

Schlesinger, Biogeochemistry, 1991


Plants regulate the environment
Plant ecophysiology
Plants respond to their environment

Plants regulate the environment

The global CO_2 cycle

Global CO_2 cycle

- 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

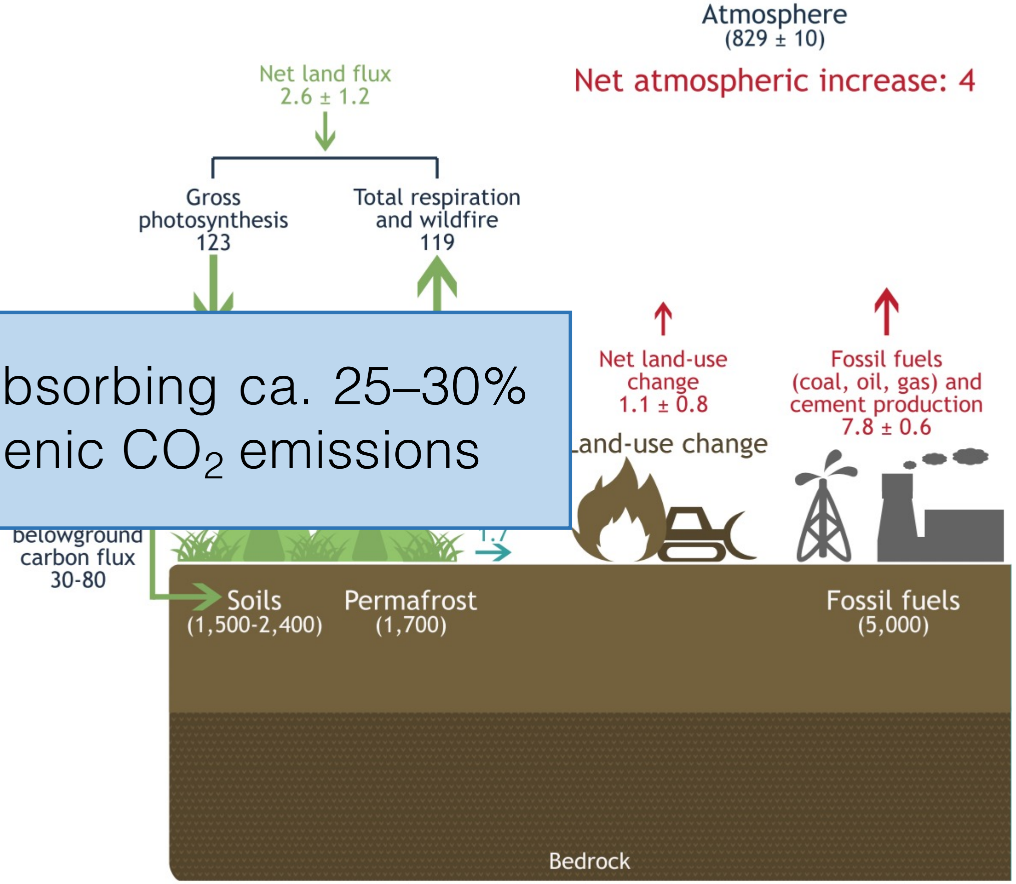


Figure 4. Global carbon cycle. Carbon (Gt C) stocks are denoted in parentheses and showr year) are associated with arrows and shown in gigatons per year.

Janowiak et al. 2017

Global carbon pools

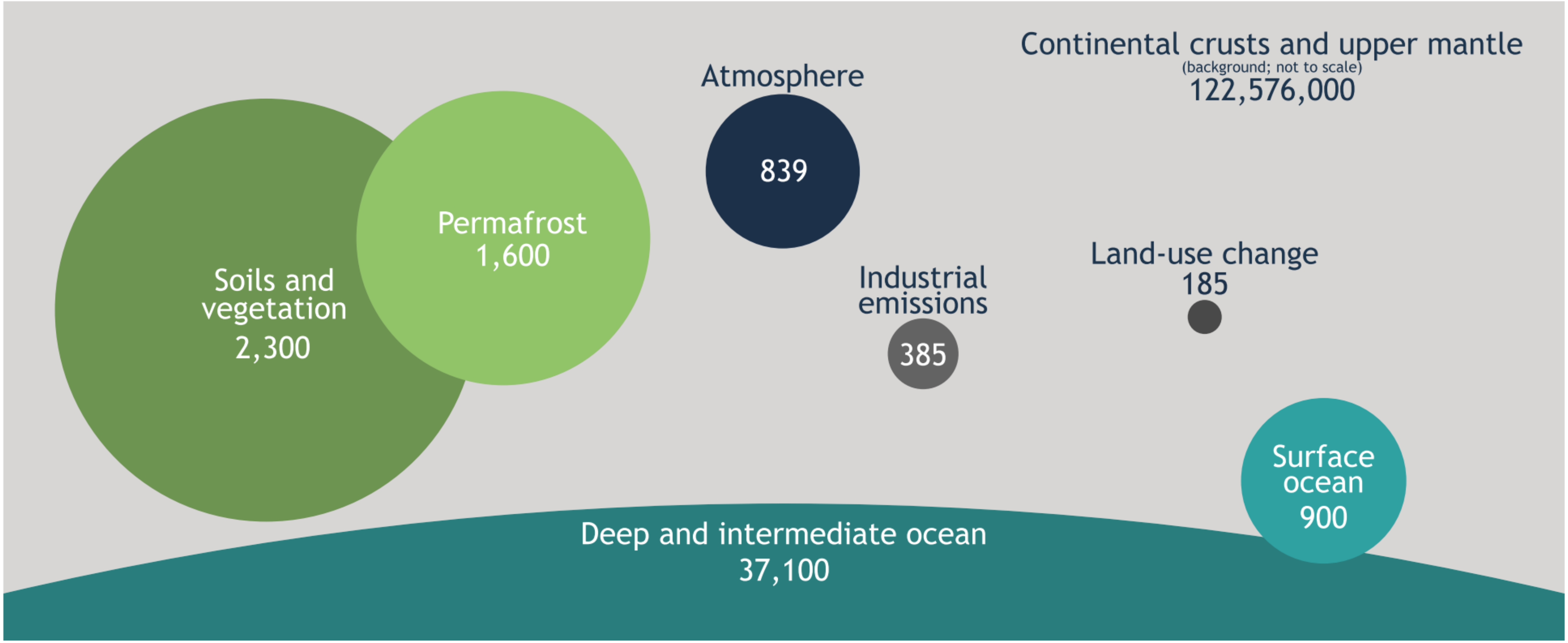


Figure 1. Global carbon stocks (carbon stored in pools), shown in gigatons.

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

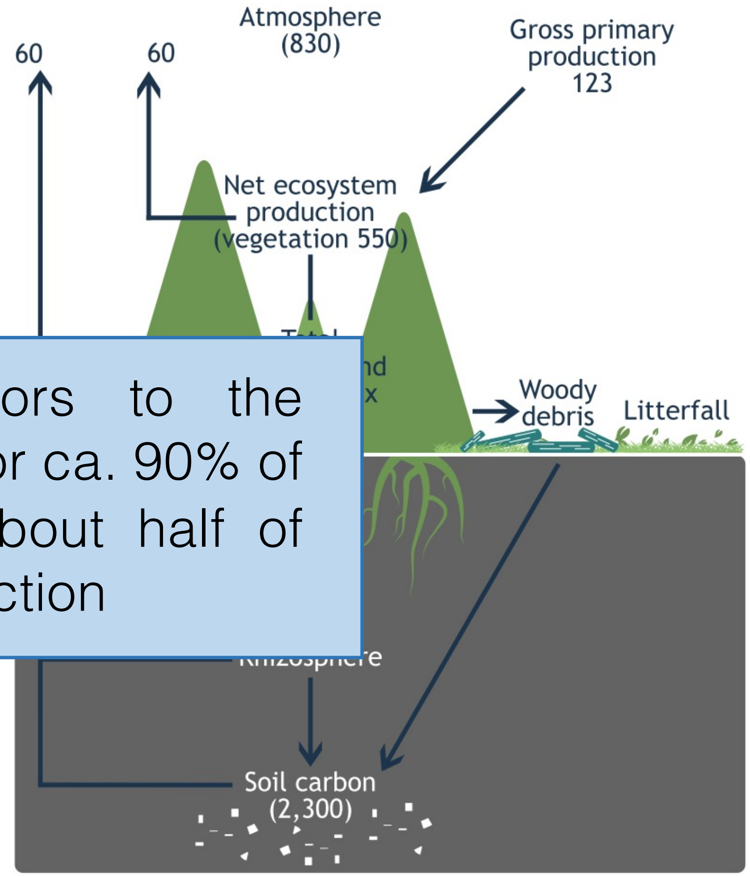


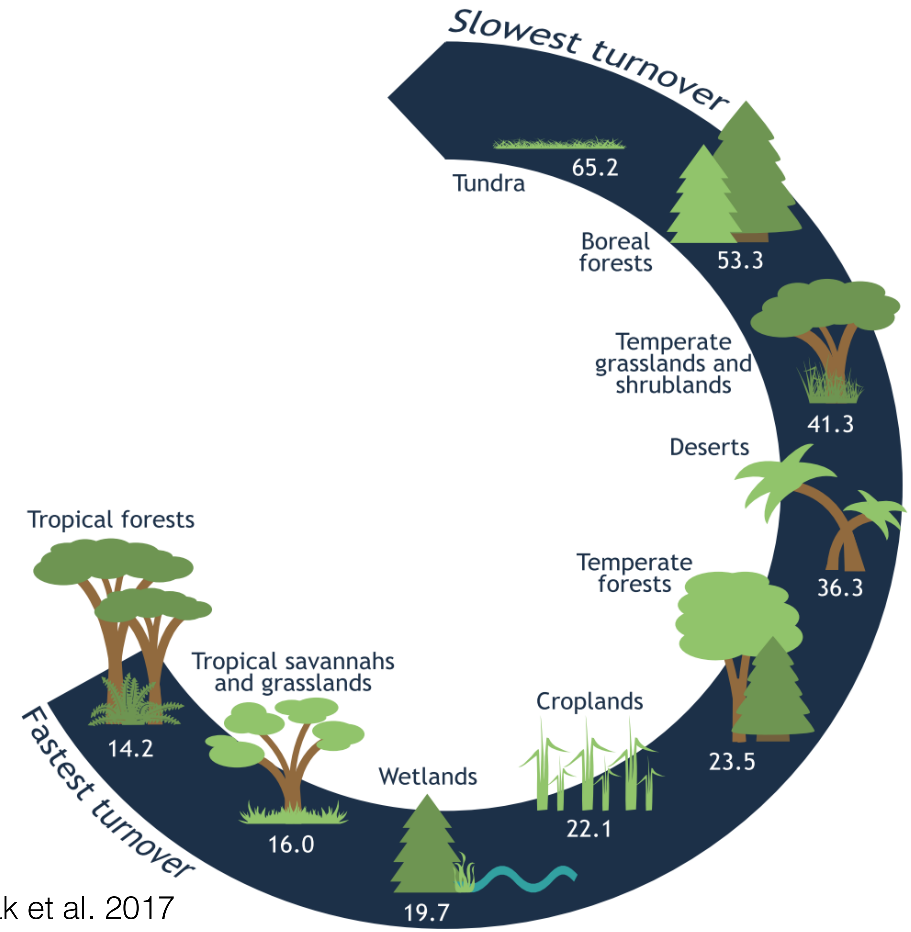
Figure 5. A depiction of the forest carbon cycle including both aboveground and belowground storage and flux terms. Carbon (Gt C) stocks are denoted in parentheses and shown in gigatons. Fluxes (Gt C per year) are associated with arrows and shown in gigatons per year.

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)



Janowiak et al. 2017

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

Importance of forests for the global CO_2 cycle

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

Importance of forests for the global CO_2 cycle

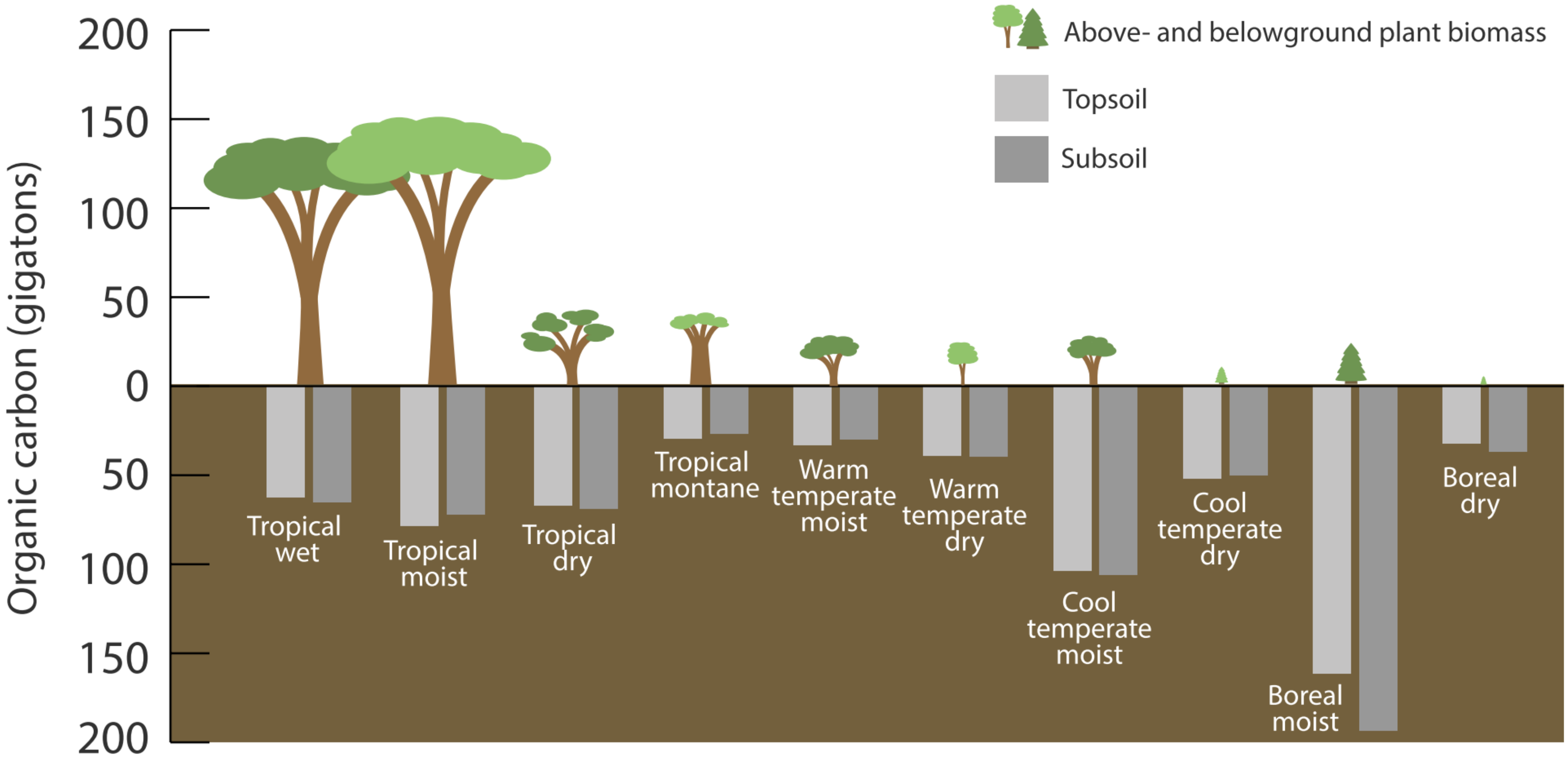


Figure 2. Carbon stored in ecosystems, shown in gigatons. Data from Scharlemann et al. (2014).

Janowiak et al. 2017

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

Image: M. Staudinger, ETH

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

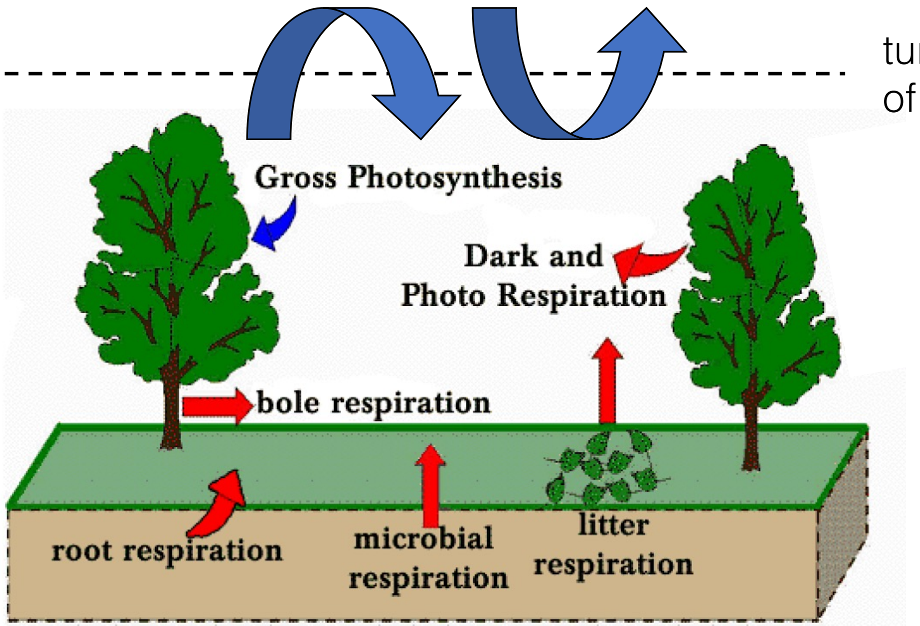
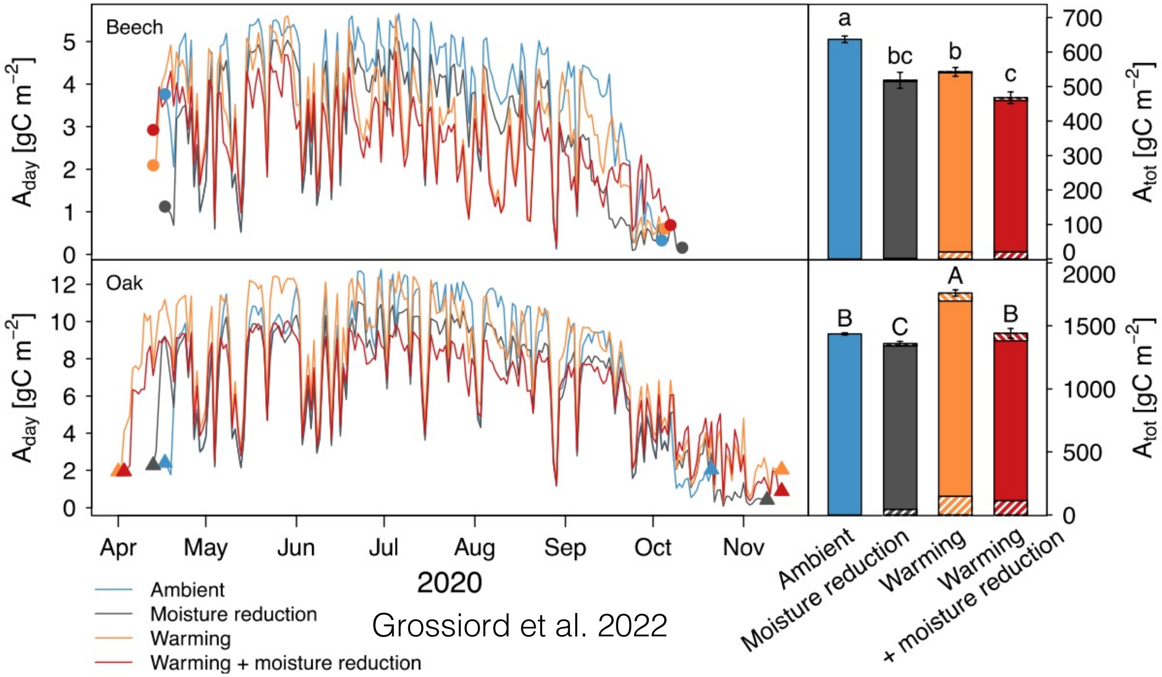
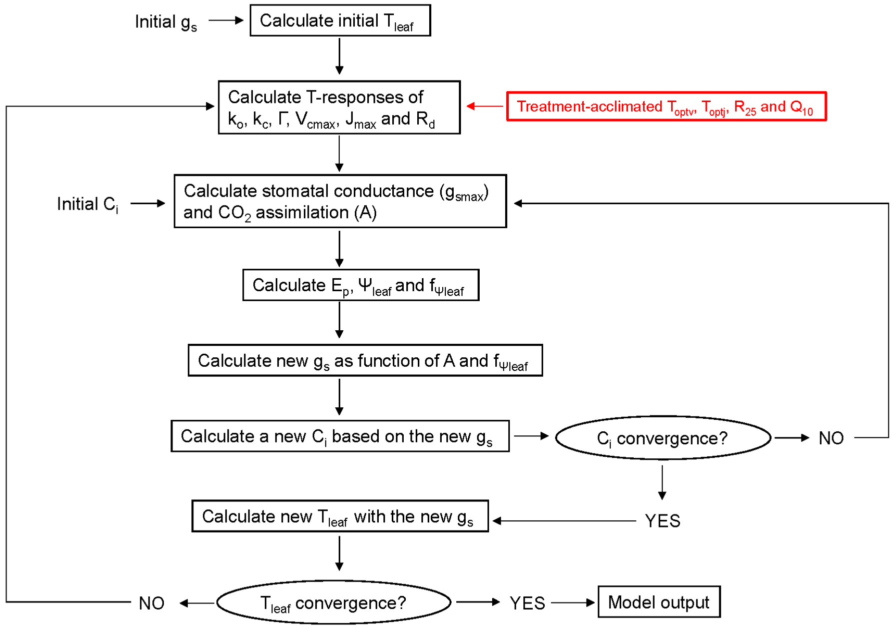


Figure 6 Flows of Carbon dioxide in and out of an ecosystem

Photosynthesis upscaling models



Grossiord et al. 2022



Deluigi et al. in prep.

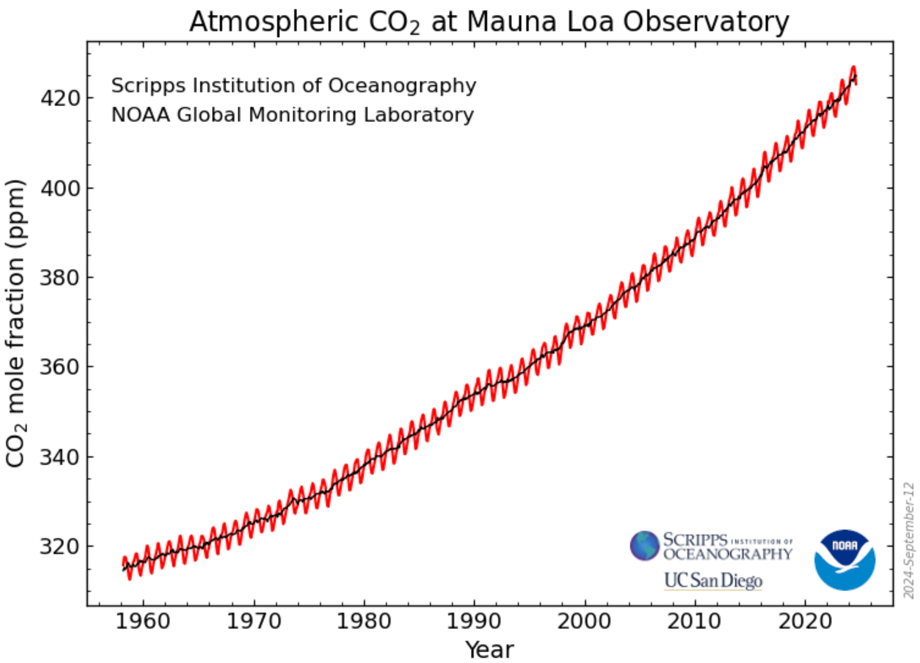

Plants respond to their environment
Impacts of CO_2 rise on plants

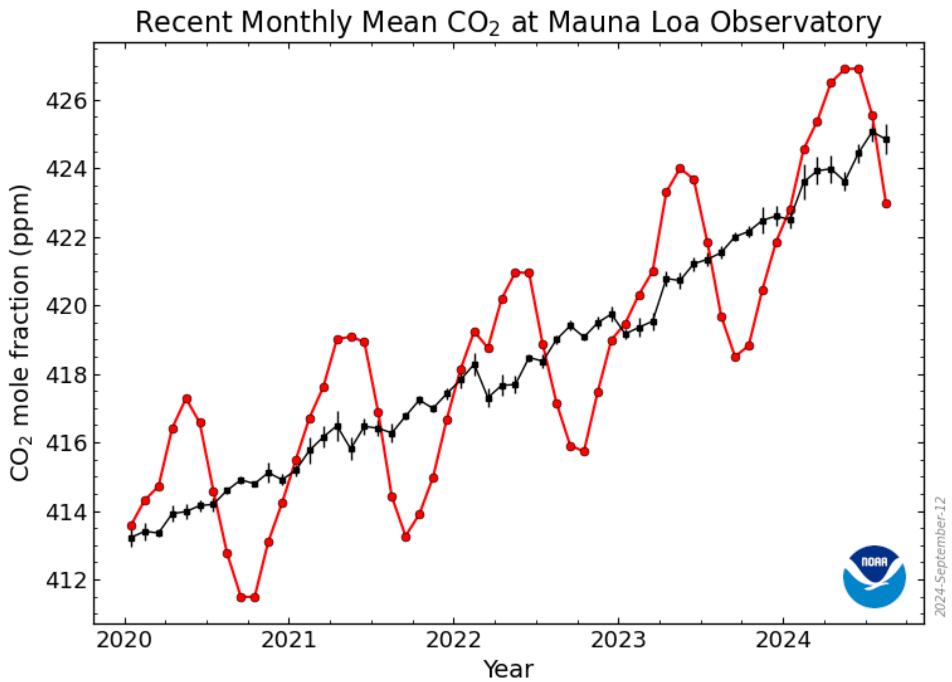
Plants respond to their environment

"Within the lifetime of an individual tree planted in the middle of the 19th century, the availability of atmospheric CO_2 concentration will have doubled from 285 ppm in 1850 to more than 500 ppm within the coming decades" (Fatichi & Leuzinger 2018)

Change in atmospheric CO_2

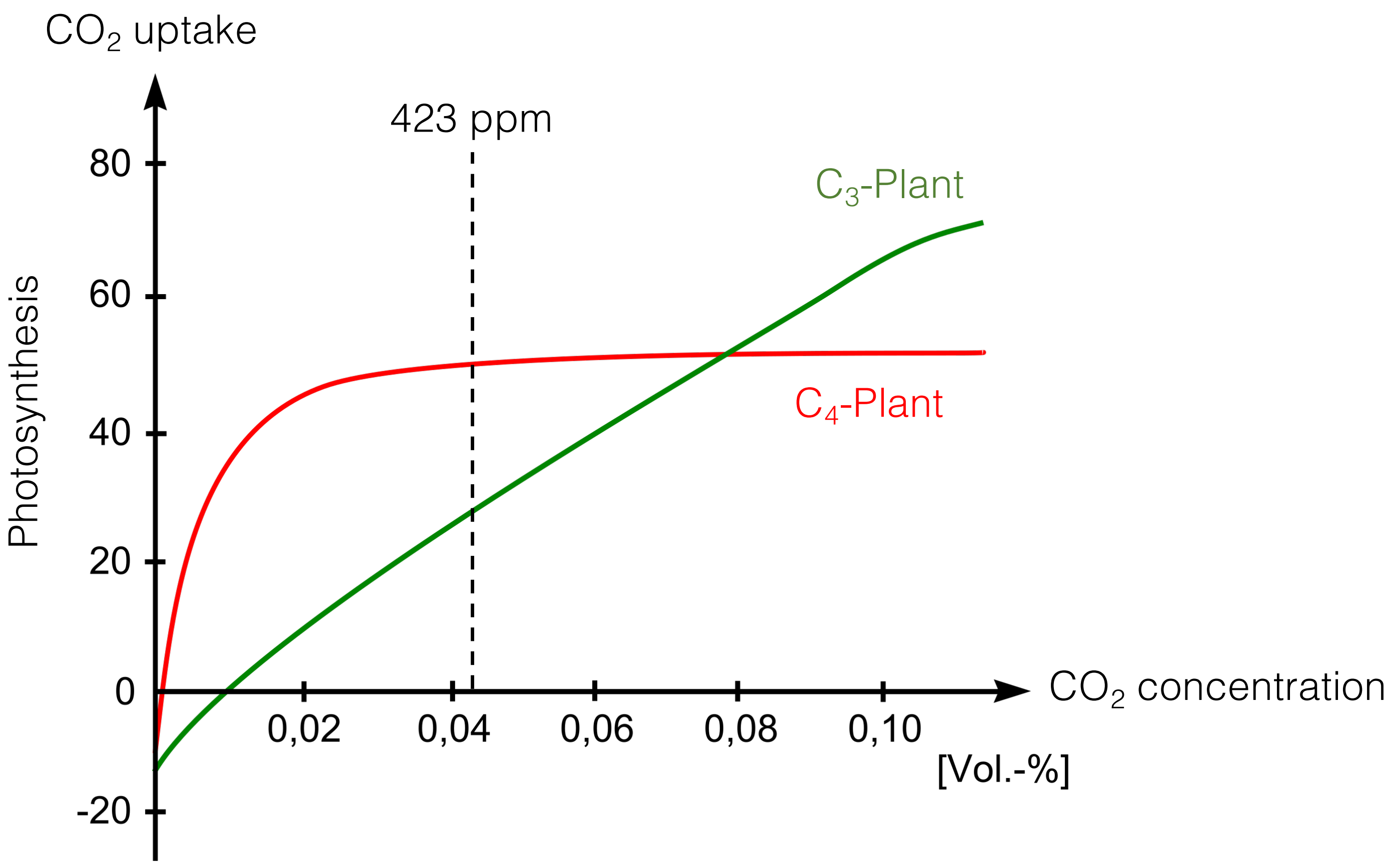
Since the Industrial Revolution began, the burning of fossil fuels has led to an exponential increase in the concentration of CO_2 and other greenhouse gases in the atmosphere.





Plants responses to higher CO_2

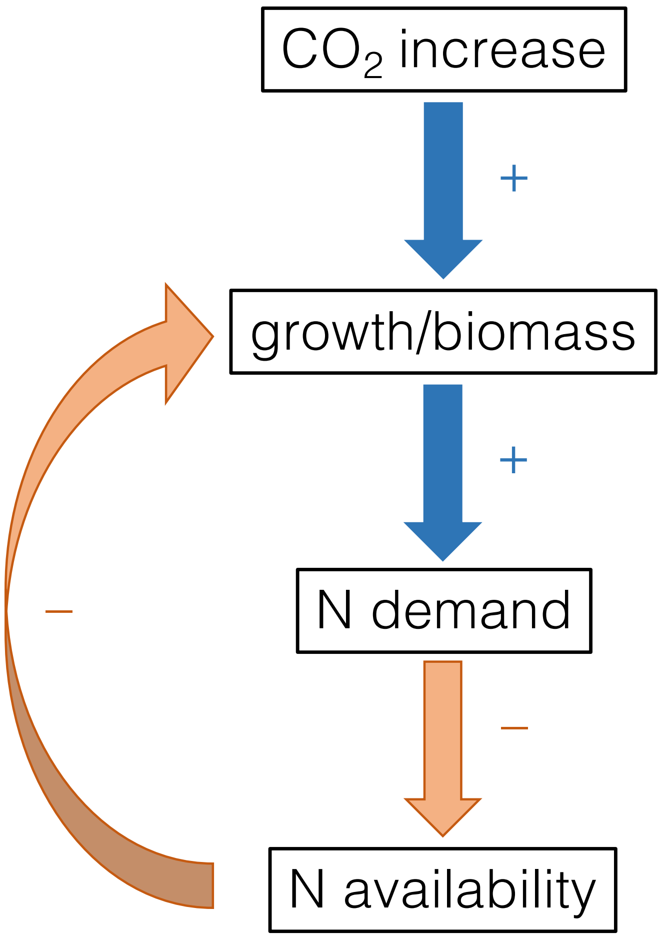
Corn: a C4 plant



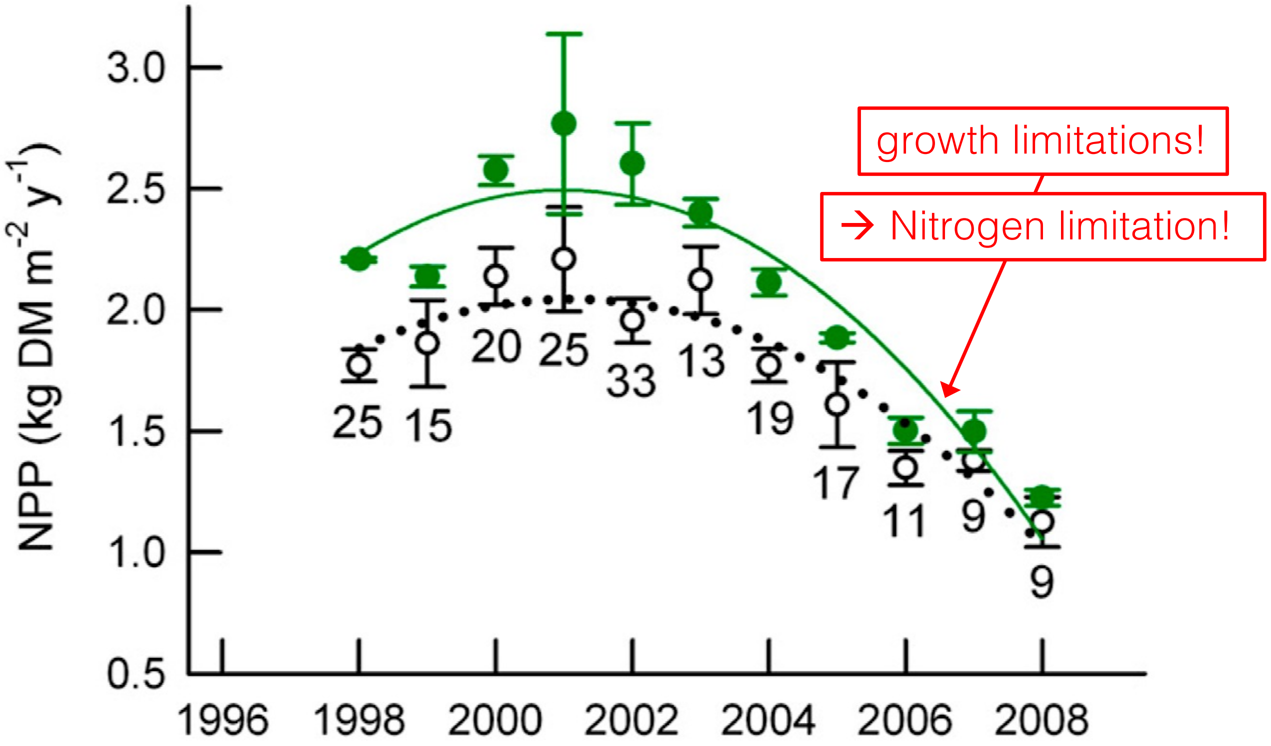
CO_2 fertilisation: Duke FACE experiment

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

CO_2 fertilisation: Duke FACE experiment



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

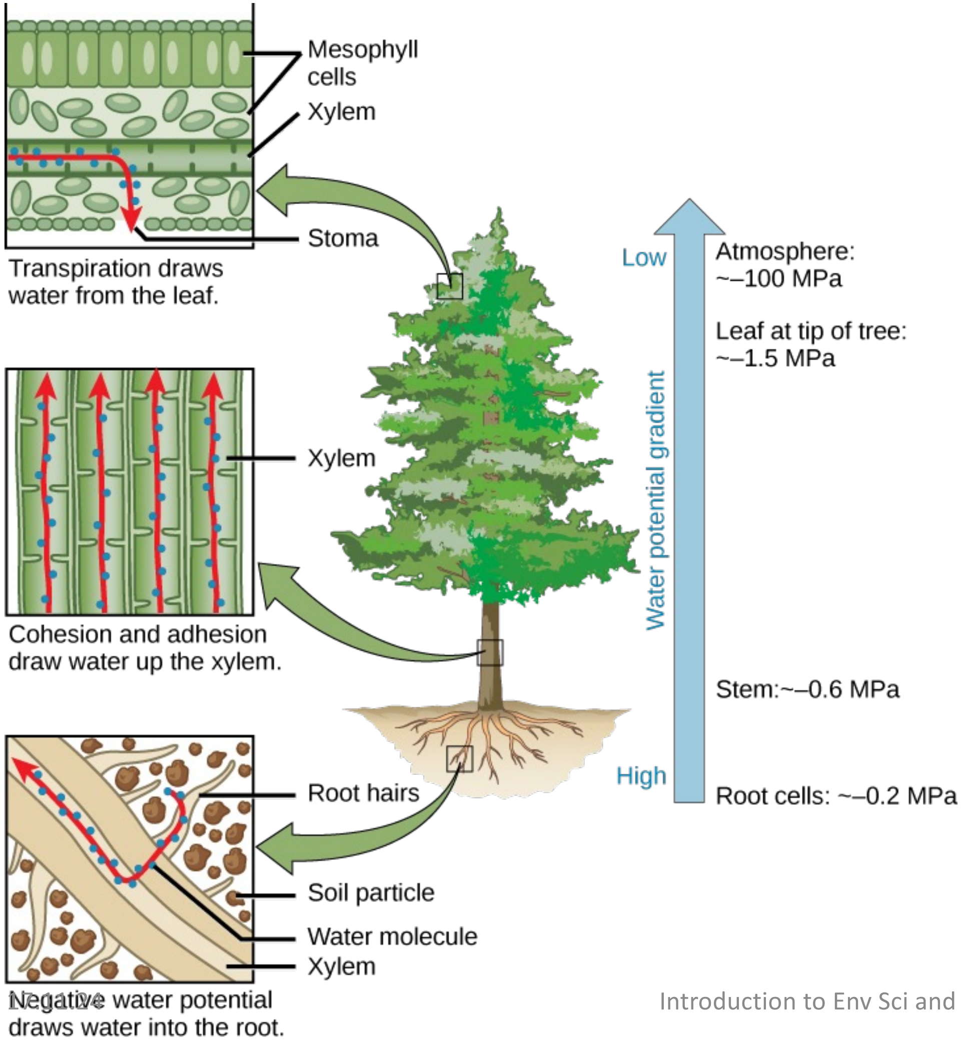


Norby et al. 2019 PNAS

Plants respond to their environment

Stomata and tree transpiration

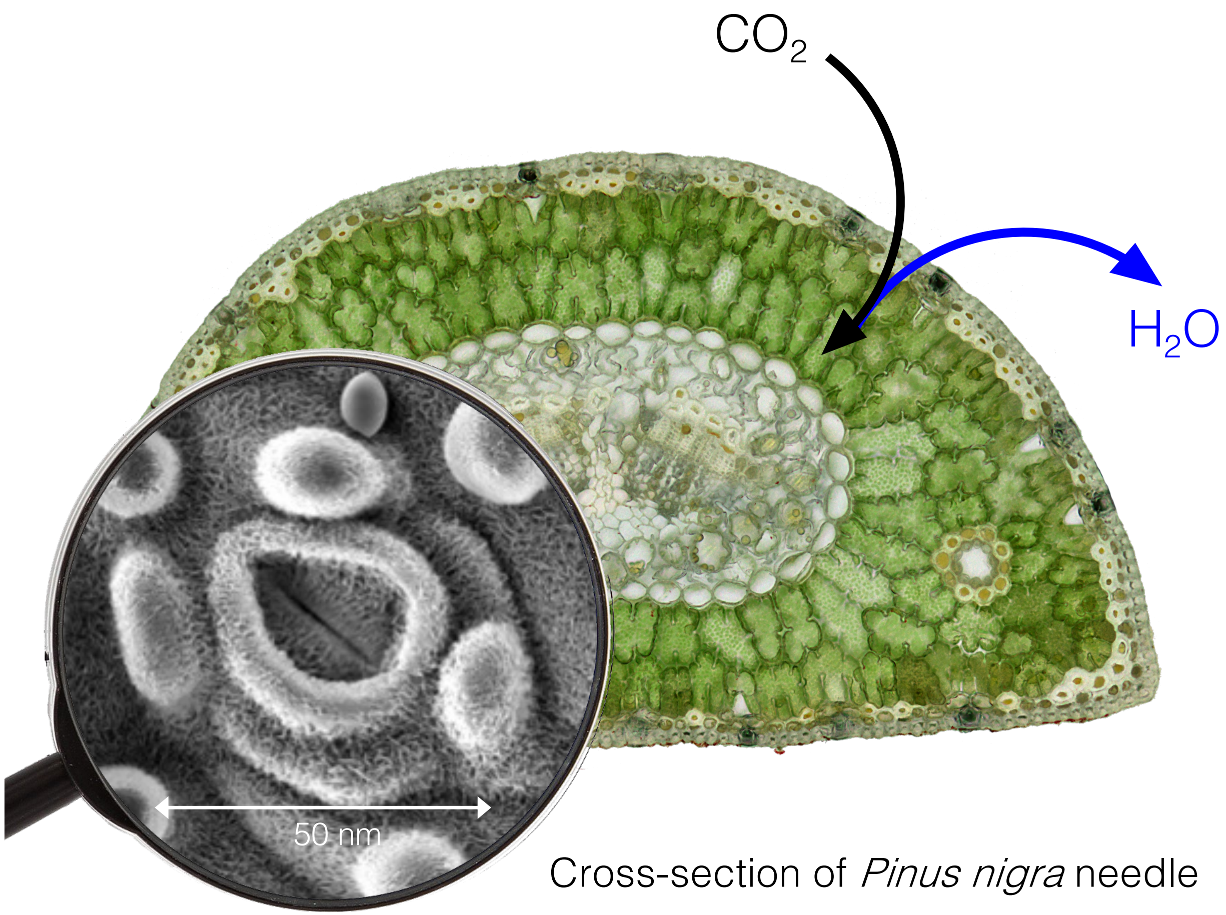
Soil – Plant – Atmosphere continuum



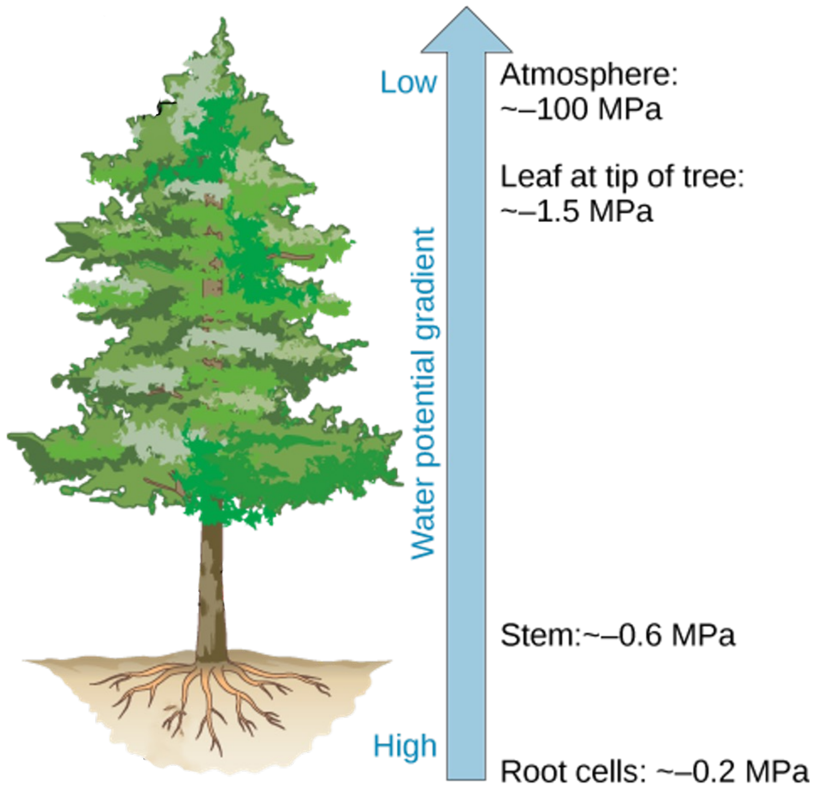
Cohesion-tension theory of water flow:

- Transpiration is the main driver of water movement in the plant
- 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

Tree transpiration



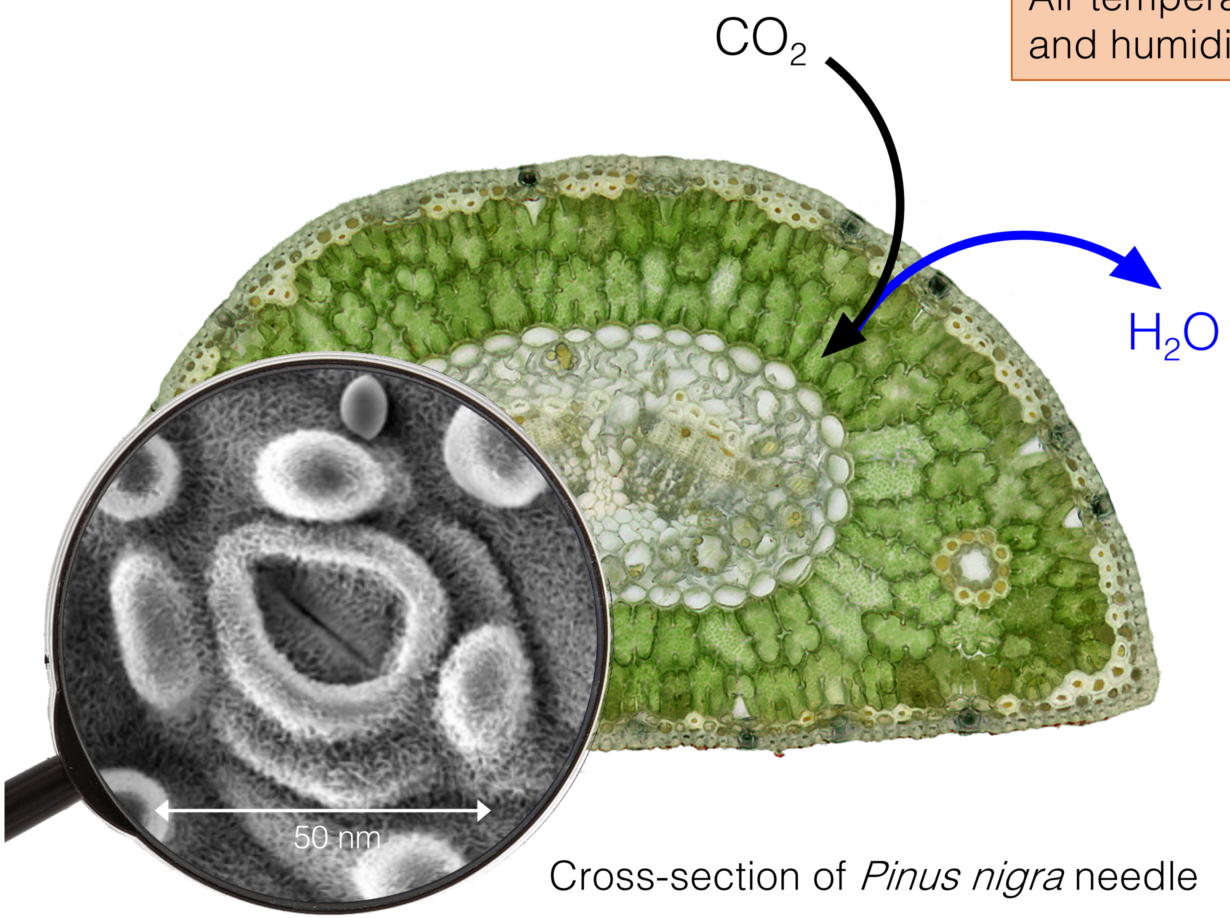
Cross-section of *Pinus nigra* needle



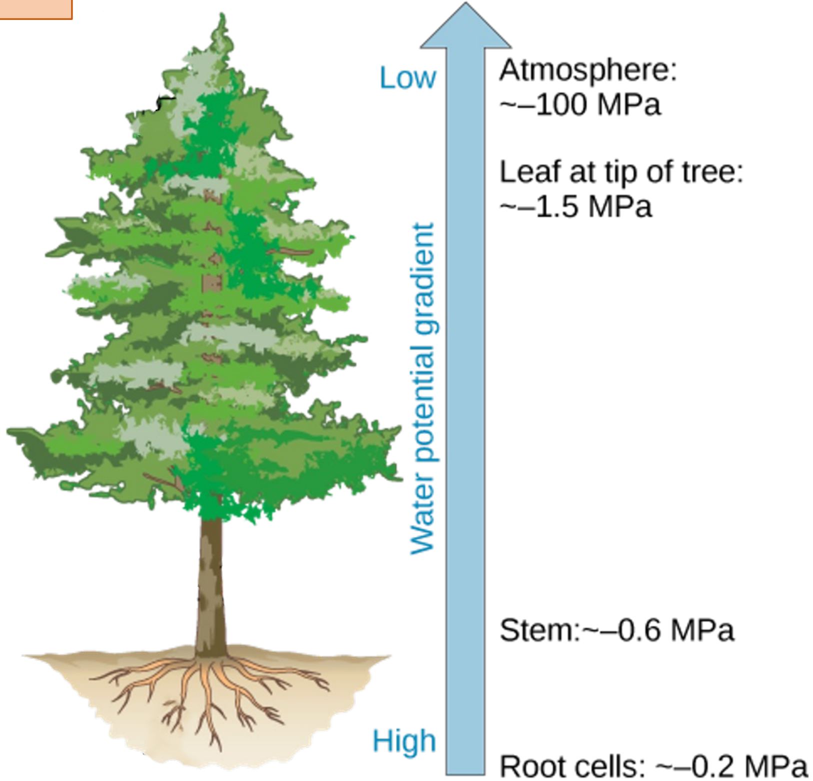
Photos: Mana Gharoun, Anouchka Perret-Gentil, Christoph Bachofen

Tree transpiration

Air temperature and humidity → Vapour pressure deficit (VPD) Stomatal conductance (g_S)



Cross-section of *Pinus nigra* needle

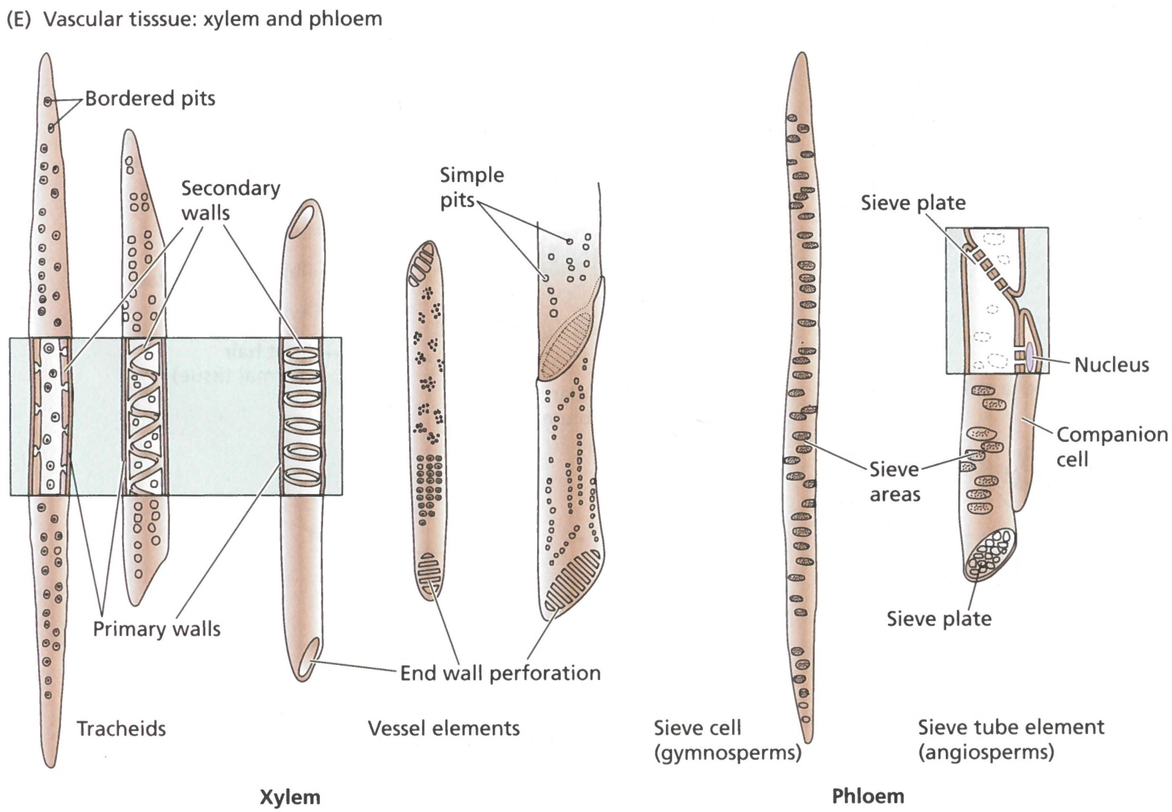


Soil water content
Soil water potential

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

Overview of plant structure & function: water transport

- Water transport takes place through specialised cells: xylem
- Xylem is a simple pathway of low water resistance
- In the tallest trees (~ 100 m), the pressure gradient required to move water from the roots to the canopy top amounts to roughly 3 MPa
- Increasing tensions in the xylem can lead to formation of **air embolism**, breaking the continuity of water transport



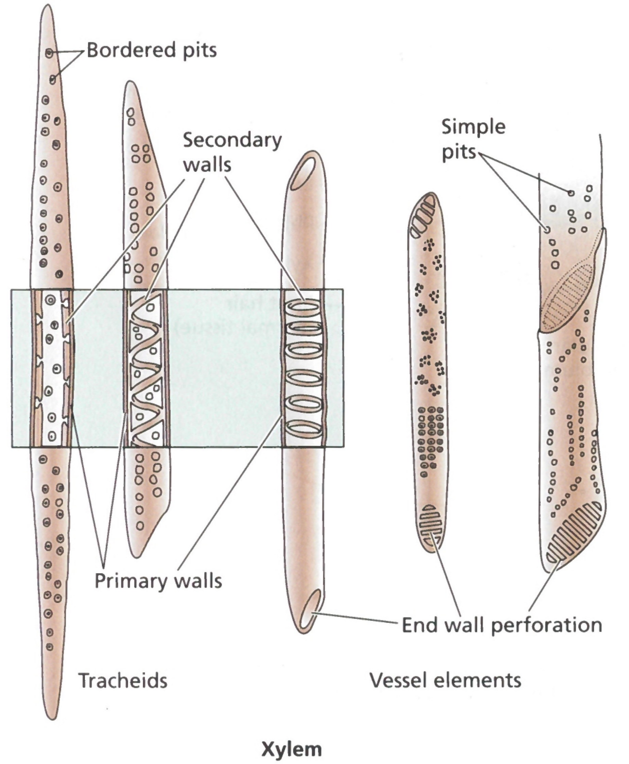
Overview of plant structure & function: water transport

More drought tolerant

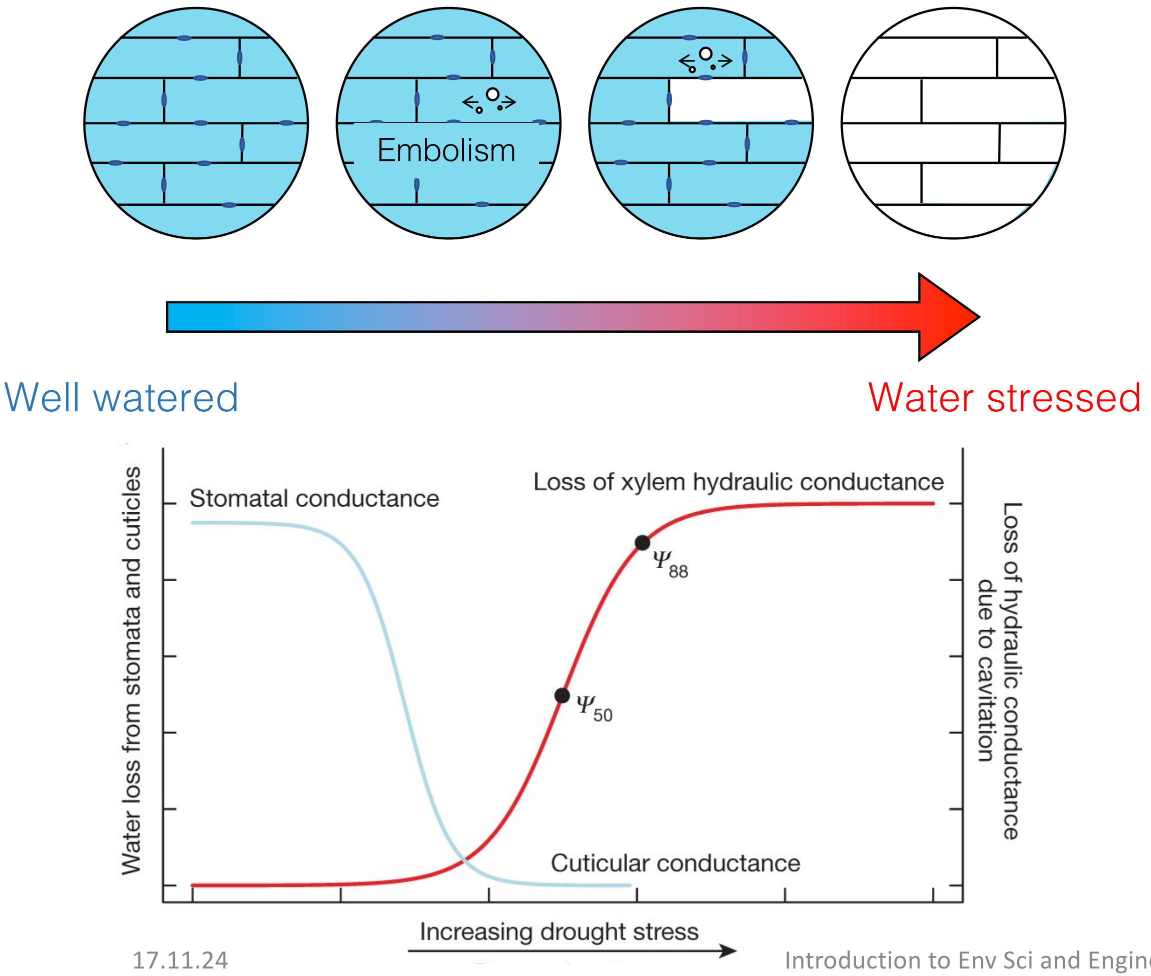
Downy oak

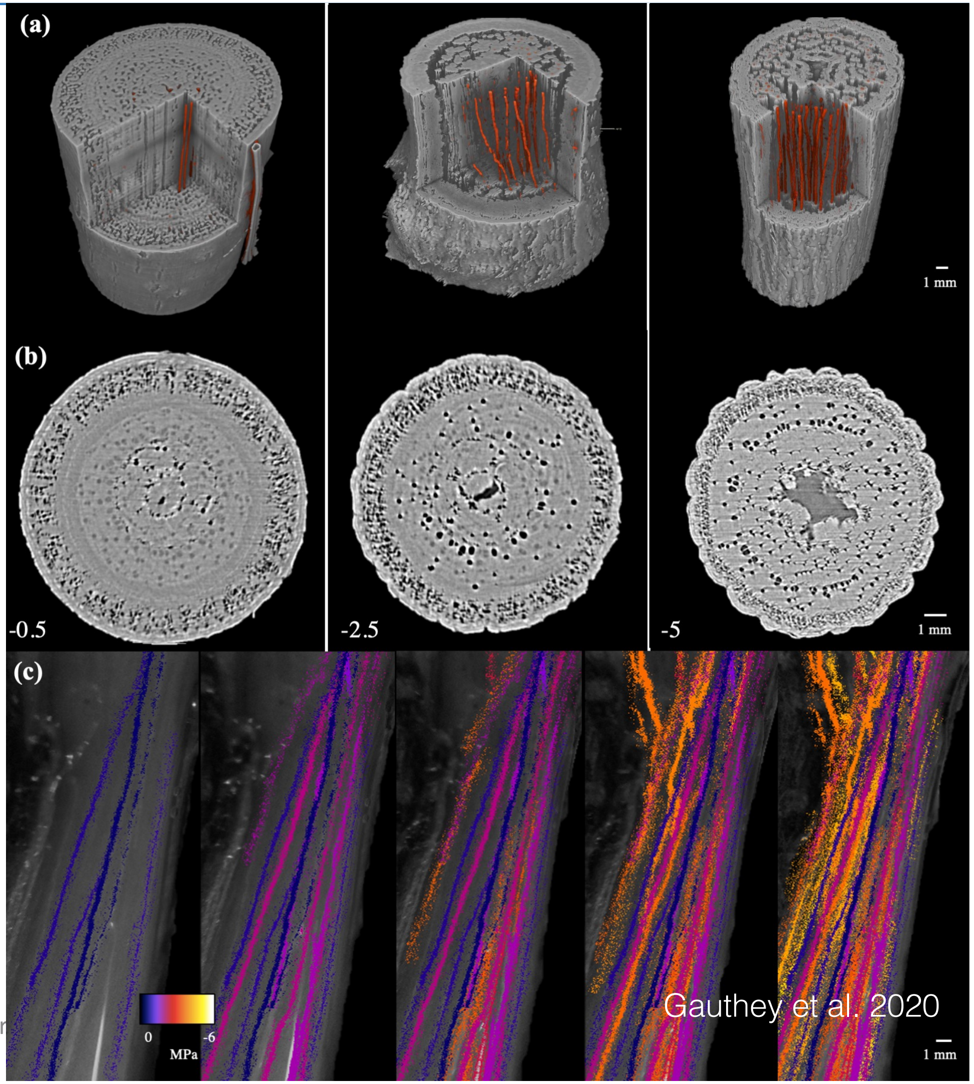
More drought sensitive

European beech



Air embolism in the xylem



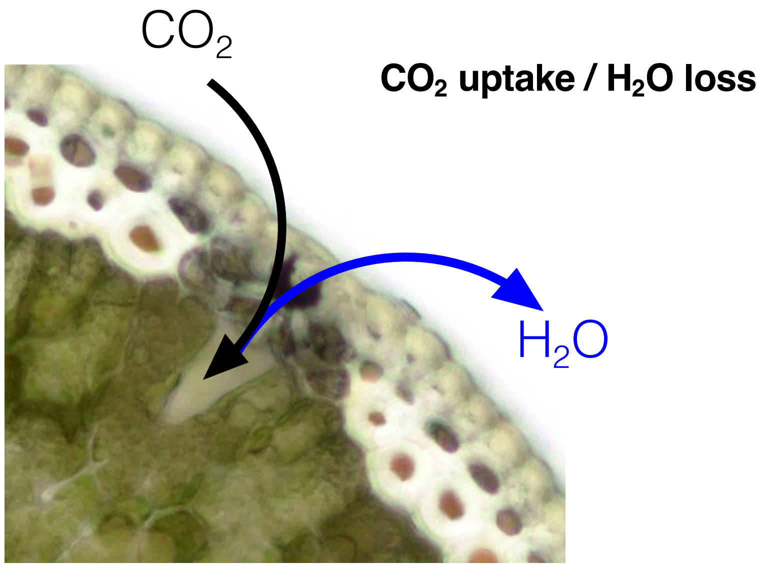


Platforme PIXE de l'EPFL

Stomata and their conductance to CO_2 and H_2O

CO_2 uptake from the atmosphere into the leaf

→ openings on the leaf surface: **stomata**



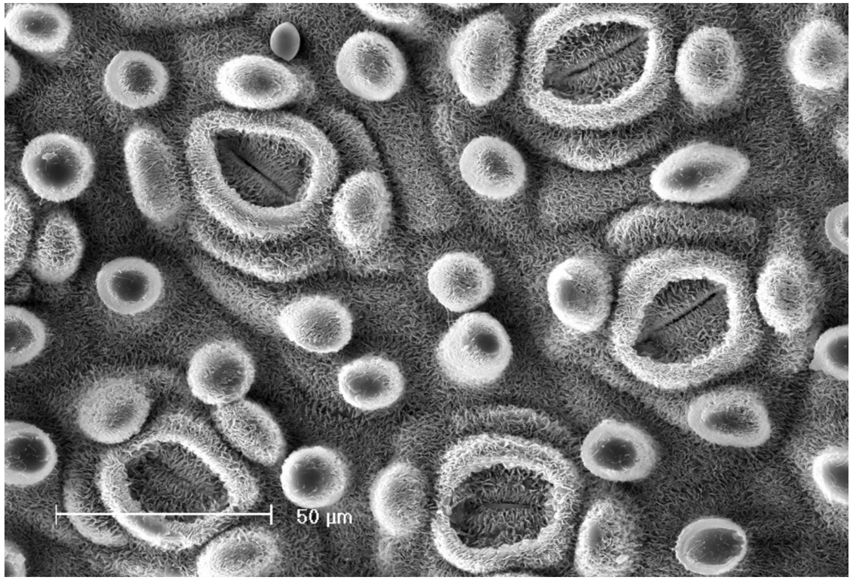
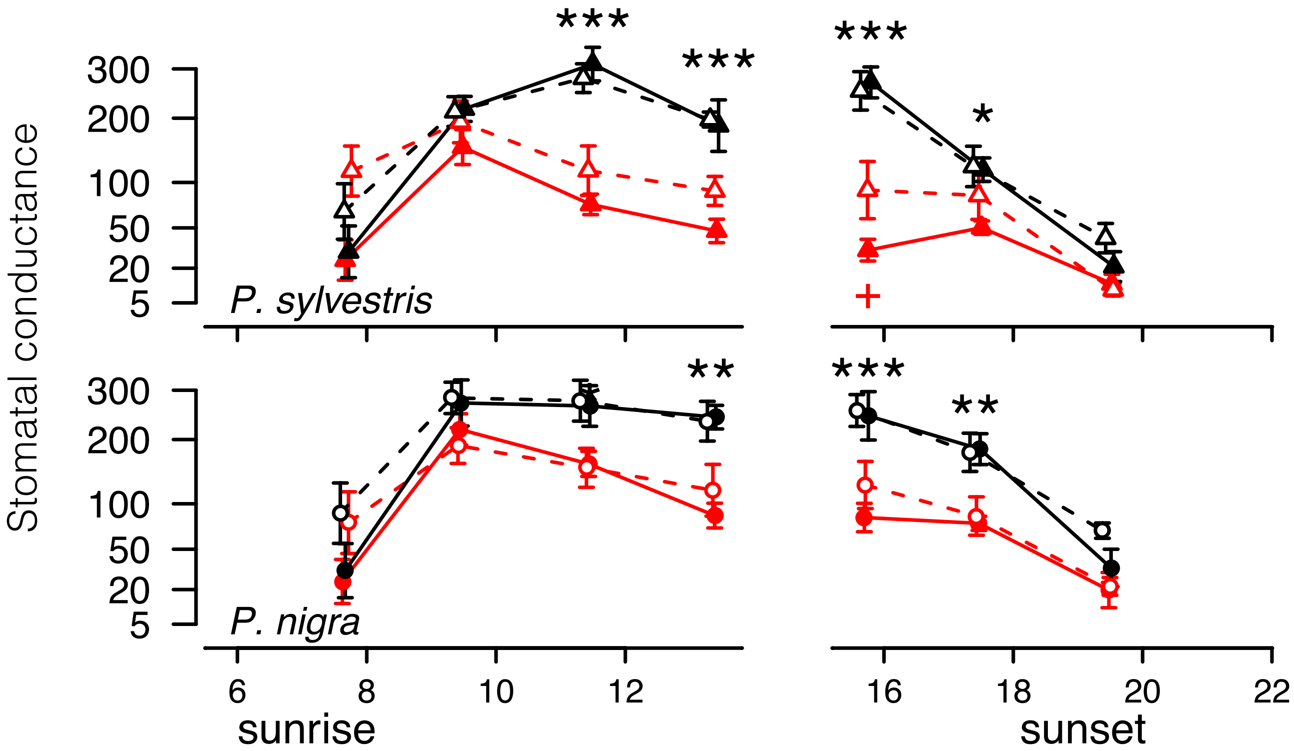


Photo: Mana Gharun ETH

- CO_2 uptake through stomata (**stomatal conductance**, µmol/m^2/s^{-1})
- **Stomatal conductance** is regulated by environmental and biochemical factors (e.g. soil moisture, light availability, plant hormones, etc.)

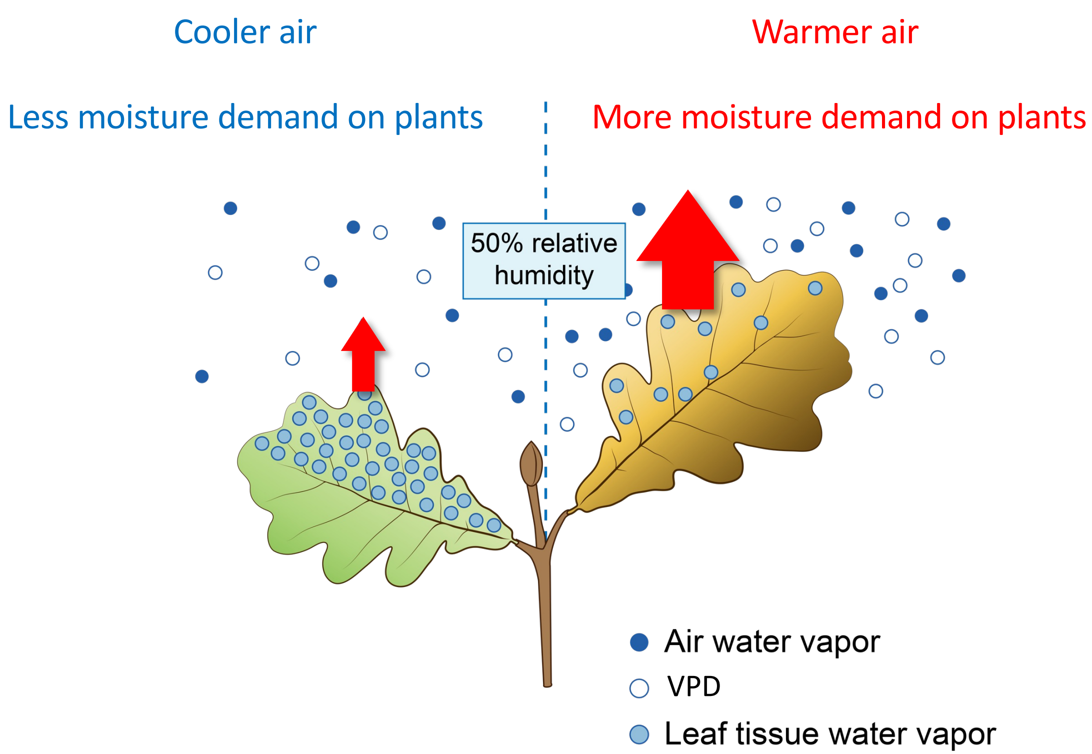
Tree transpiration is sensitive to soil drought



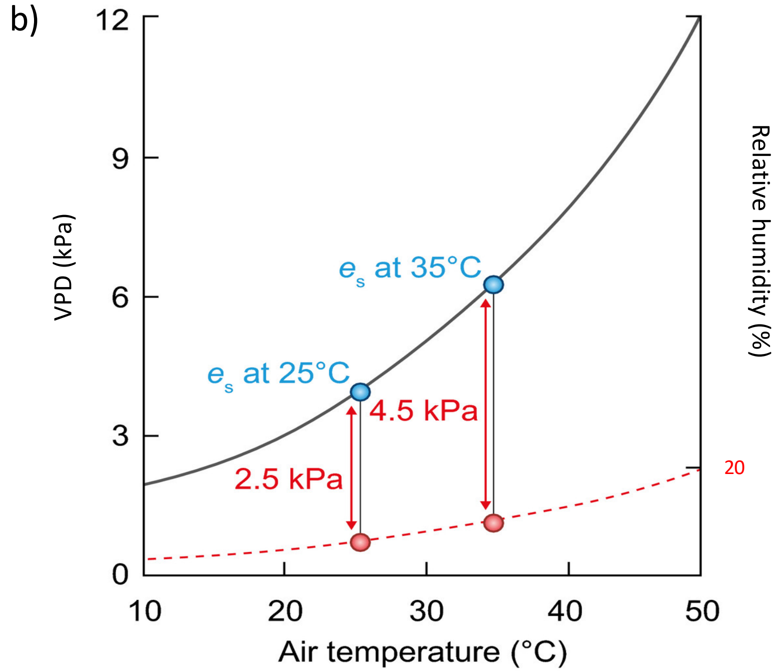
Bachofen et al. 2017

Transpiration responses to VPD

$$VPD = e_s - e_a = (611\exp(17.27 \times \mathbf{T} / 237.3 + \mathbf{T})) - (\mathbf{RH} \times e_s/100)$$

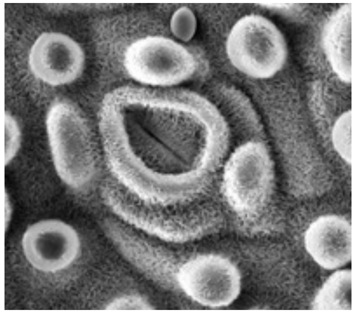


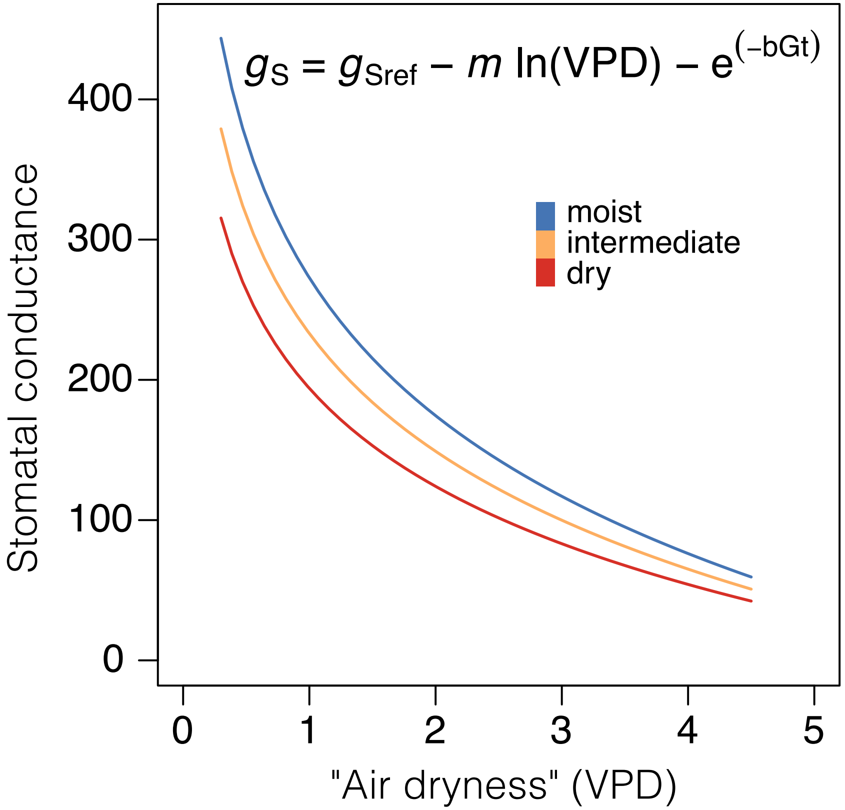
USGCRP, 2018



Grossiord et al. (2020) New Phytologist

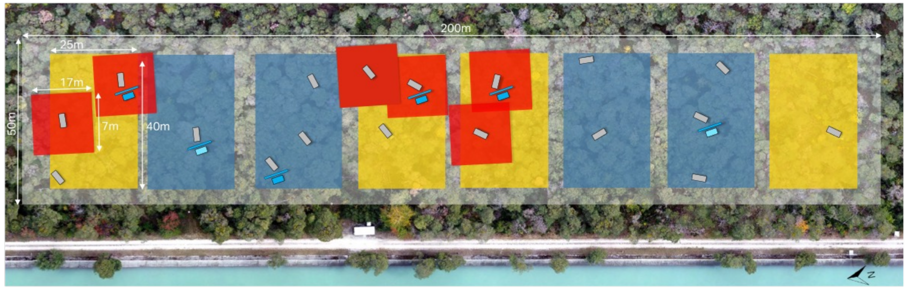
Transpiration responses to VPD and soil water





- 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

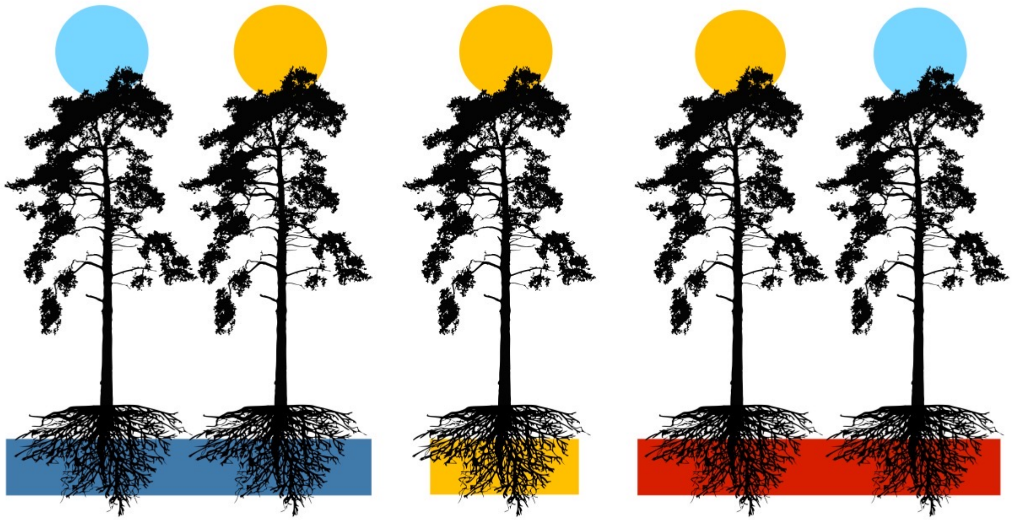


Soil Treatments
- Control (soil)
- Irrigation
- Drought

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

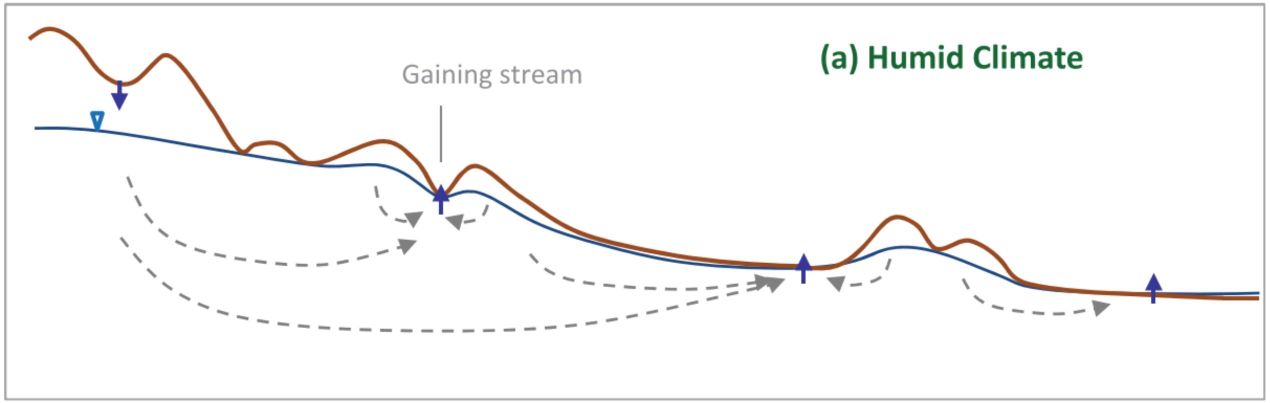
Atmospheric Treatments
- Control (air)
- VPD manipulation

Plants respond to their environment

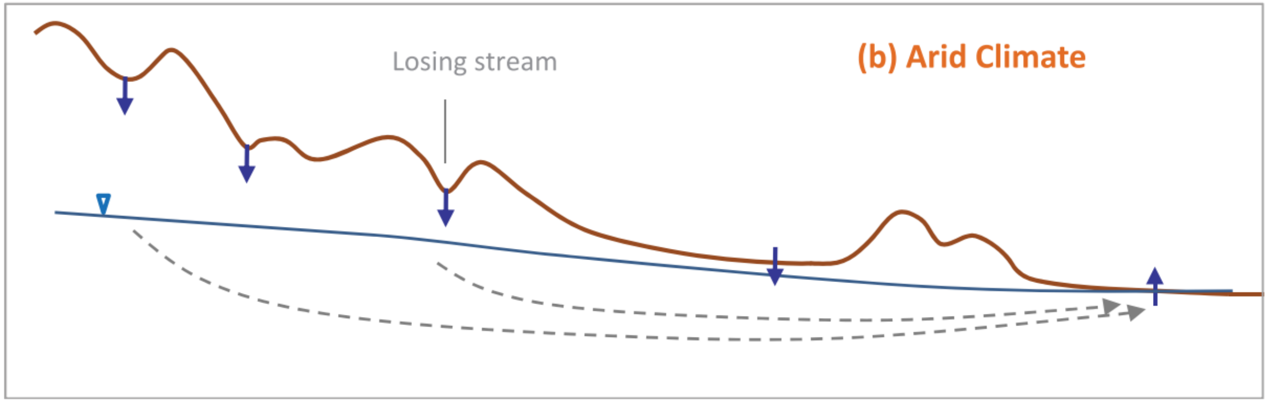
Roots and water uptake

Water table and rooting depth

(a) In a humid climate, the water table is high and discharges into streams with both shallow/short and deep/long flow paths



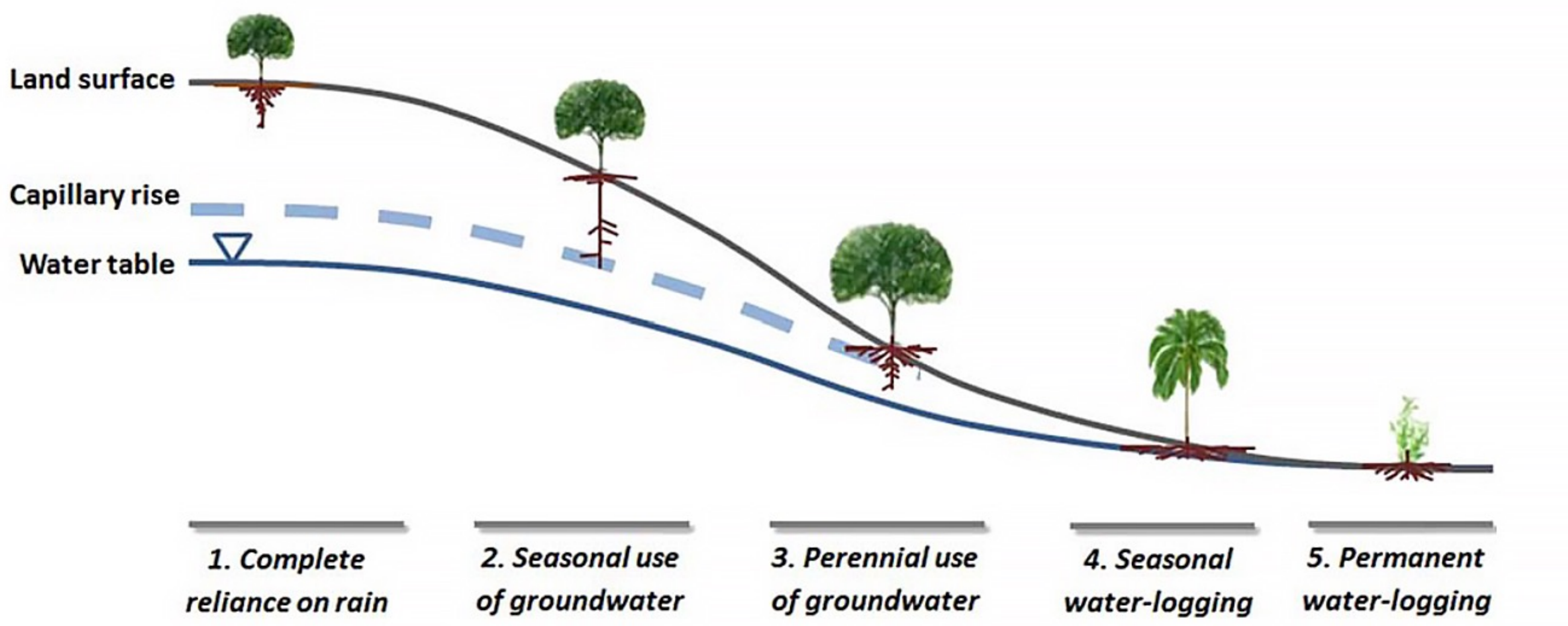
(b) In an arid climate, the water table is low and streams lose their water via seepage into the bed sediments with deeper and longer flow paths.



Fan 2015, Water Resources Research

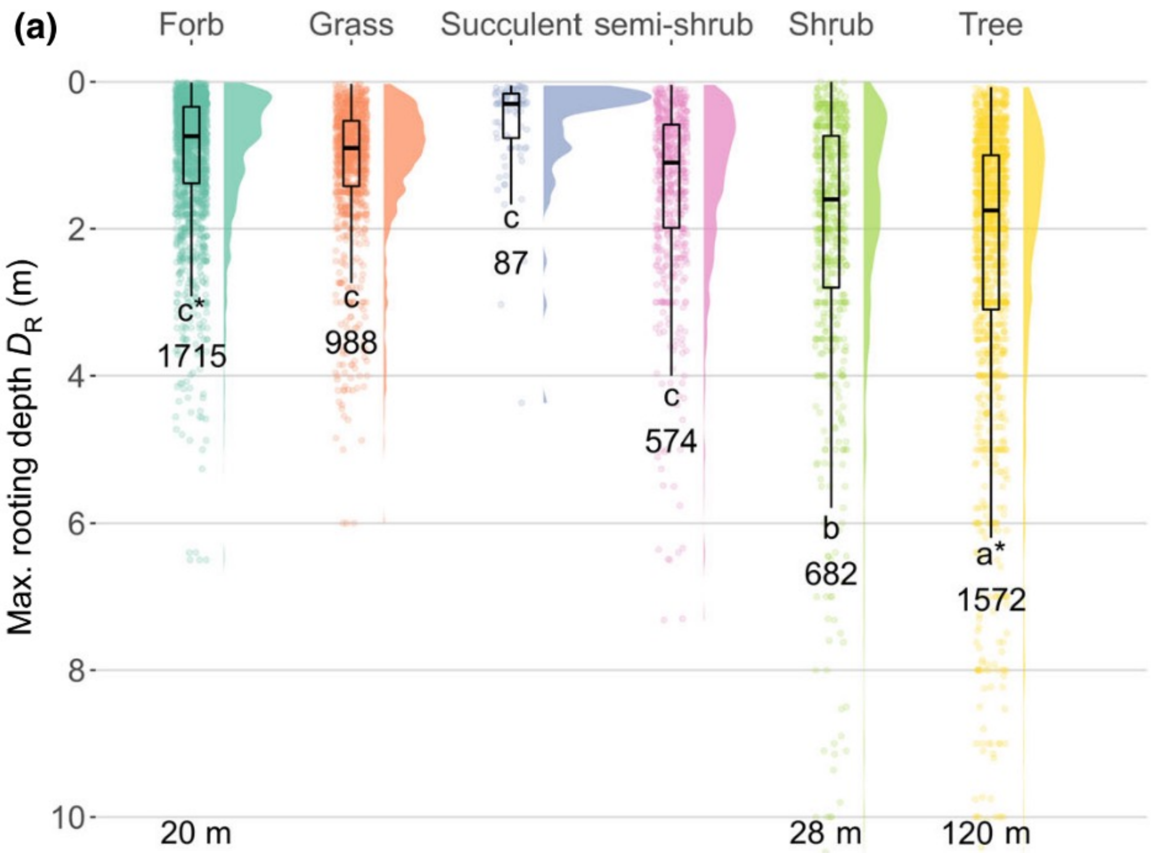
Water table and rooting depth

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



Fan 2015, Water Resources Research

Tree water uptake: rooting depth



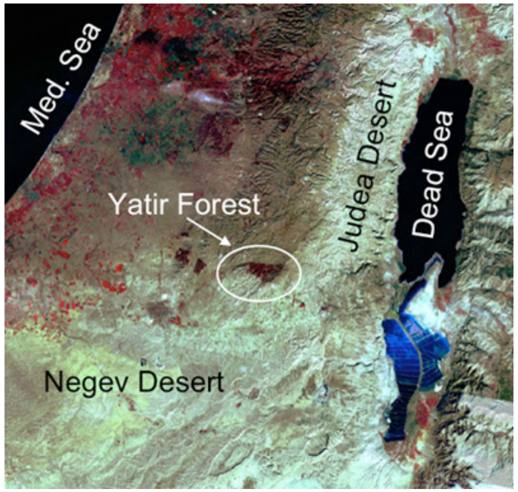
Quantifying plant water uptake based on root distribution of roots is difficult for three reasons:

- Presence of roots does not necessarily mean that roots take up water at this depth.
- Not all roots found in the soil are physiologically active.
- Assigning roots to different species is almost impossible. Genetic analyses are very laborious and expensive.

Tumber-Dávila et al. 2022

Aforestation and tree water uptake

- Yatir forest: largest aforestation in Israel
- Extremely dry: 300–350 mm annual rainfall
- Mainly drought-tolerant Aleppo pine (*Pinus halepensis*), which has a relatively shallow root system with a few taproots penetrating into deeper soil-filled crevices in the bedrock



Tree water uptake in the Yatir aforestation

Higher surface rock cover and stoniness resulted in higher soil water concentration. This extended the time above wilting point by several months across the long dry season.

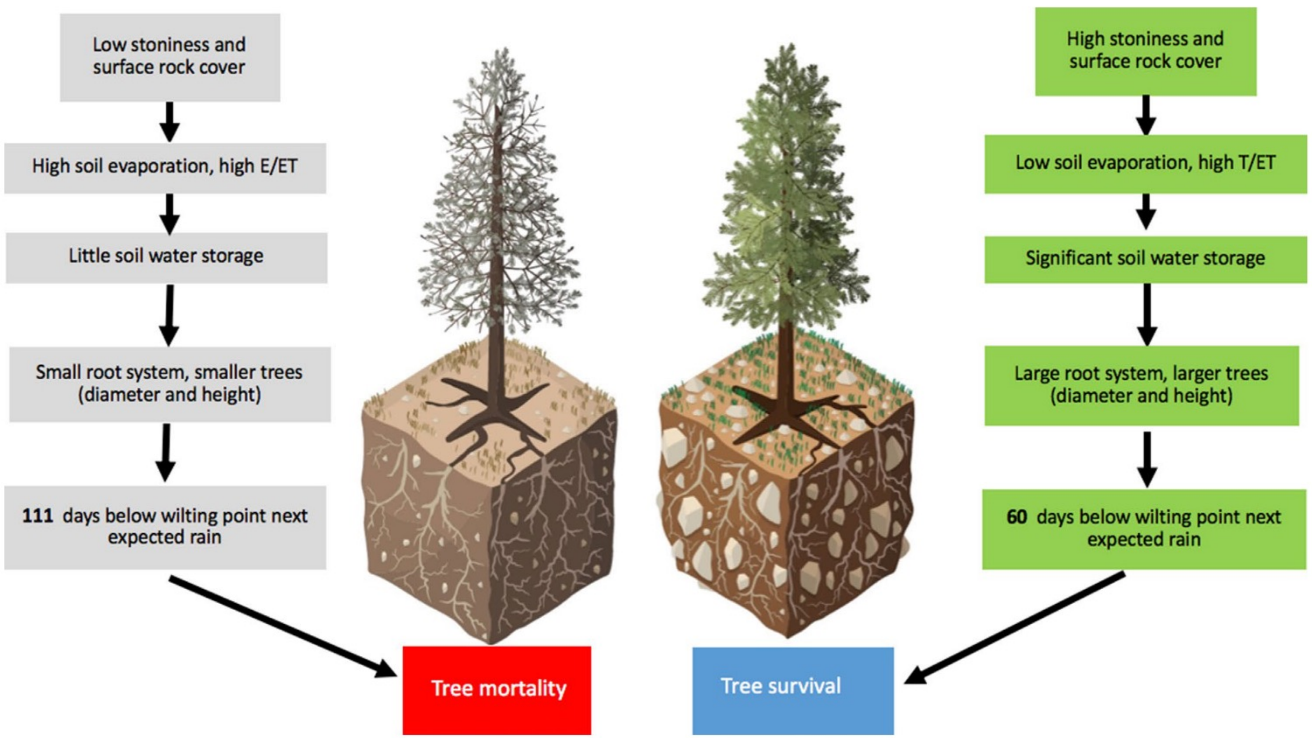


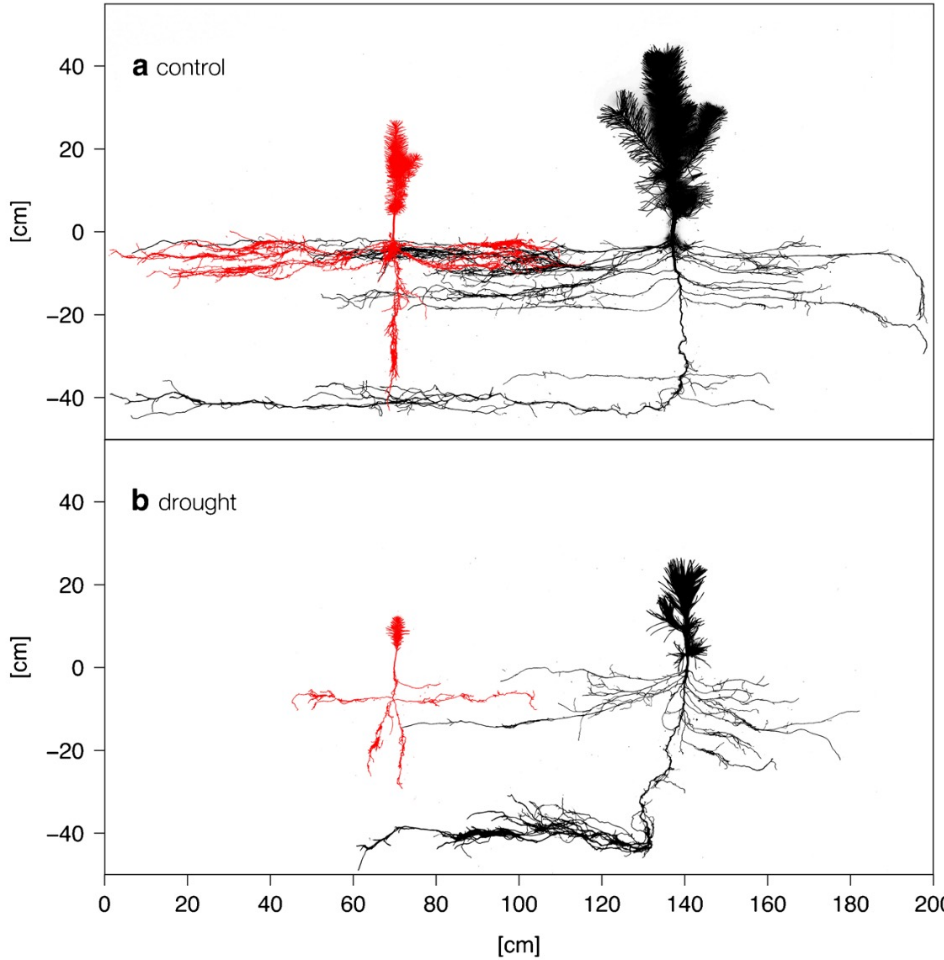
Fig. 6: A proposed conceptual sequence to mortality or survival associated with observed site variability in stoniness and rock cover, indicating the simulated shortening in of the period with no transpirable soil moisture content in the study site where seasonal drought can last well over 6 months.

Preisler 2019, Functional Ecology

Root research is hard!

Dig out plants!

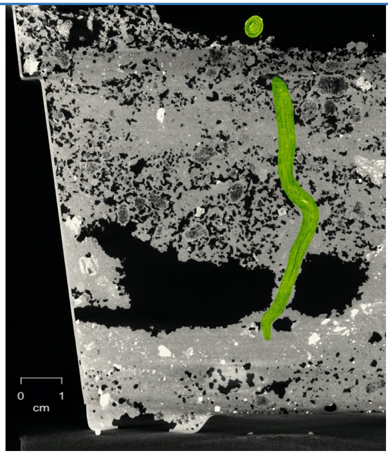
Bachofen et al. 2018

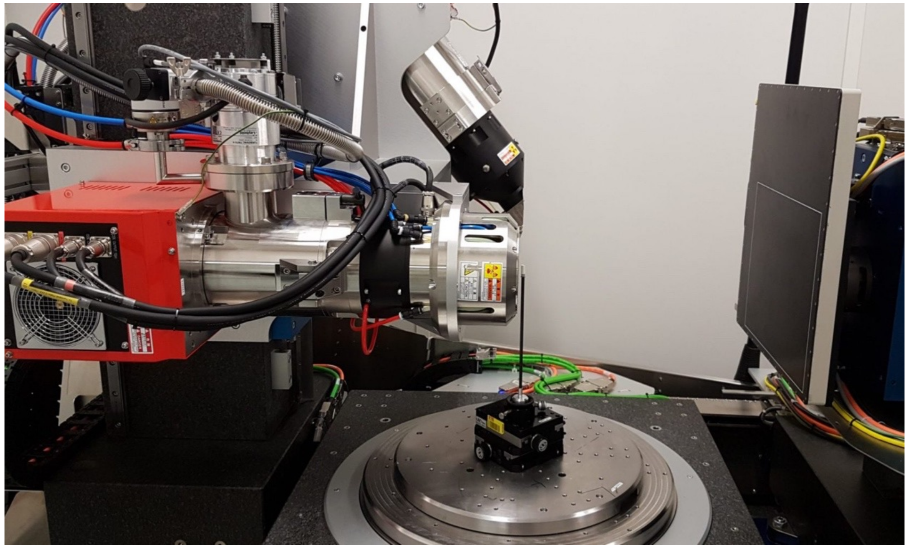


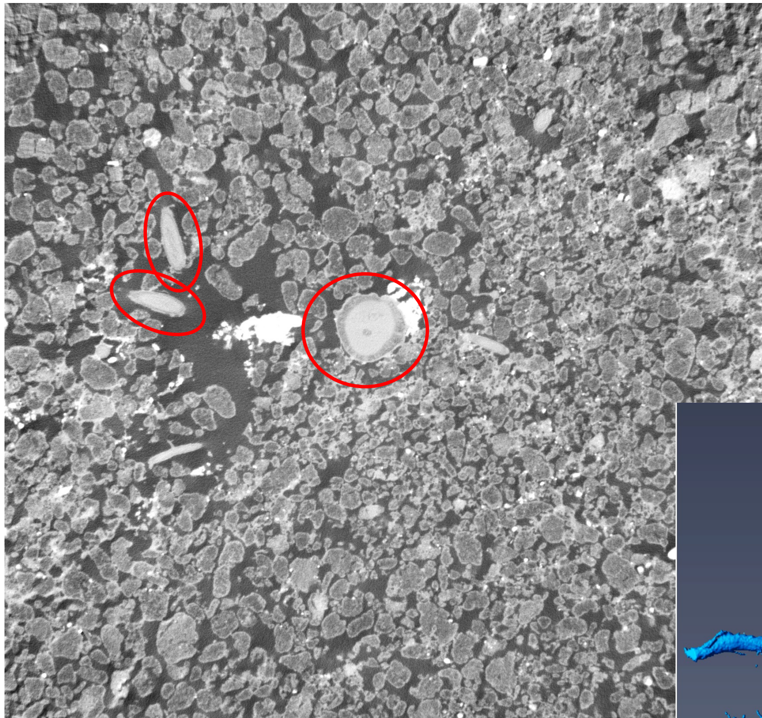
Moser et al. 2016

Root research is hard!

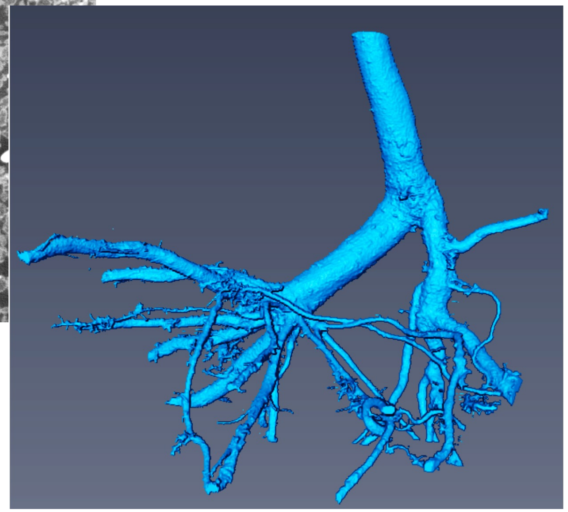
Micro-CT scan (X rays) of a spruce growing in perlite substrate





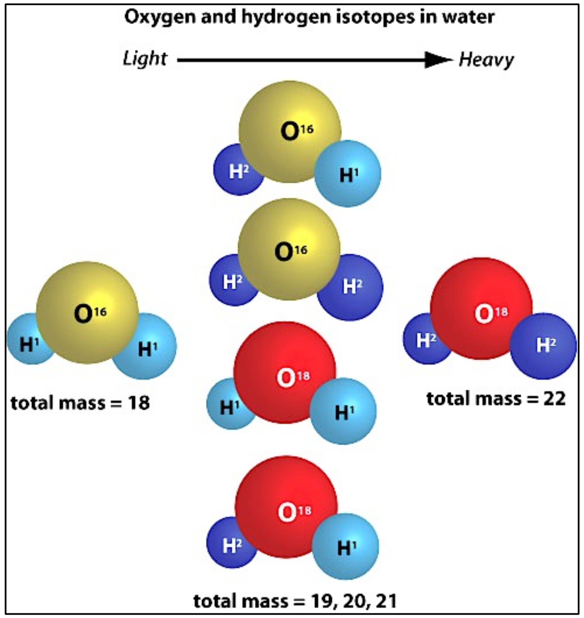


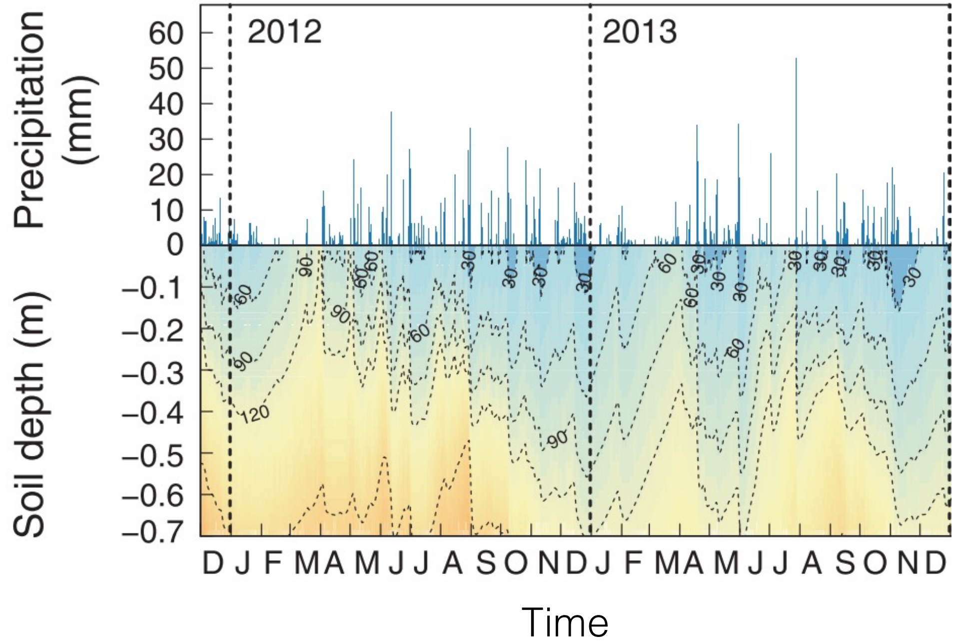
Van der Meer 2020

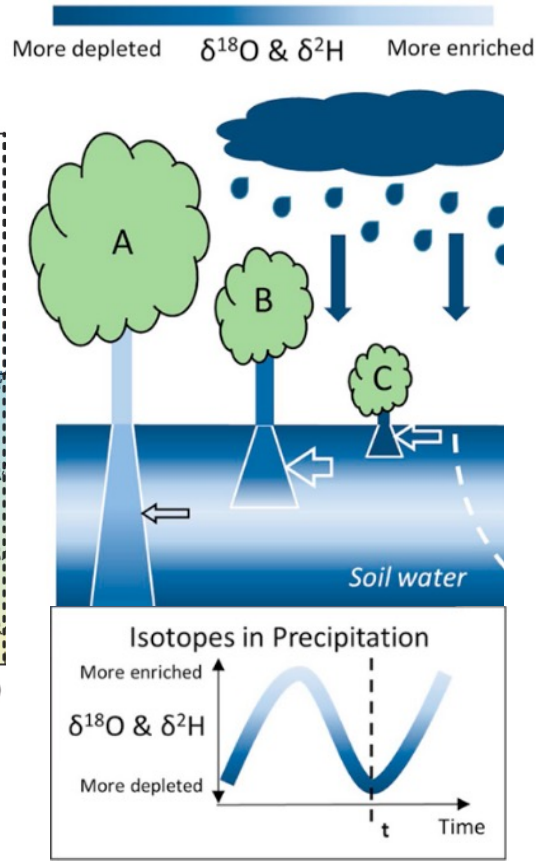


Root research is hard!

Soil and plant water isotopic composition

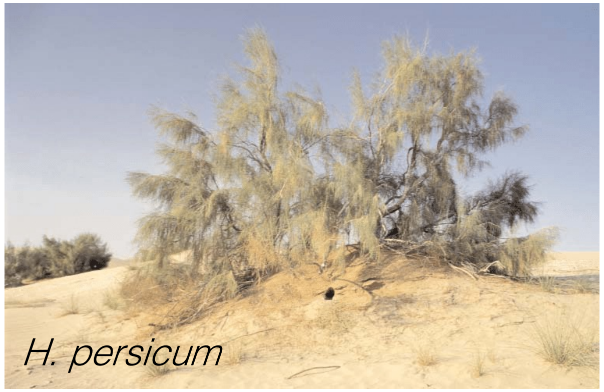






Water uptake depth in desert plants

- *Haloxylon ammodendron* and *Haloxylon persicum* are the dominant species in the Gurbantünggüt Desert (10–150 mm annual rainfall) in Xinjiang (China)
- Important plant to fixate sand
- *H. ammodendron* grows at inter-dune lowland and *H. persicum* grows at the sand dune
- How can they survive there?



Gurbantünggüt Desert, Xinjiang

Water uptake depth in desert plants

- In spring, topsoil was humid
  - *H. ammodendron* mainly used shallow soil water
  - *H. persicum* mainly used middle soil water
- In summer, topsoil was dry
  - *H. ammodendron* mainly used groundwater
  - *H. persicum* mainly used deep soil water.
- The ability to exploit a deep, reliable water source makes it possible for *H. ammodendron* to survive long periods without rain

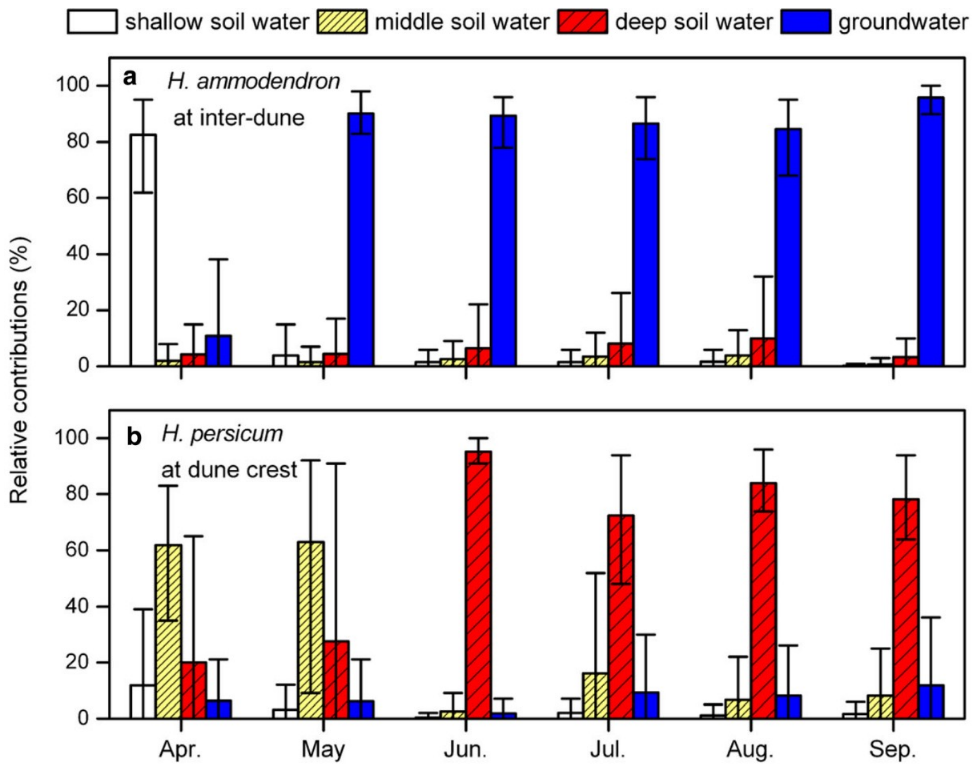
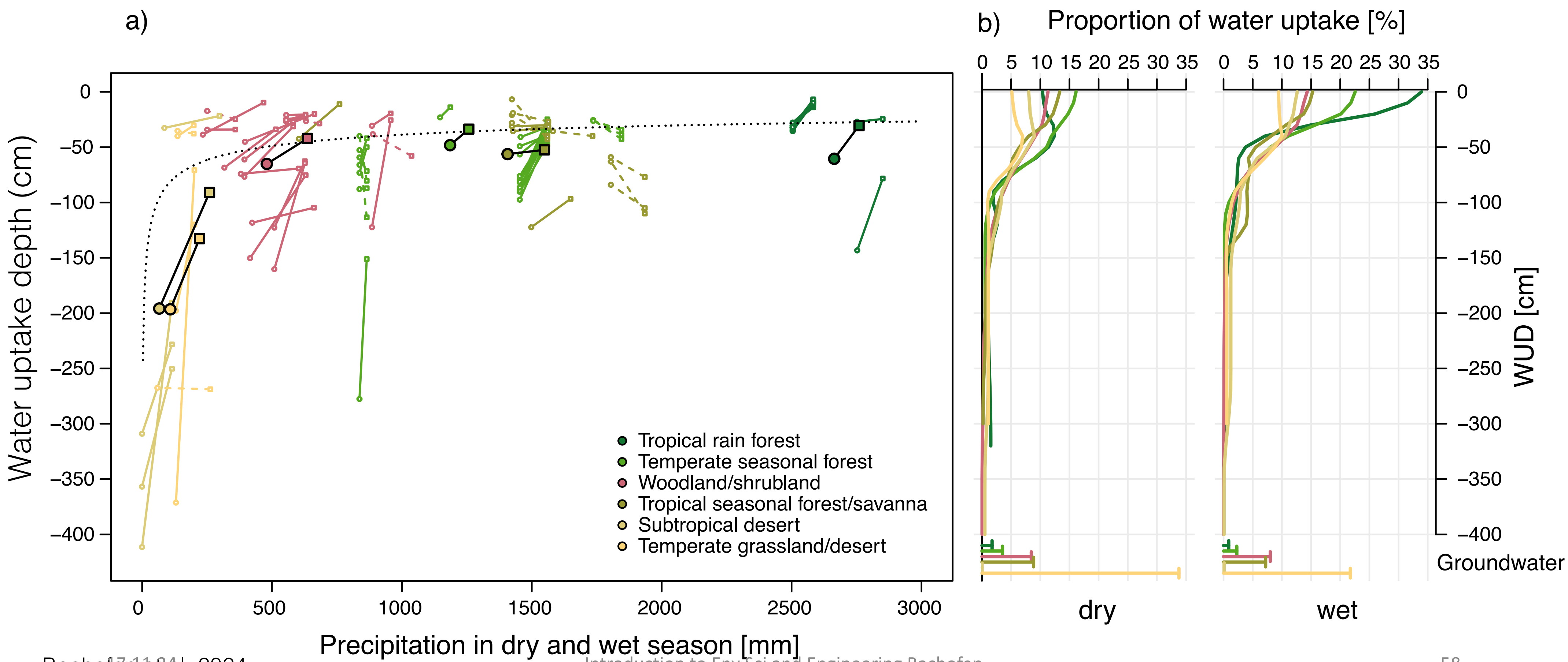


Fig. 4 Monthly changes in percentage contribution of potential water sources for H. ammodendron at inter-dune (a) and H. persicum at dune crest (b)

Dai 2015, Plant and Soil

Global water uptake depth

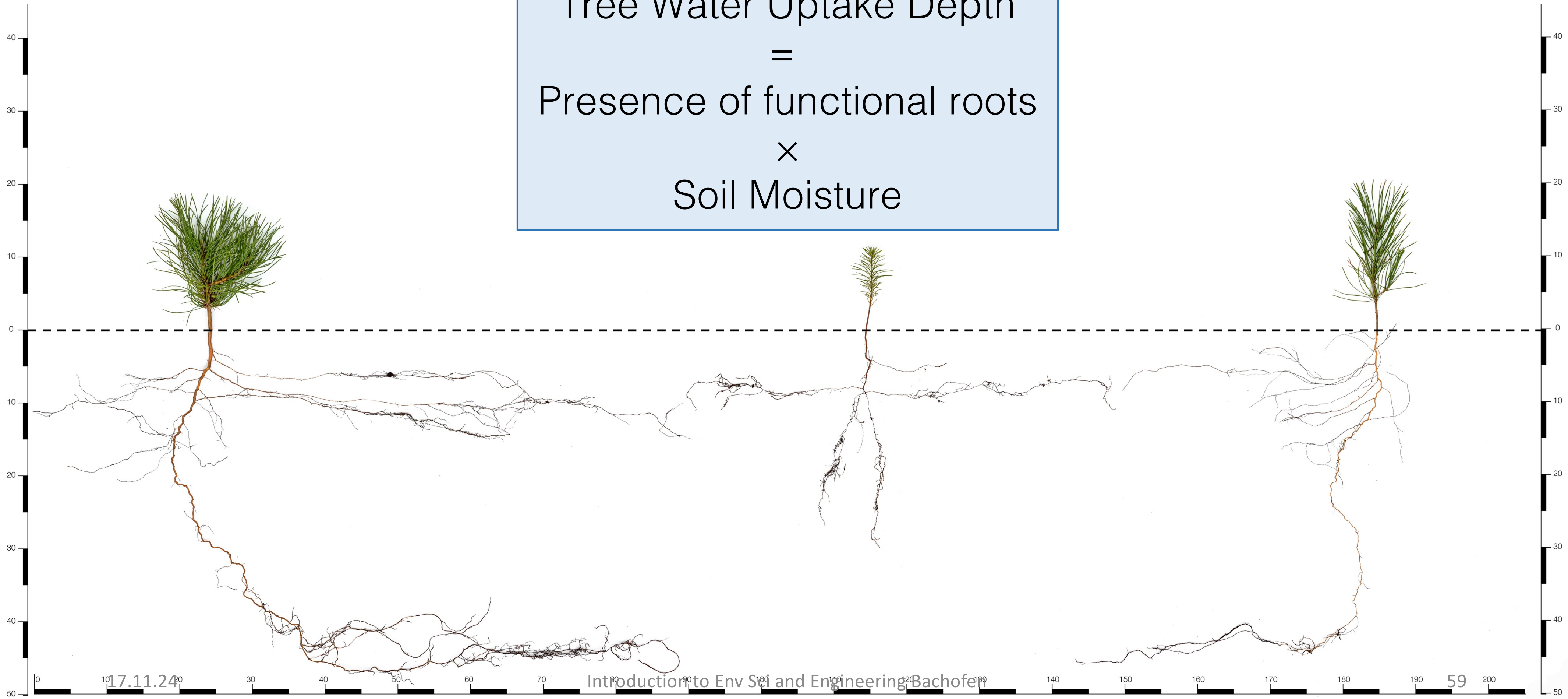
Trees can switch between shallow and deep-water sources depending on soil water availability



Bachofen et al. 2024

Global water uptake depth

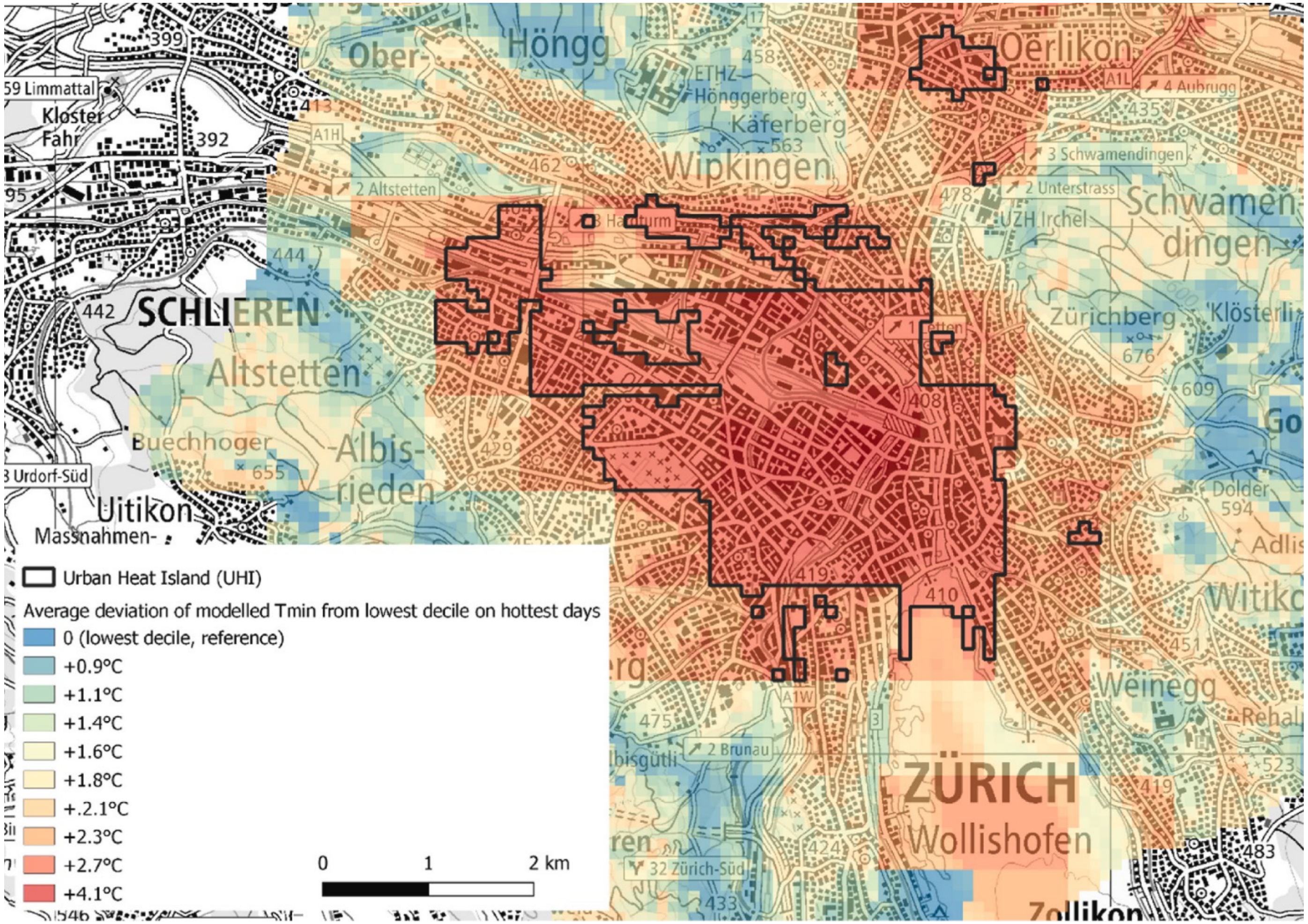
Tree Water Uptake Depth
=
Presence of functional roots
×
Soil Moisture



Plants regulate the environment

Transpiration cooling of trees

The urban heat island

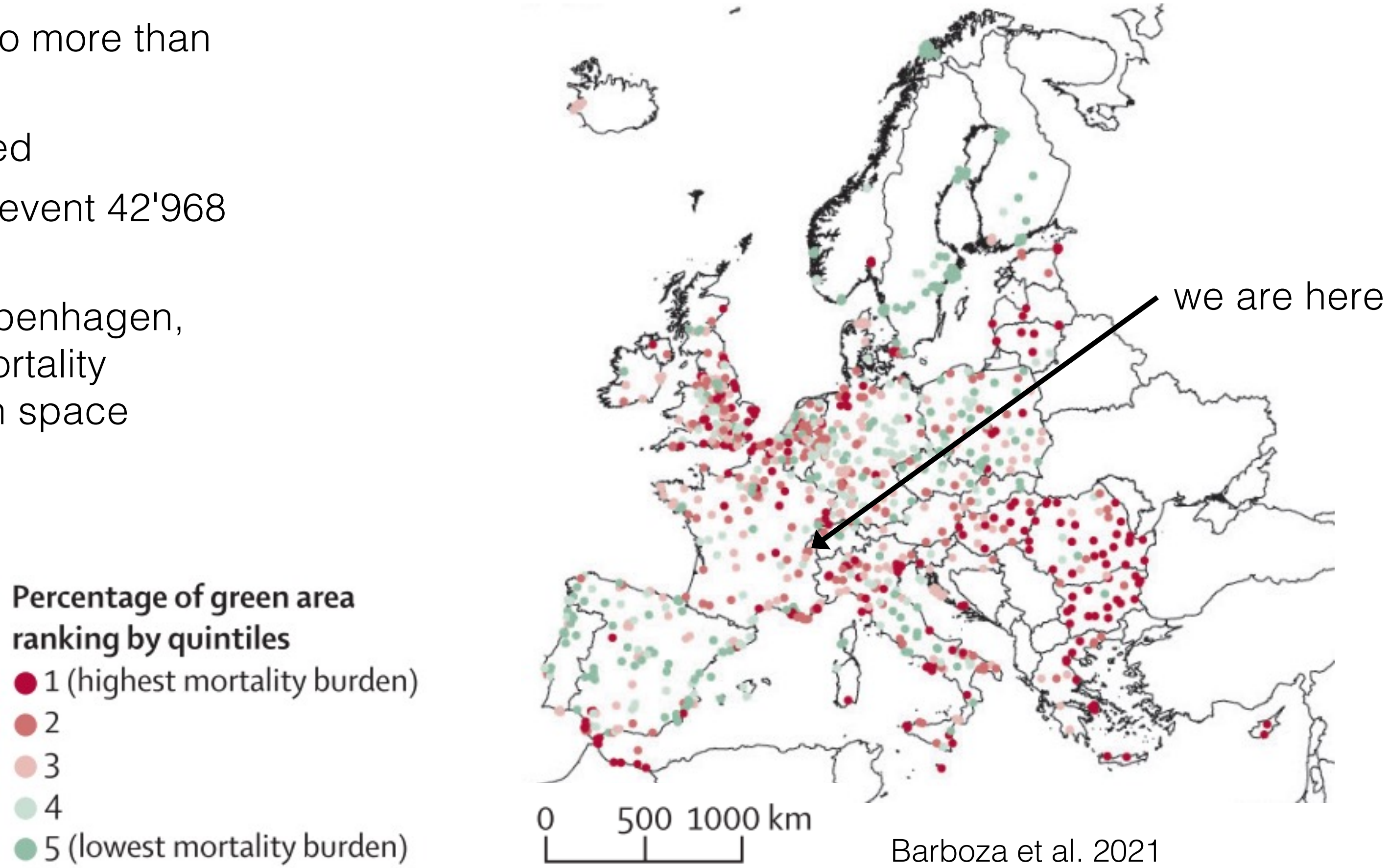


"In 2018, only 15 stations out of 576 were located in inner cities"

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

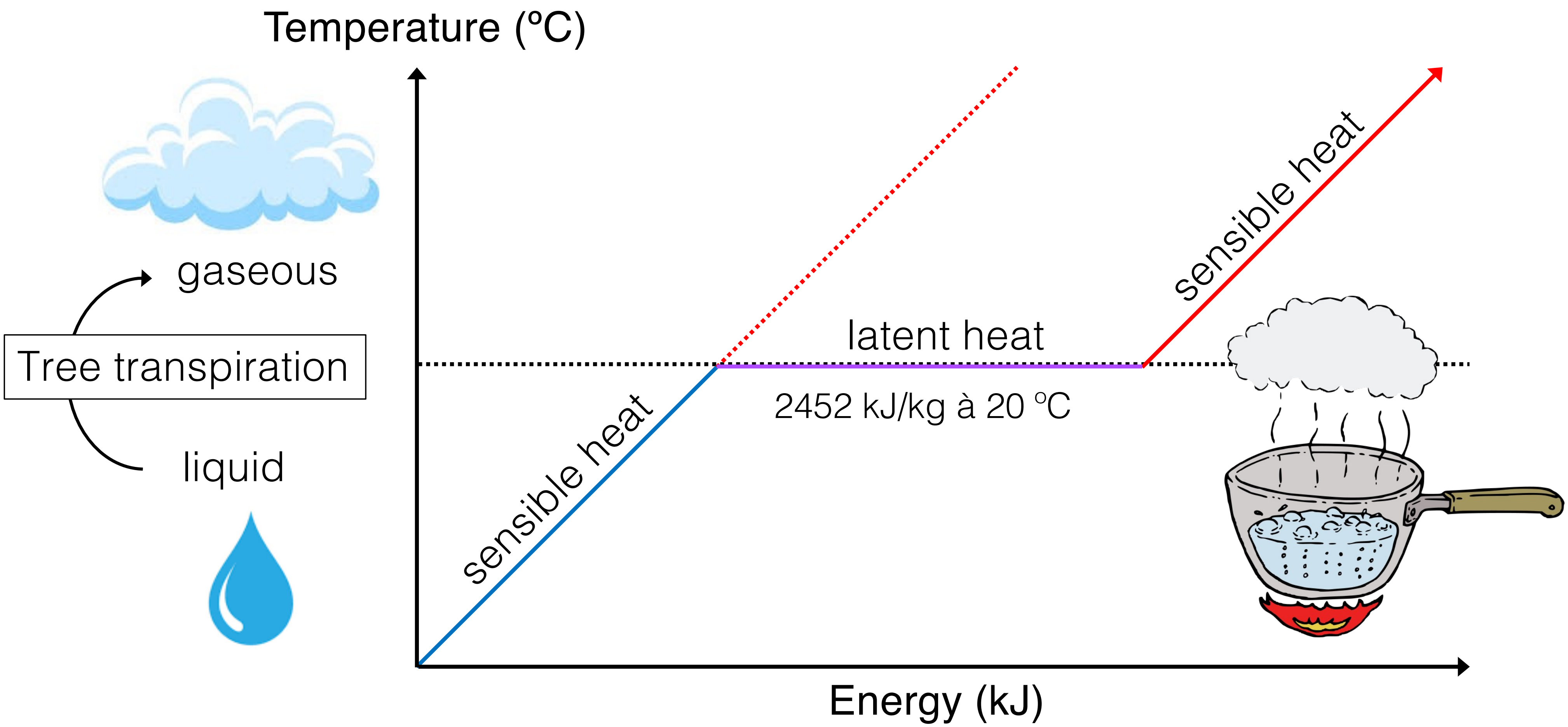


Barboza et al. 2021

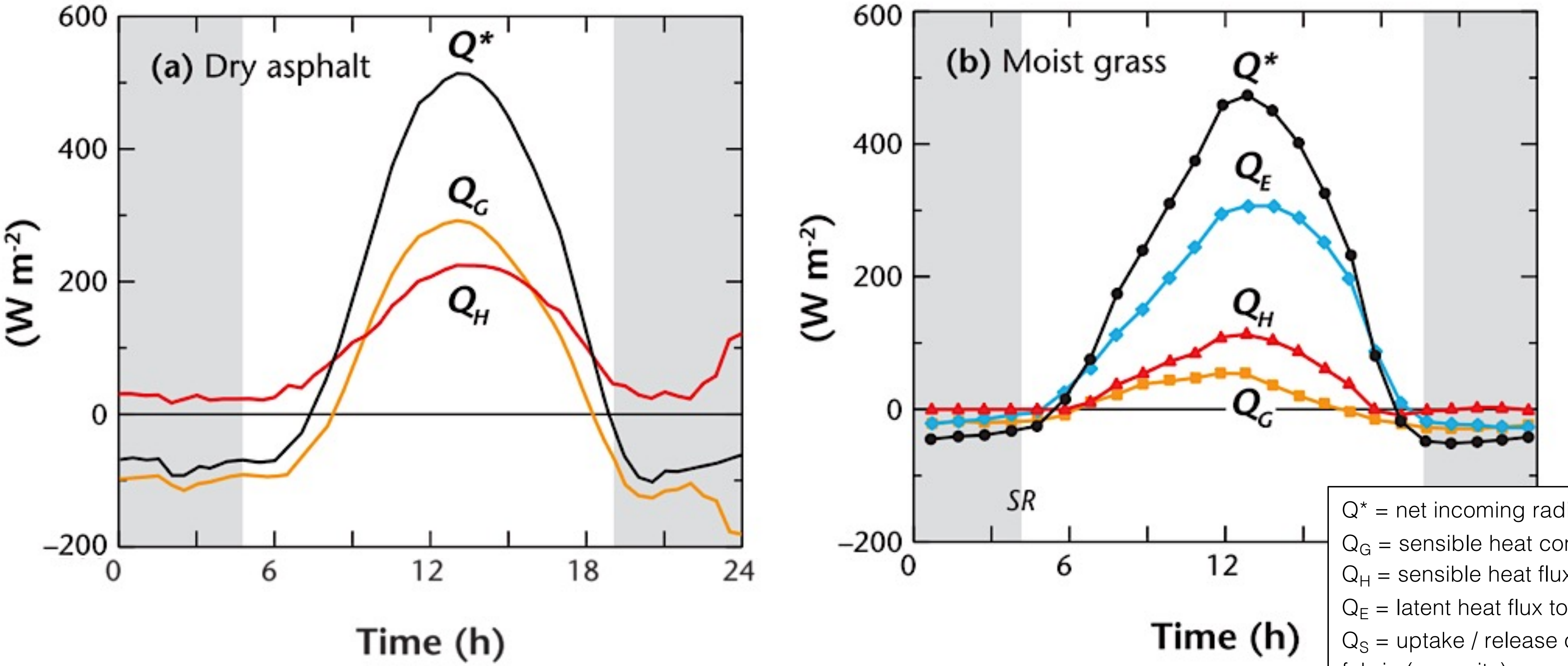
Urban heat island mitigation

"îlots de fraîcheur" in Paris, 2018

Cooling by transpiration: latent heat flux



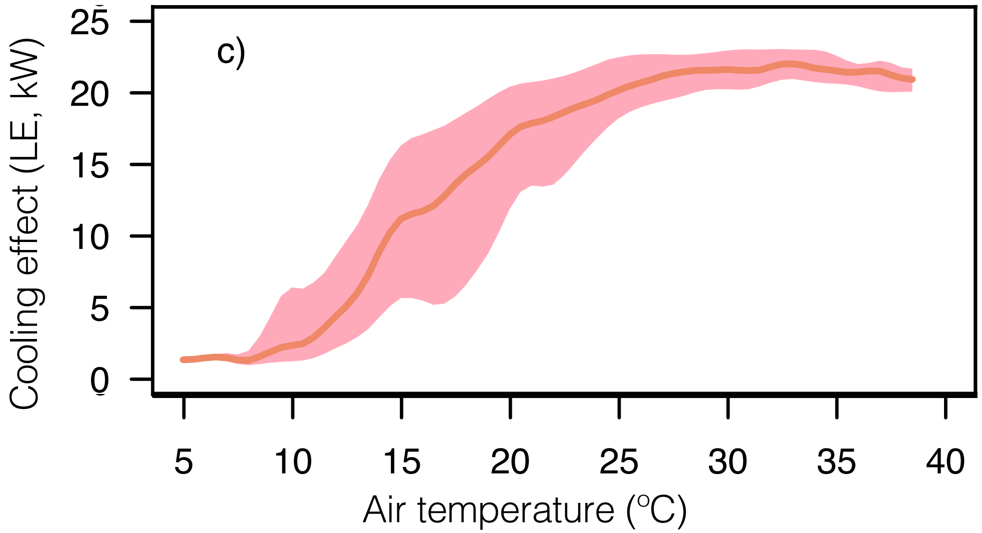
Example SEBs of unobstructed urban facets: (a) dry asphalt road near Vienna, Austria. (b) slightly moist grassed site in an urban park in Vancouver, Canada. (Oke et al. 2017)

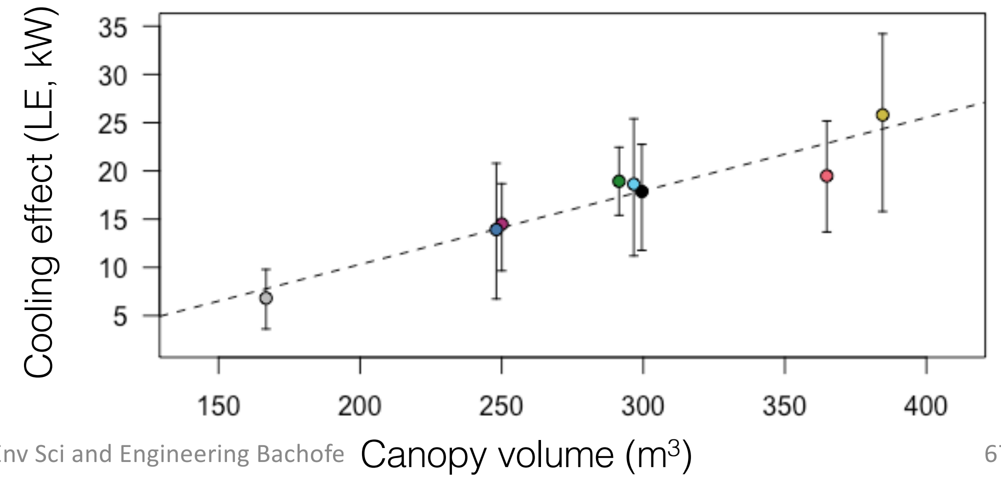


Q^* = net incoming radiation
Q_G = sensible heat conducted to the soil
Q_H = sensible heat flux to the air
Q_E = latent heat flux to the air
Q_S = uptake / release of heat from urban fabric (capacity)
SR and SS = sunrise and sunset

Can trees mitigate the urban heat island?

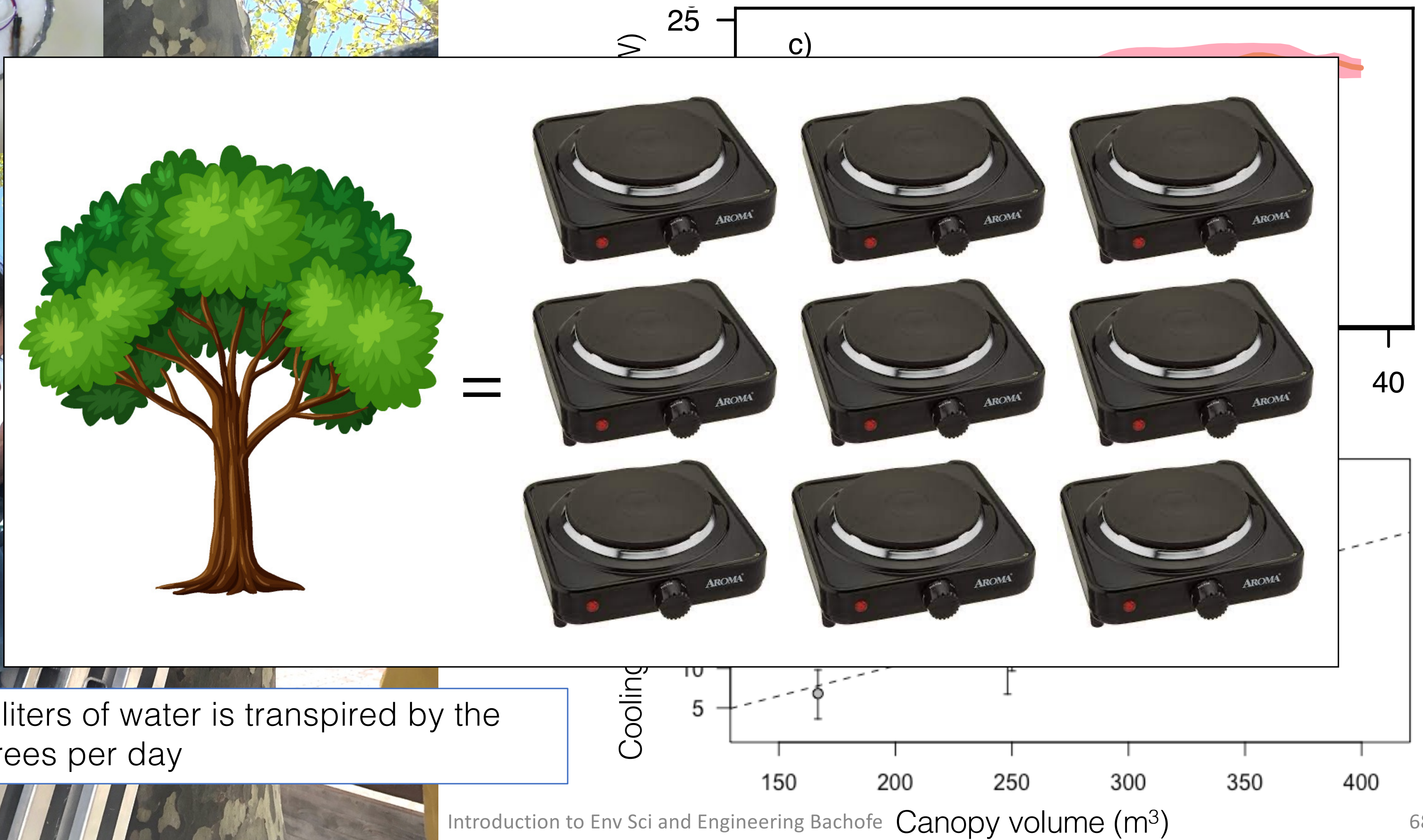
Transpiration cooling of trees





→ 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.