UT7.2 Terrestrial forest ecosystems

Photosynthesis and water use

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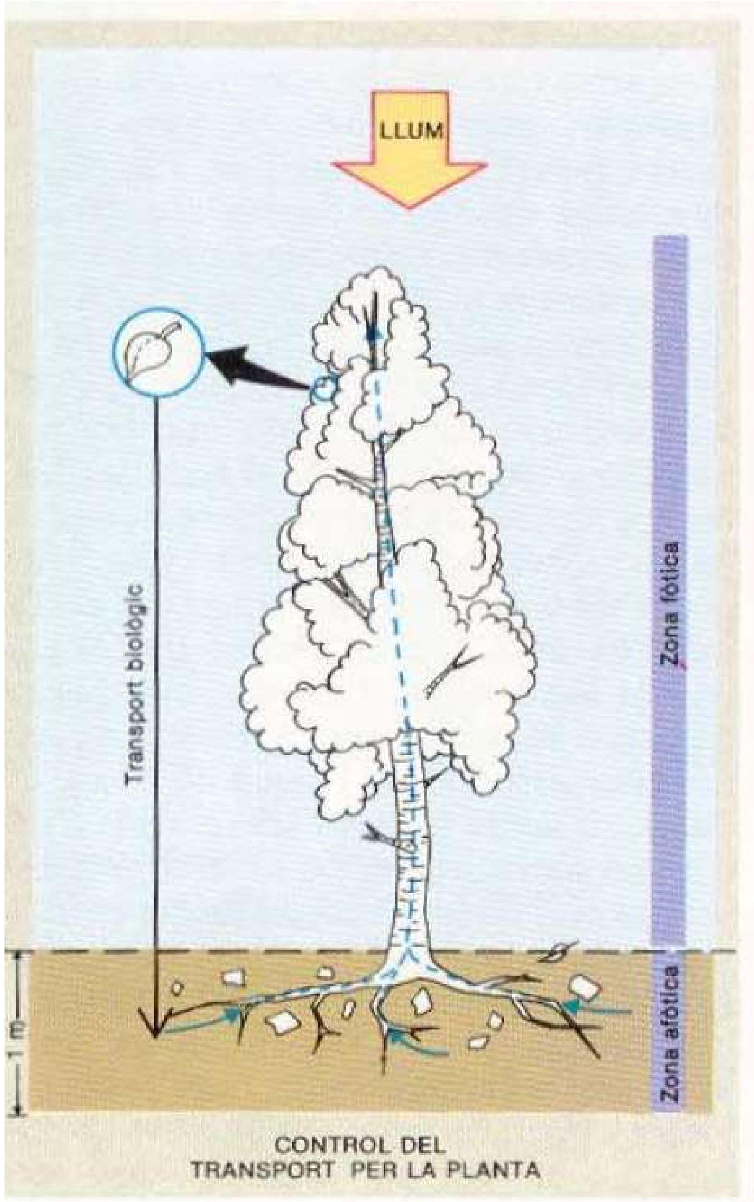
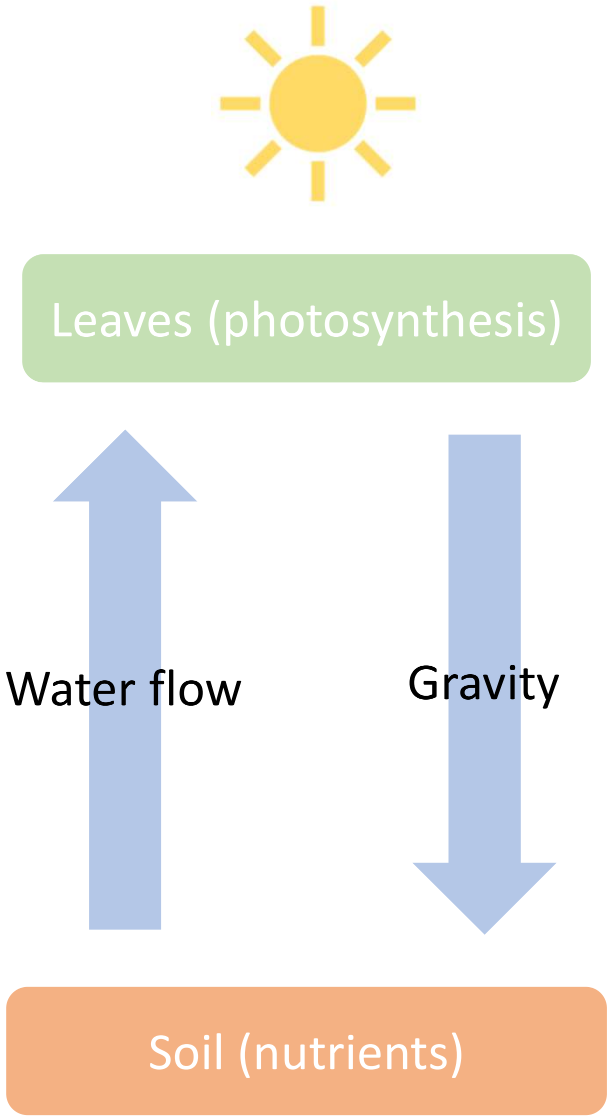
Ecologia d'Ecosistemes i Biogeoquímica // 2023-2024

BEECA Department, Ecology Section

Contents

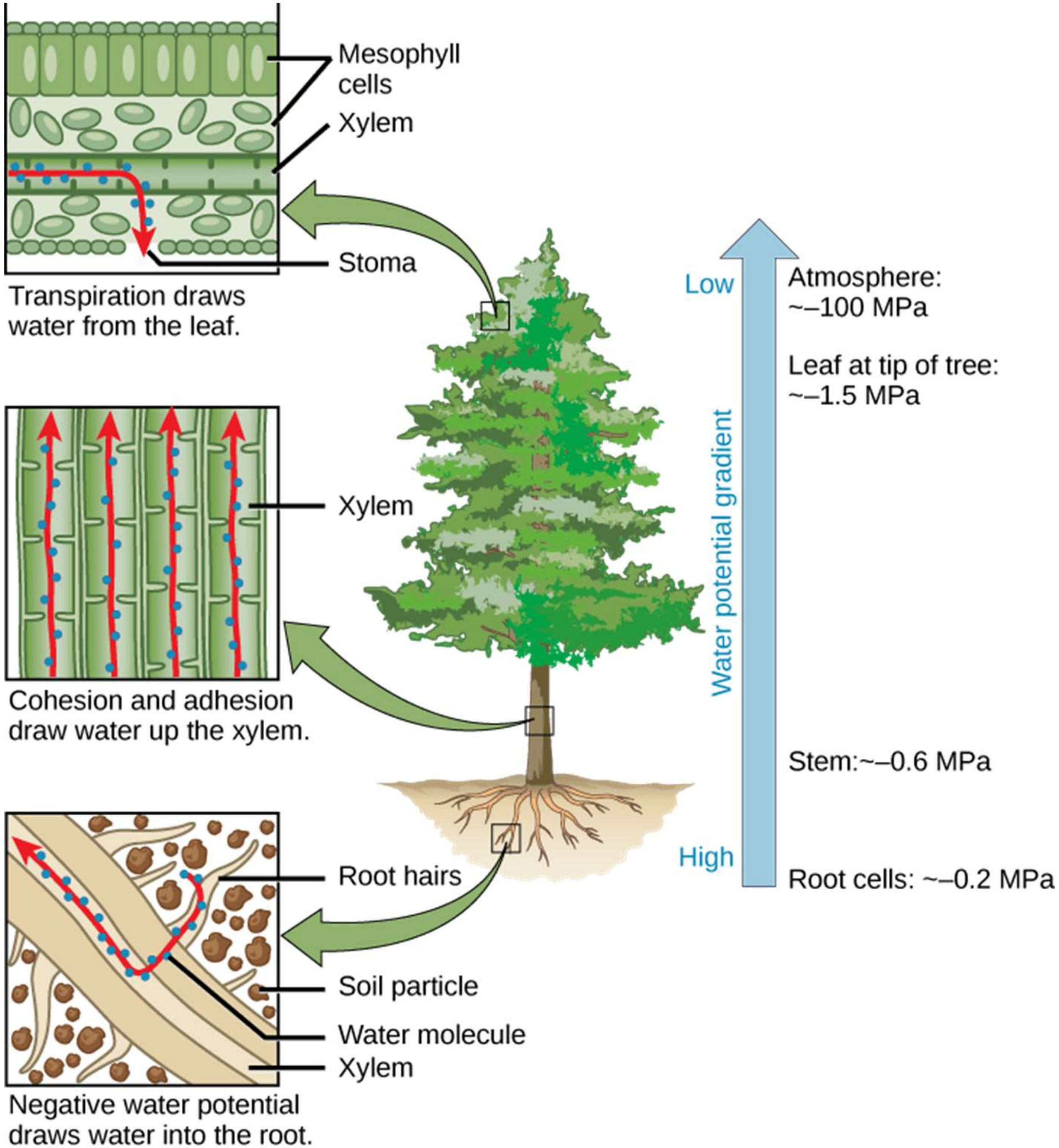
The tree, a bio-reactive machine





Terradas et al., 1989

Water pump within the tree



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Fick's law (diffusion)
Darcy's law (conductance)

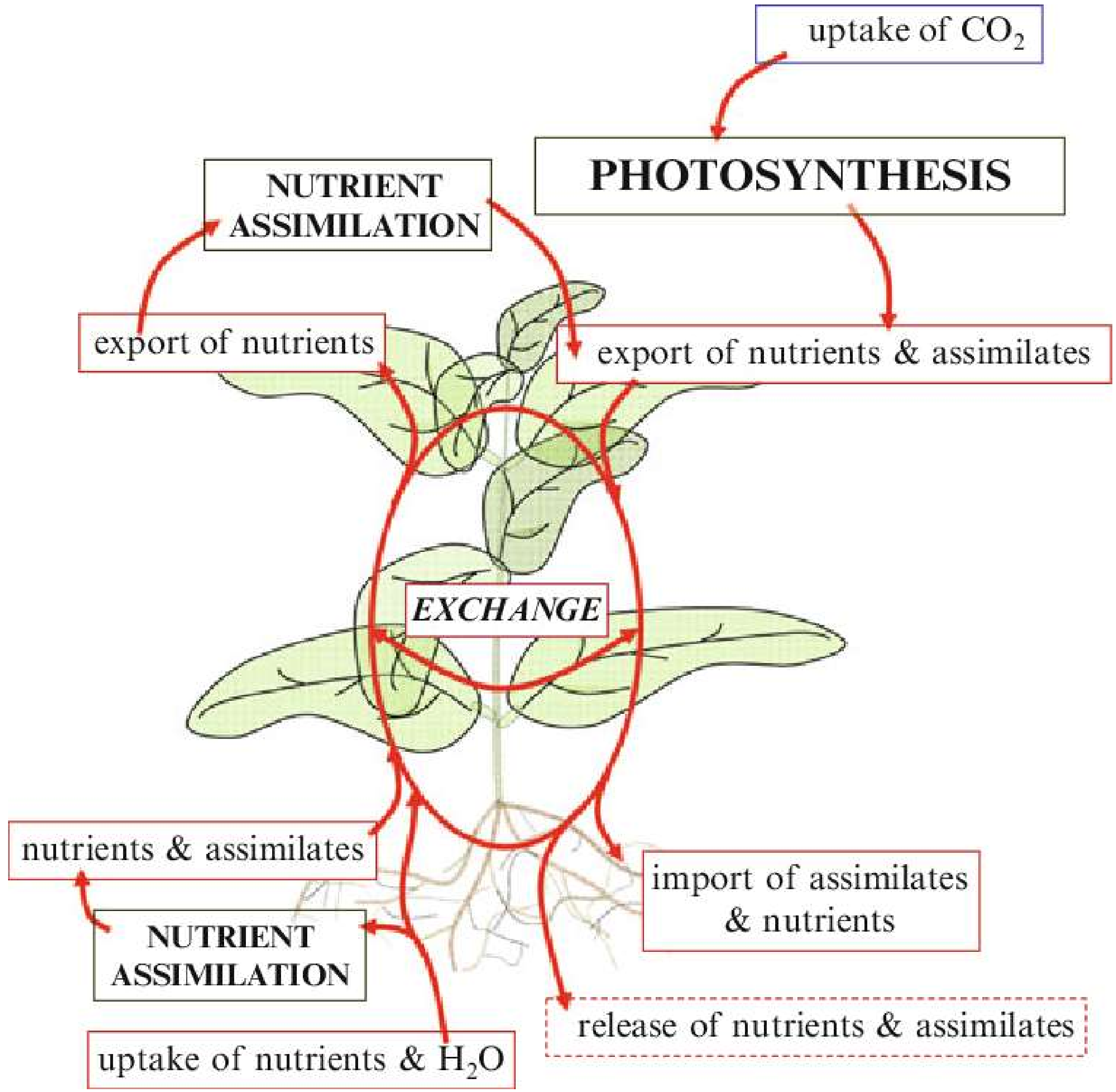
$$G = \frac{A_l k}{\eta h A_s D}(\varphi_l - \varphi_r)$$

Important for us:

$$(\boldsymbol{\varphi_l} - \boldsymbol{\varphi_r})$$

Water pull directly proportional to water potential gradient between leaves and roots

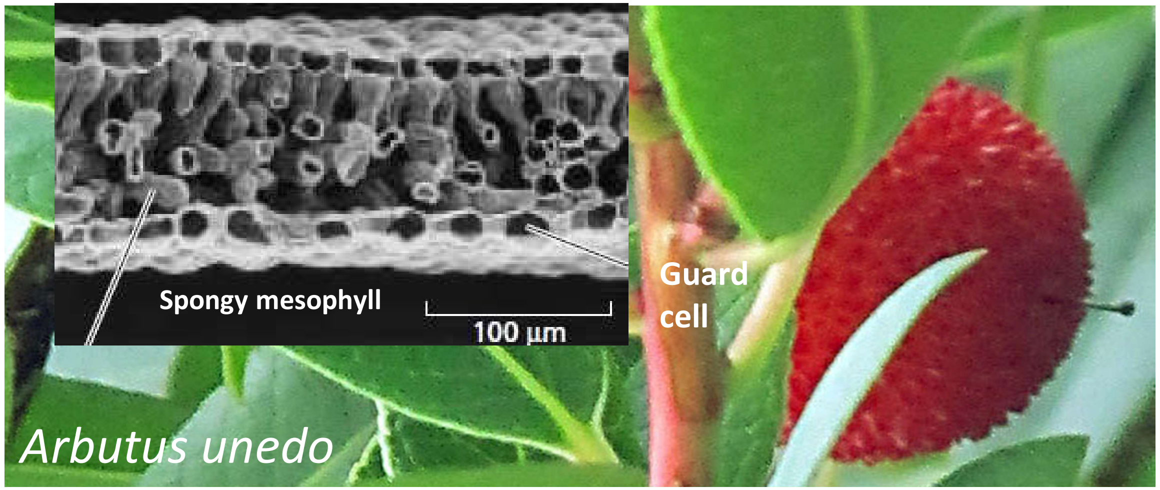
McDowell and Allen, 2015

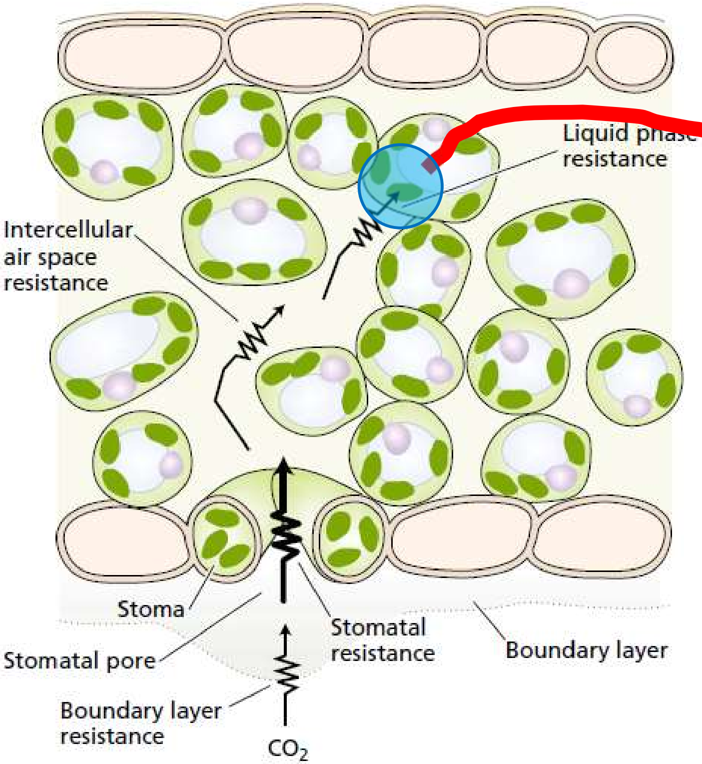


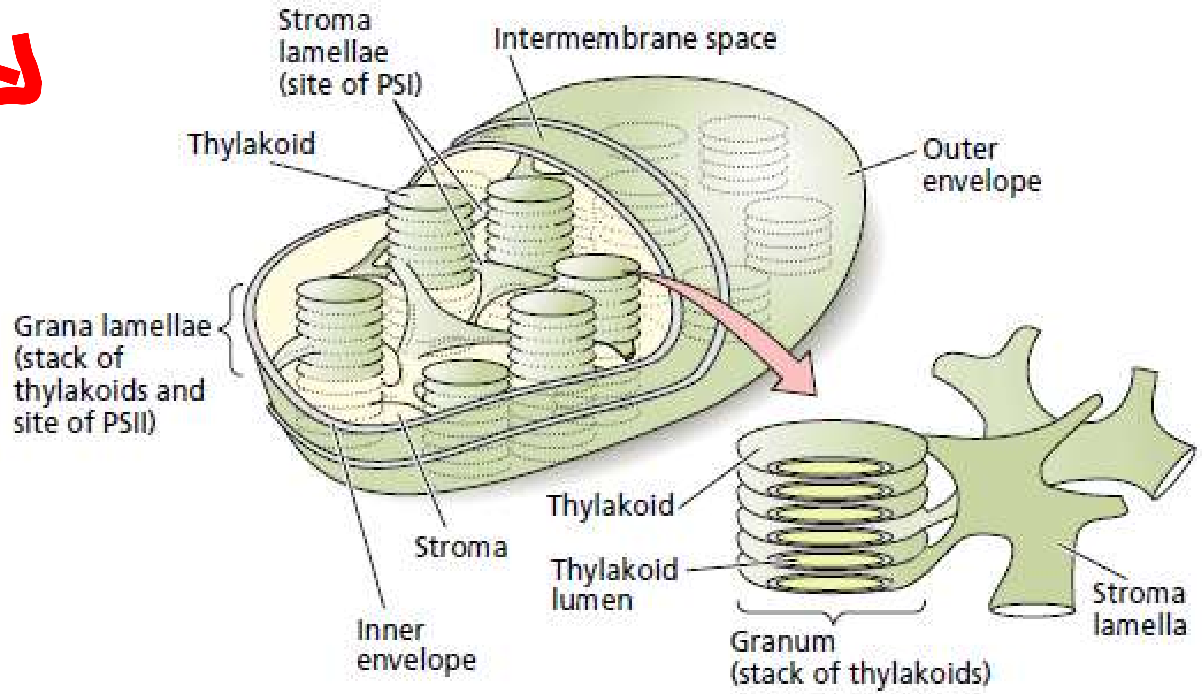
Herschbach et al., 2012

Photosynthesis, basic concepts

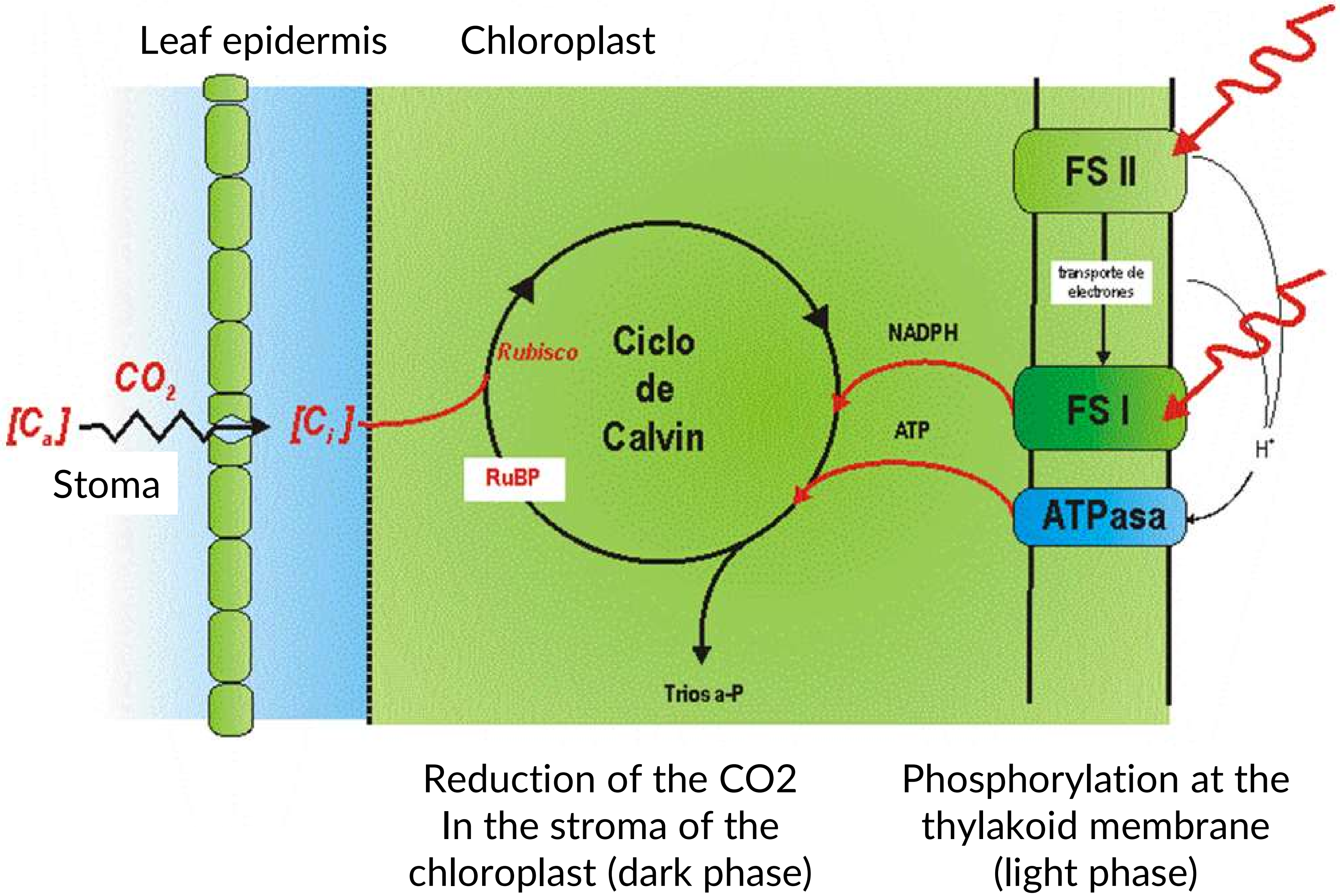
Leaf structure

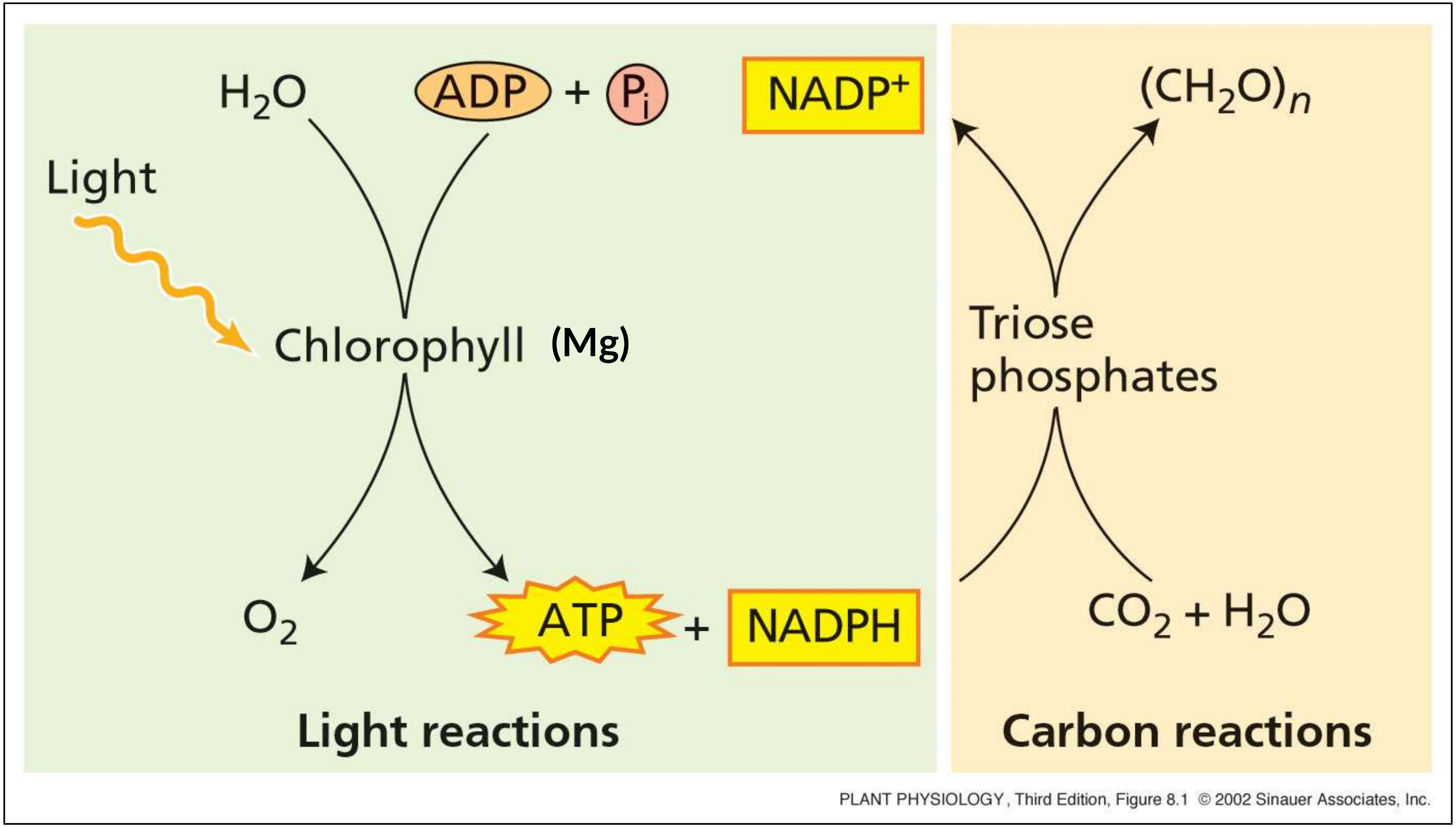






Taz & Zeiger 2010


Leaf epidermis
Chloroplast
FS II
transporte de electrones
NADPH
Ciclo de Calvin
Rubisco
CO_2
$[C_a]$
$[C_i]$
Stoma
FS I
ATP
H+
RuBP
ATPasa
Trios a-P
Reduction of the CO2 In the stroma of the chloroplast (dark phase)
Phosphorylation at the thylakoid membrane (light phase)



NADPH & ATP generated during the light phase of the photosynthesis. Then, they are used to produce the photo assimilates during the dark phase of the photosynthesis

Trivia (1')

Which of the following statements is **not** true?

Water flows through the plant following a negative pressure gradient	C assimilation occurs inside cell's chloroplasts and only requires light	Plant water use depends on leaf area, climate conditions, and root uptake	Plants regulate leaf permeability to water and carbon via stoma aperture

Measuring photosynthesis in trees (and forests)

Whole-tree chambers (IMK-IFU, GAP)

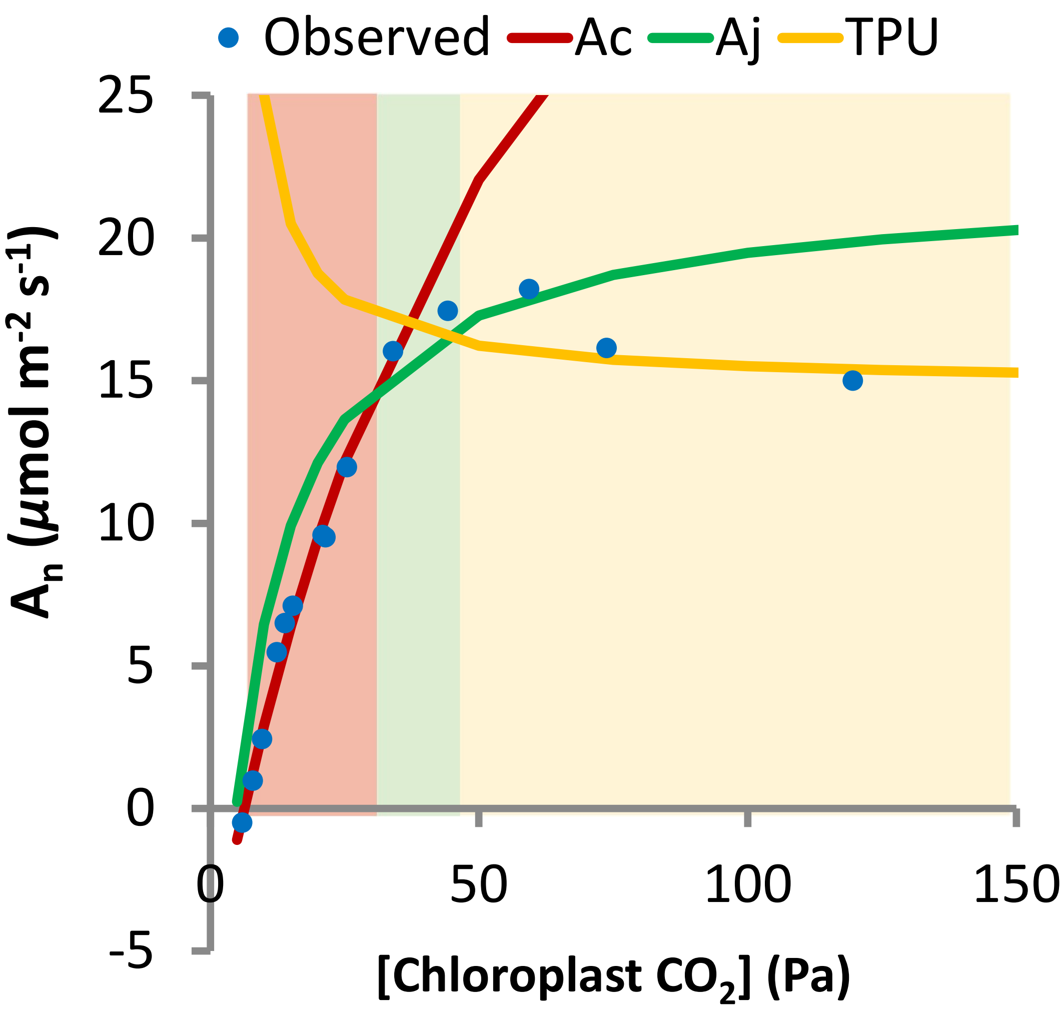
Eddy-covariance tower (Hyytiälä, Finland)

Li-Cor leaf chamber (LI-6400XT)

Farquhar model (carboxylation VS RuBP regeneration)

$$A_n = \min(A_j, A_{ic}, A_{TPU}) - R_d$$

Farquhar, von Caemmerer, Berry (1980)



1)

$$A = V_{cmax}\left[\frac{C_c - \Gamma^*}{C_c + K_C(1 + O/K_O)}\right] - R_d$$

Rubisco-limited photosynthesis (associated with low CO_2)

2)

$$A = J\frac{C_c - \Gamma^*}{4C_c + 8\Gamma^*} - R_d$$

RuBP-regeneration-limited photosynthesis (at higher CO_2 Concentrations)

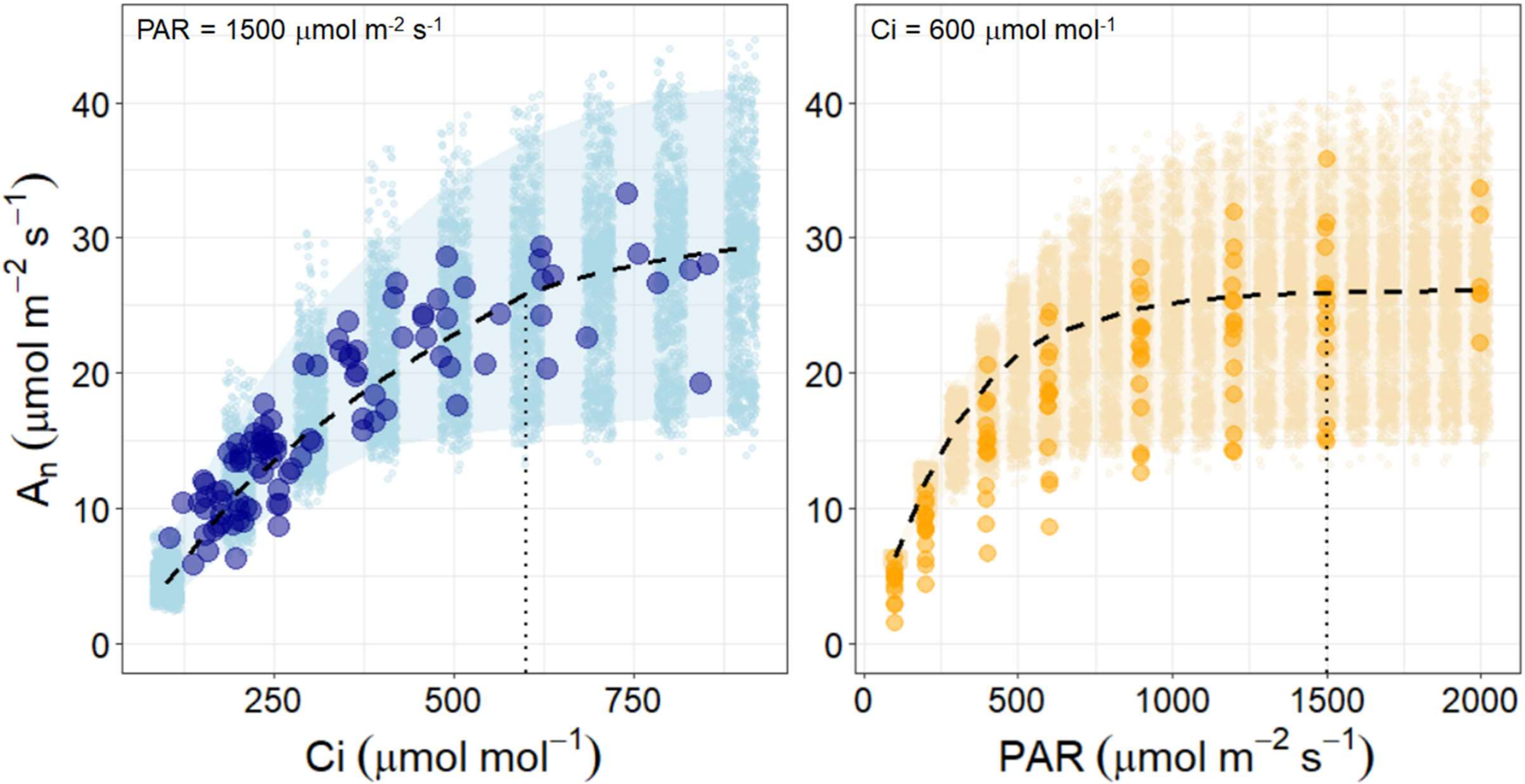
3) *

$$A = 3TPU - R_d$$

Triose-phosphate use limitations (T-related)

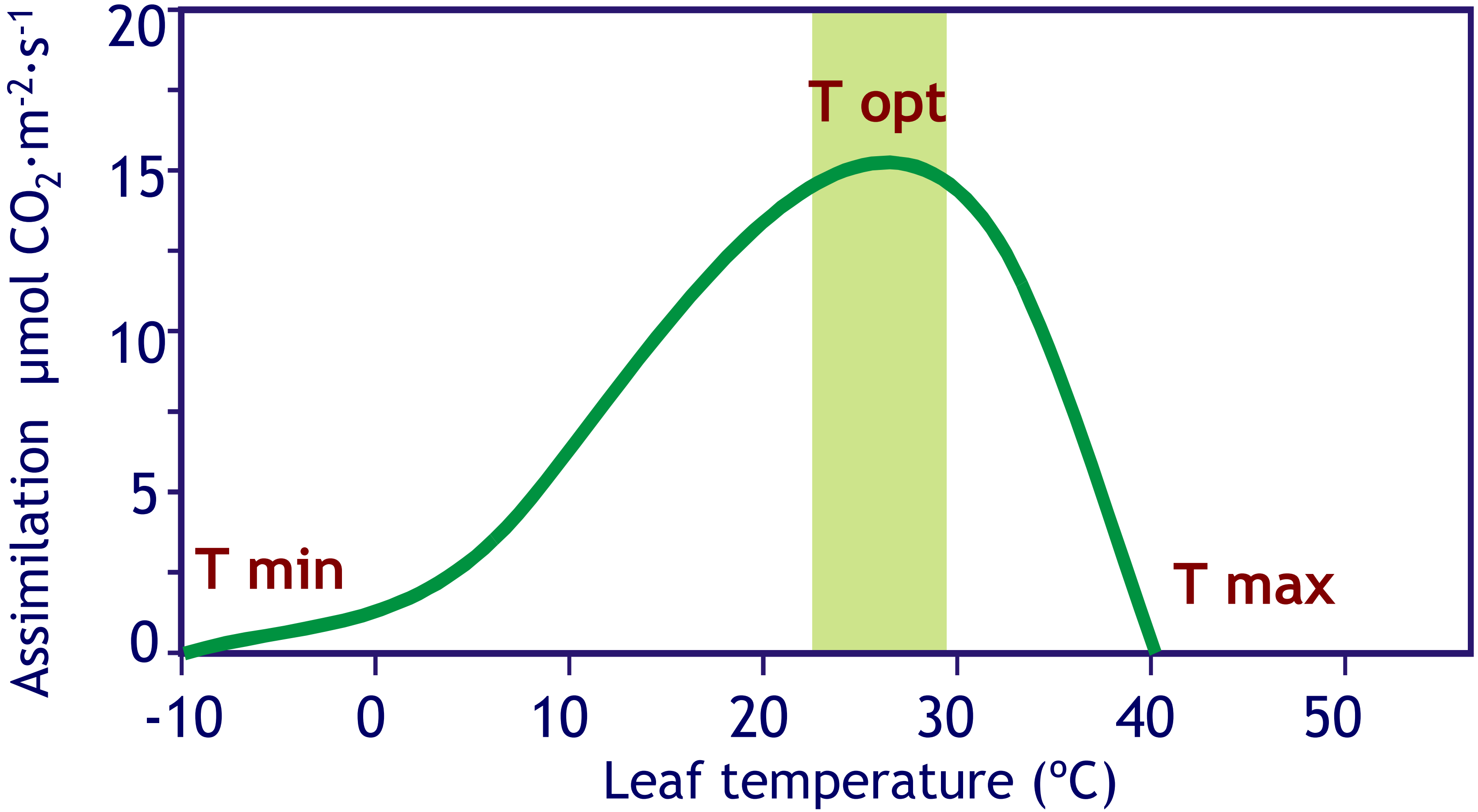
*(Sharkey *et al.* 1985)

Photosynthesis dependent on Ci and PAR



Hidalgo, Nadal-Sala & Sabaté (in rev.)

Temperature optima for the photosynthesis



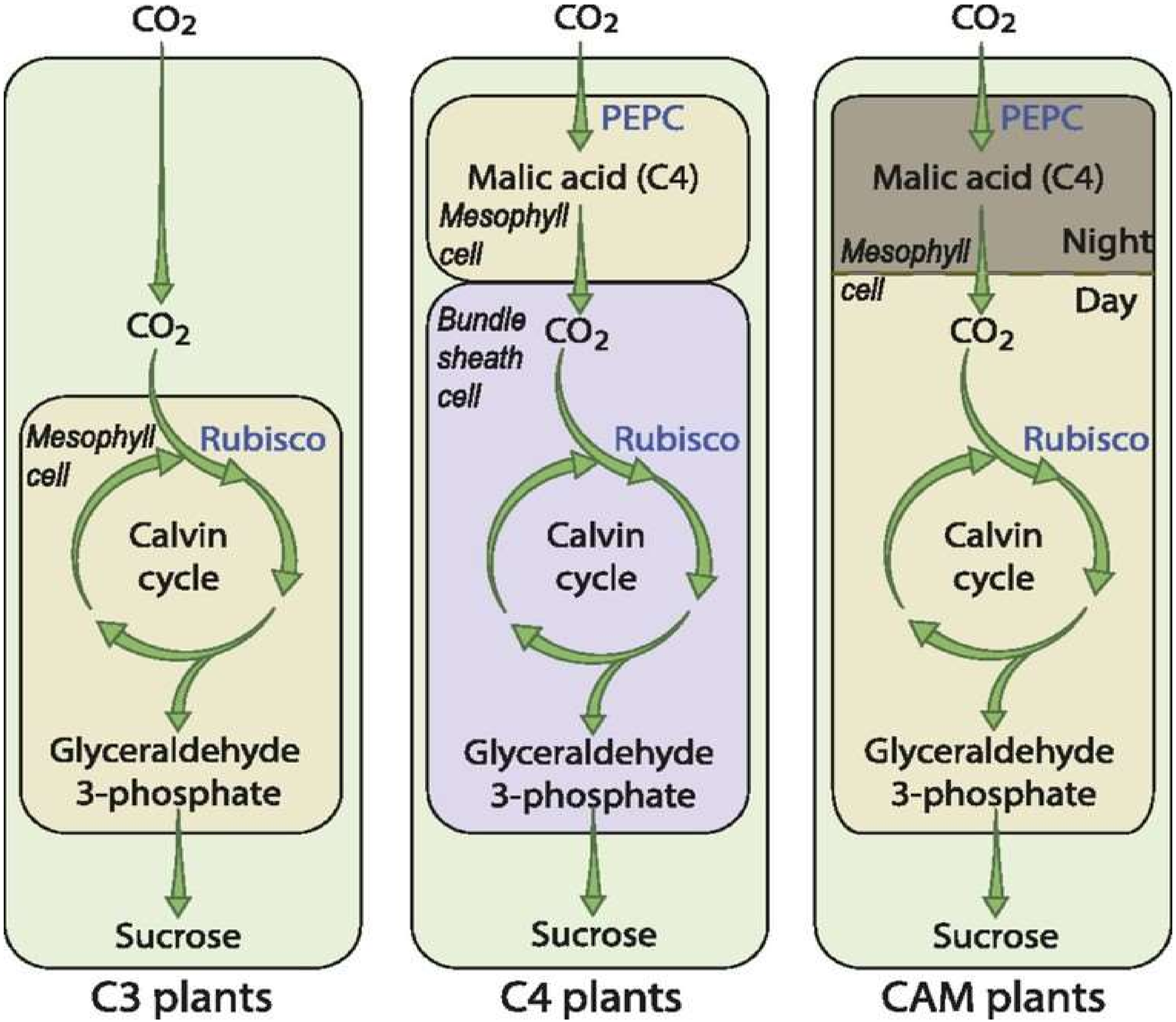
Double Arrhenius response

$$P_t = P_{25^o} \exp\left[\frac{\Delta H_a \cdot (t_h - 25)}{R_{gas} \cdot 298.1 \cdot (t_h + 273.1)}\right] \left[\frac{1+\exp\left(\frac{S_j \cdot 298.1 - \Delta H_d}{R_{gas} \cdot 298.1}\right)}{1+\exp\left(\frac{S_j \cdot (273.1 + t_h) - \Delta H_d}{R_{gas} \cdot (273.1 + t_h)}\right)}\right]$$

Exponential increase

Peaked response

Differences among C3, C4 and CAM plants



CAM states for: Crassulacean Acid Metabolism

Balance of the reaction

Mitocondrial respiration

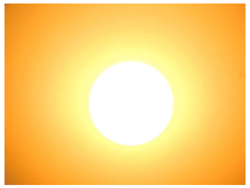
$$6CO_2 + 6H_2O \rightleftharpoons C_6H_{12}O_6 + 6O_2$$

Chloroplast photosynthesis

Or in mass / energy terms:

energy sugar

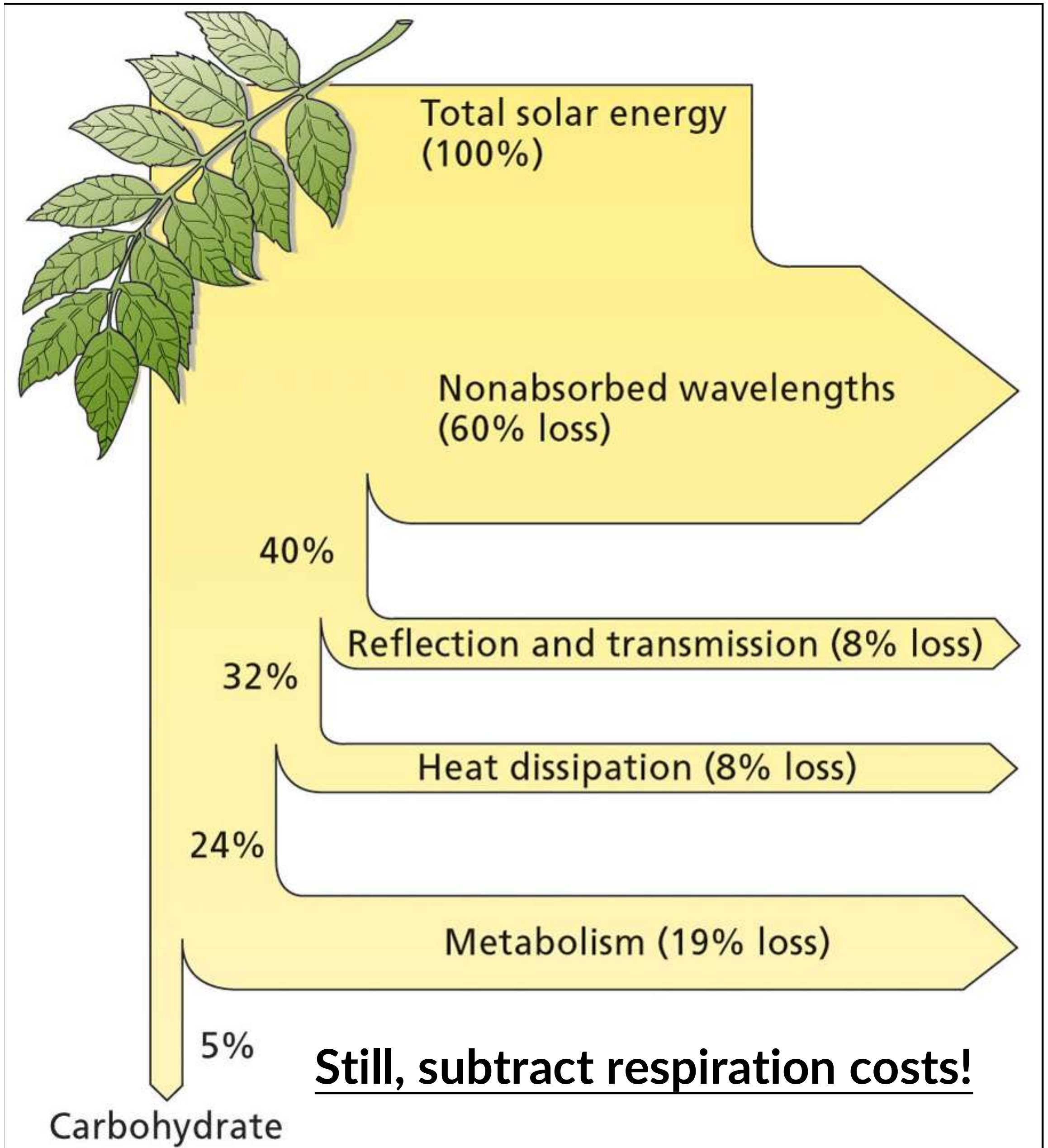
$44g\ CO_2 (12g\ C) + 18g\ H_2O + \underline{123\ kcal}\ (515\ kJ) \leftrightarrows \underline{30g}\ CH_2O + 32g\ O_2$



+

=

Light use efficiency by the plants



<u>Still, subtract respiration costs!</u>

PLANT PHYSIOLOGY, Third Edition, Figure 9.2 © 2002 Sinauer Associates, Inc.

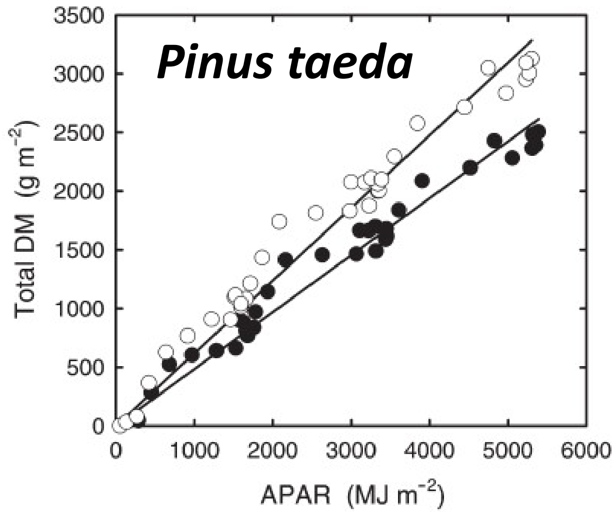


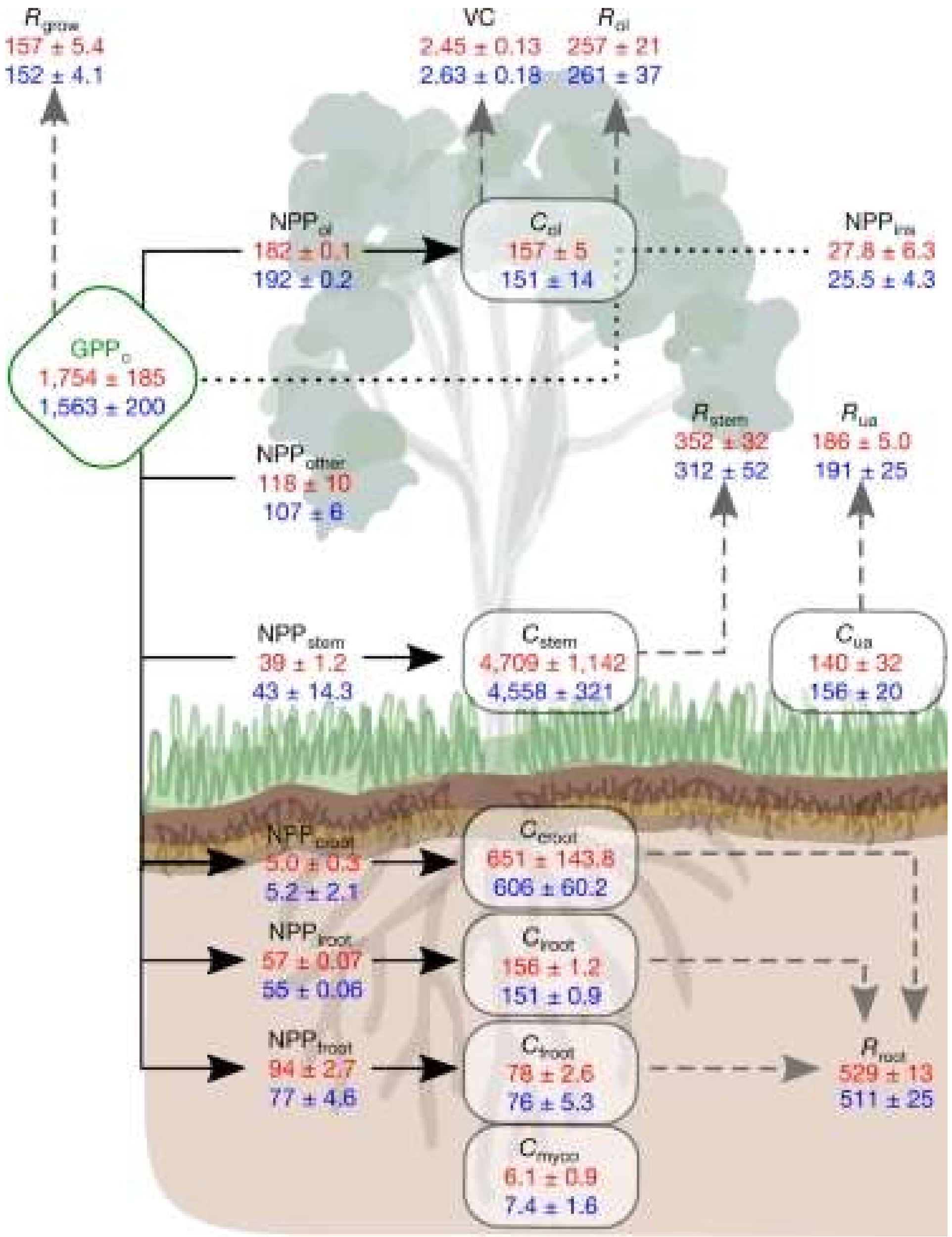
Figure 3. Cumulative total biomass (Total DM; aboveground dry mass + belowground dry mass) for loblolly pine as a function of cumulative absorbed photosynthetically active radiation (APAR) for plots exposed to ambient (~360 µl l^{-1}, ●) and elevated (~560 µl l^{-1}, ○) atmospheric [CO_2]. Radiation-use efficiency (ε) was calculated as the slope of the relationship between total dry mass and APAR, where APAR was calculated from pine L^* derived from allometric equations

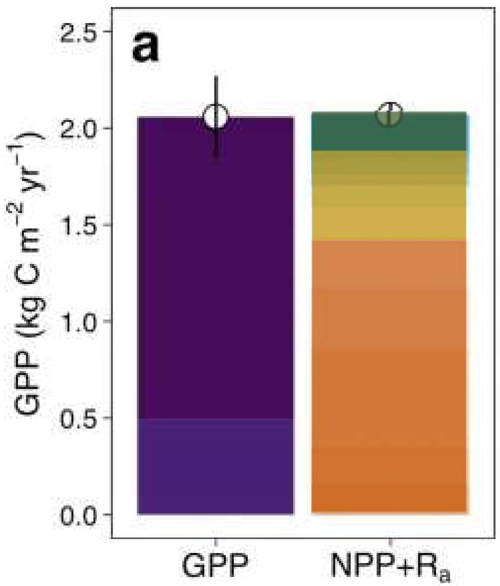
DeLucia and Hamilton, 2002

1 g C ≈ 42 kJ ≈ 10.3 kcal

1 g MO ≈ 0.47 g C ≈ 20 kJ ≈ 5 kcal

Respiration and turnover rates





Biomass increase (~10%)

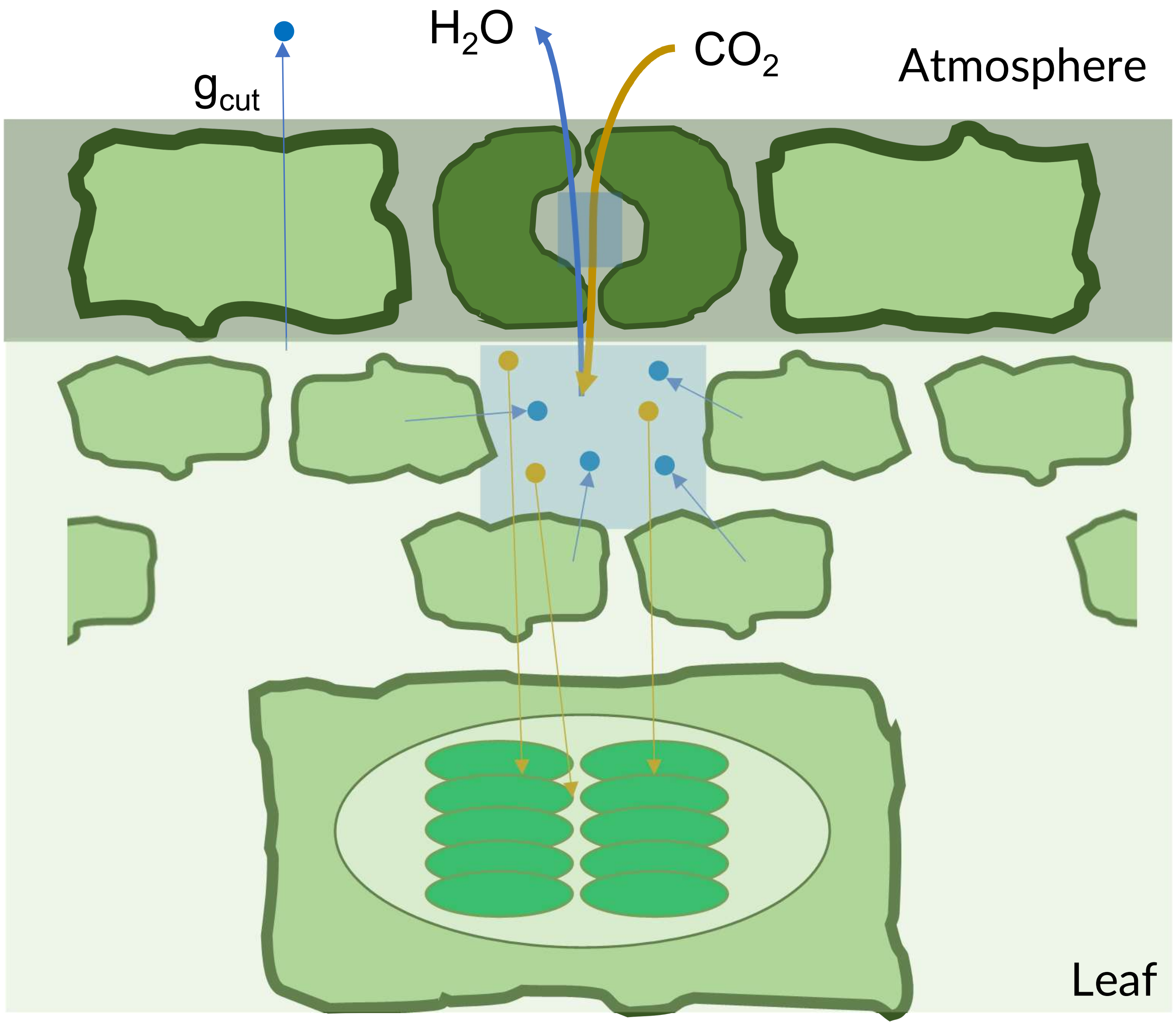
Biomass turnover (~20%)

Respiration (~70%)

Eucalyptus tereticornis, EucFACE, Sydney, Australia (Jiang et al., 2020)

Trading water for carbon

Expensive trading of water for carbon



Water conductance in mmol m^{-2} s^{-1}

Carbon conductance in µmol m^{-2} s^{-1}

A factor of ~ 10^3!

Water use efficiency

Water availability

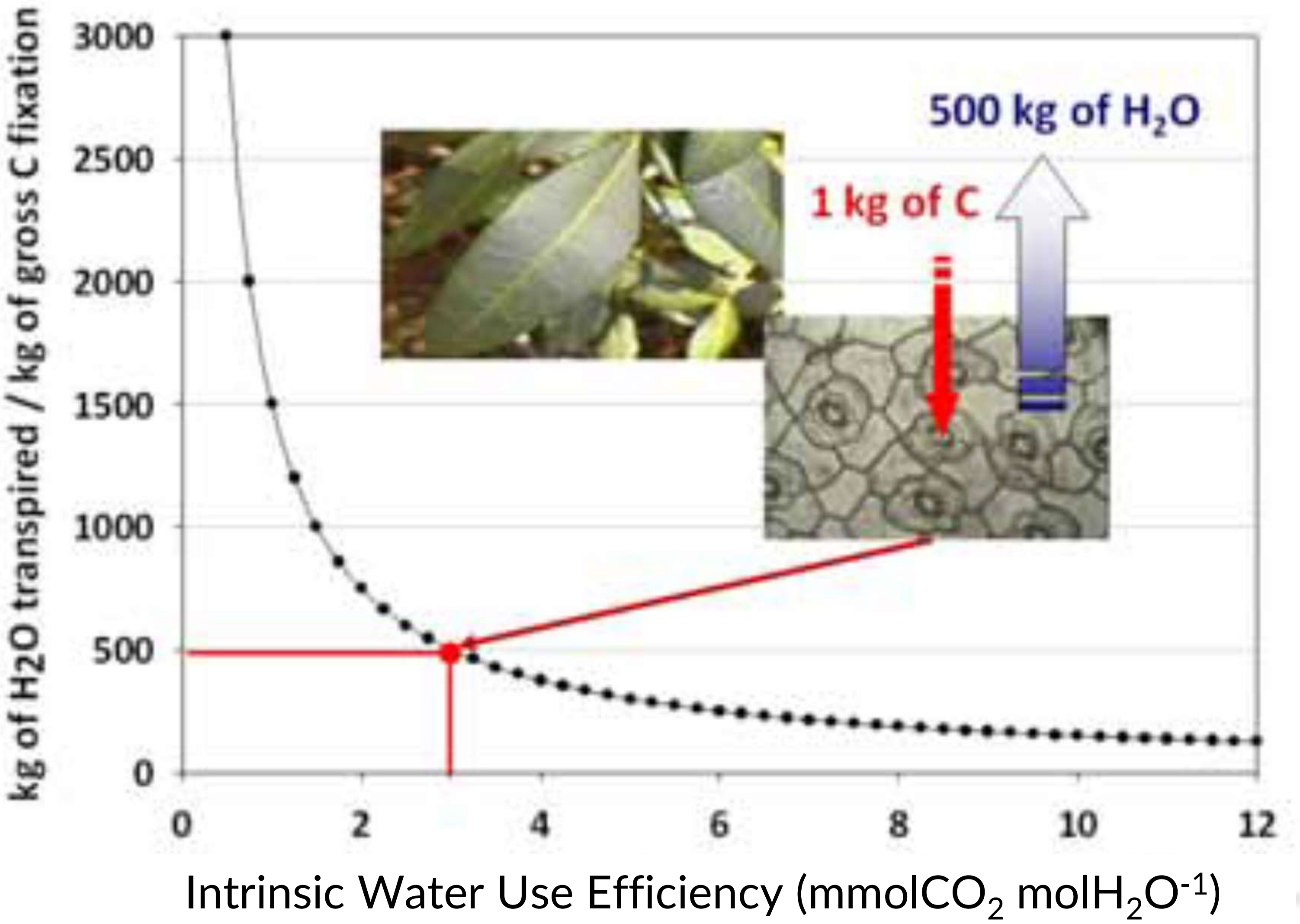
	$mmolCO_2 / molH_20$
Sunflower crop (Irrigated)	2.00[a]
Sunflower crop (Water deficit)	2.20[a]
Pinus halepensis (Andorra, Teruel)	5.05[b]
Quercus ilex (Prades, Tarragona)	4.98 [c]
Pinus halepensis (Yatir, Israel)	5.45[d]

(a) Lauteri, Brugnoli y Spaccino, 1993 (b) Gracia y Barrantes, 1995 (c) Gracia, 2000 (d) Nadal-Sala et al (2024)

...express how much carbon is fixed in photosynthesis per unit of water lost.

Plants transpire about 1000 g of water to fix between 2 and 3 g of C, so the amount of water transpired is 300 -500 times the weight of carbon.

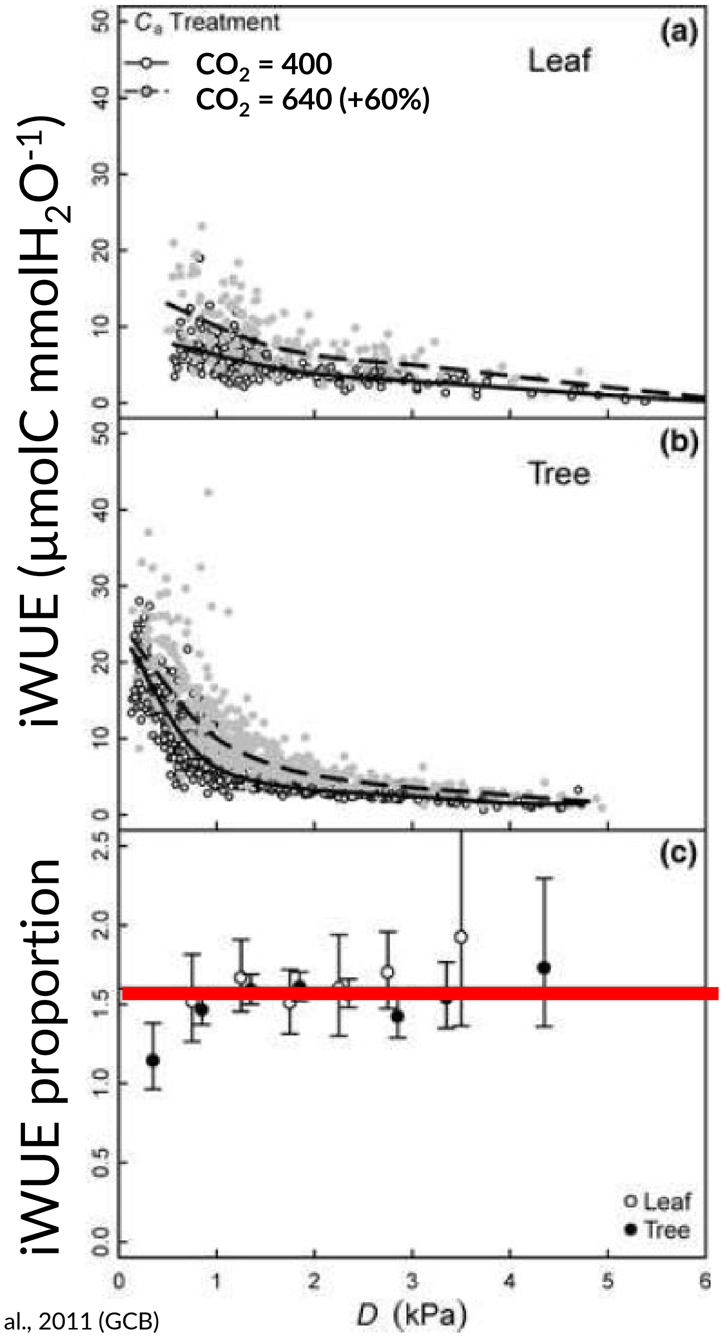
Intrinsic Water use Efficiency (iWUE)



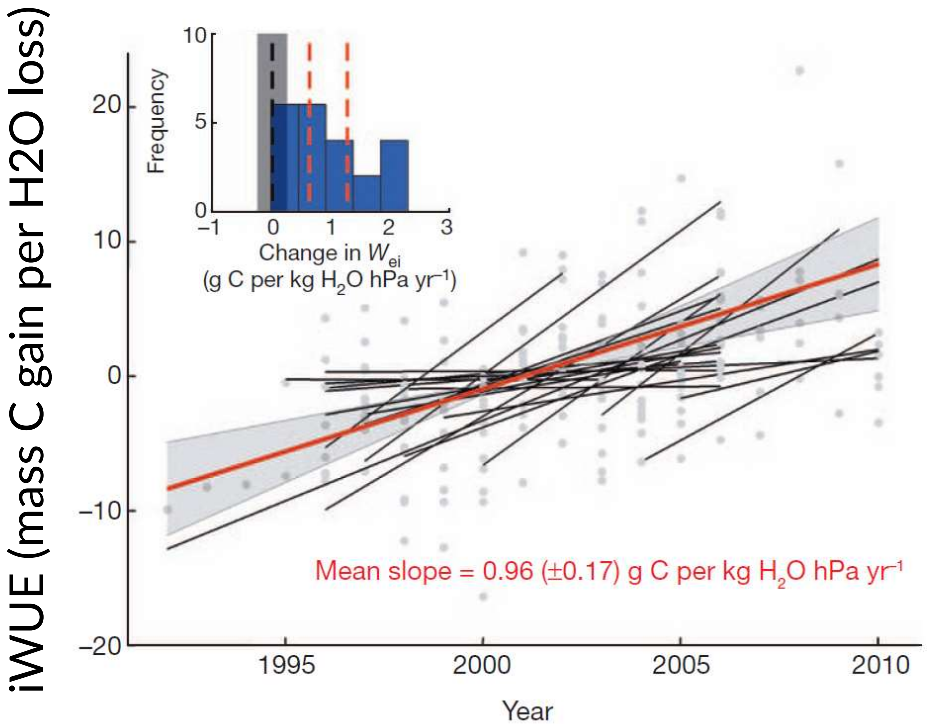
Sabaté et al., 2011

iWUE increases with atmospheric [CO_2]

Eucalyptus saligna (Sydney)



Barton et al., 2011 (GCB)

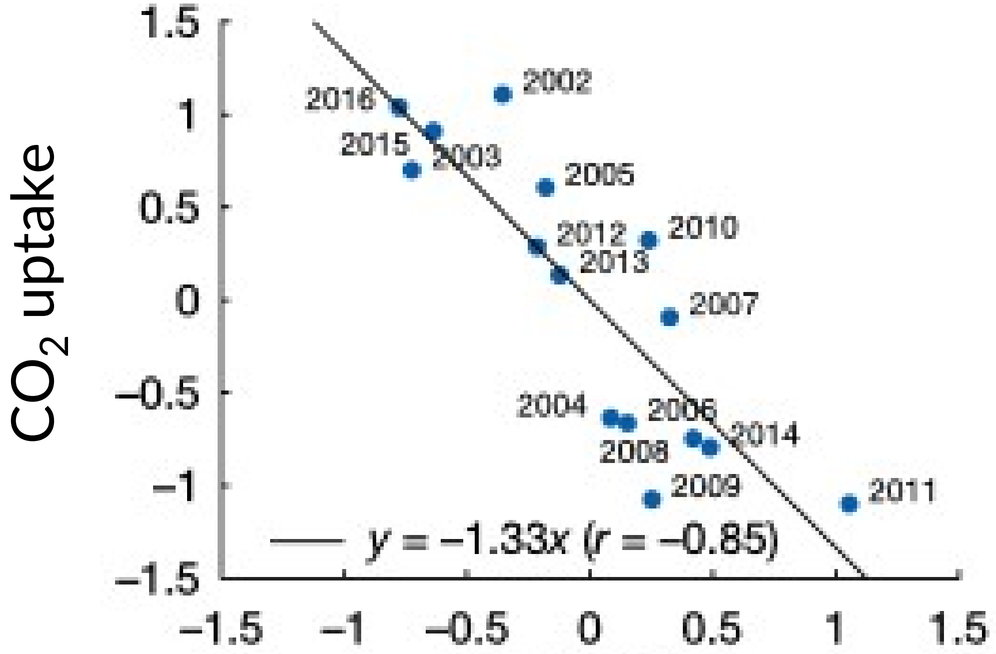


Keenan et al., 2013 (Nature)

iWUE at elevated CO2 = 1.6 times iWUE at ambient CO2

Atmospheric [CO_2] increases result in stomatal closure and photosynthetic boost, which enhances iWUE.

Abiotic stress (WATER!) limits vegetation C sink

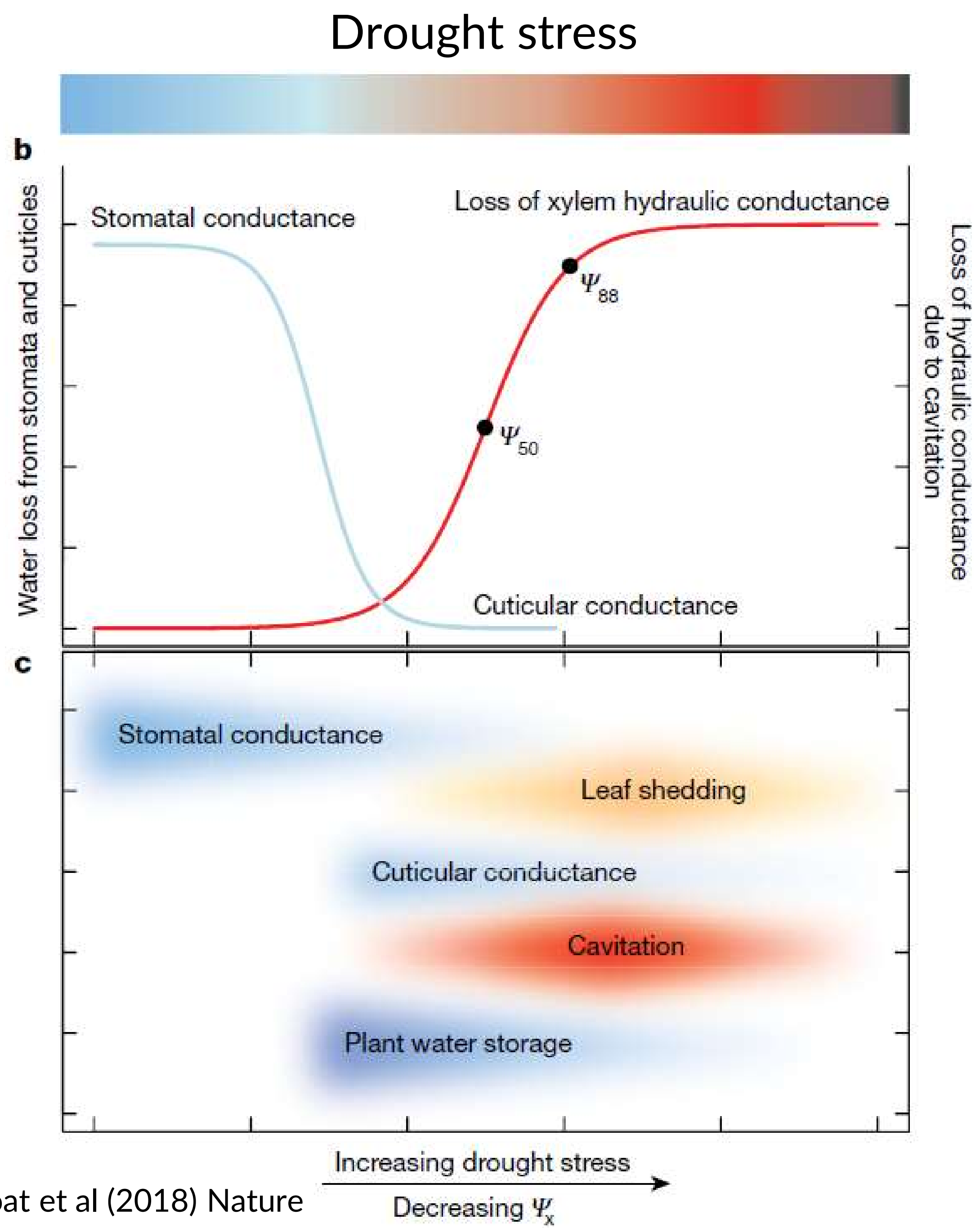


Soil moisture deficit (GRACE observations)

\- Aridity +

Humphrey et al., 2018 (Nature)

Tree responses to water deficit



Choat et al (2018) Nature

Trees reduce g_s under drought

Minimize water loss
Reduce carbon uptake
Limits growth

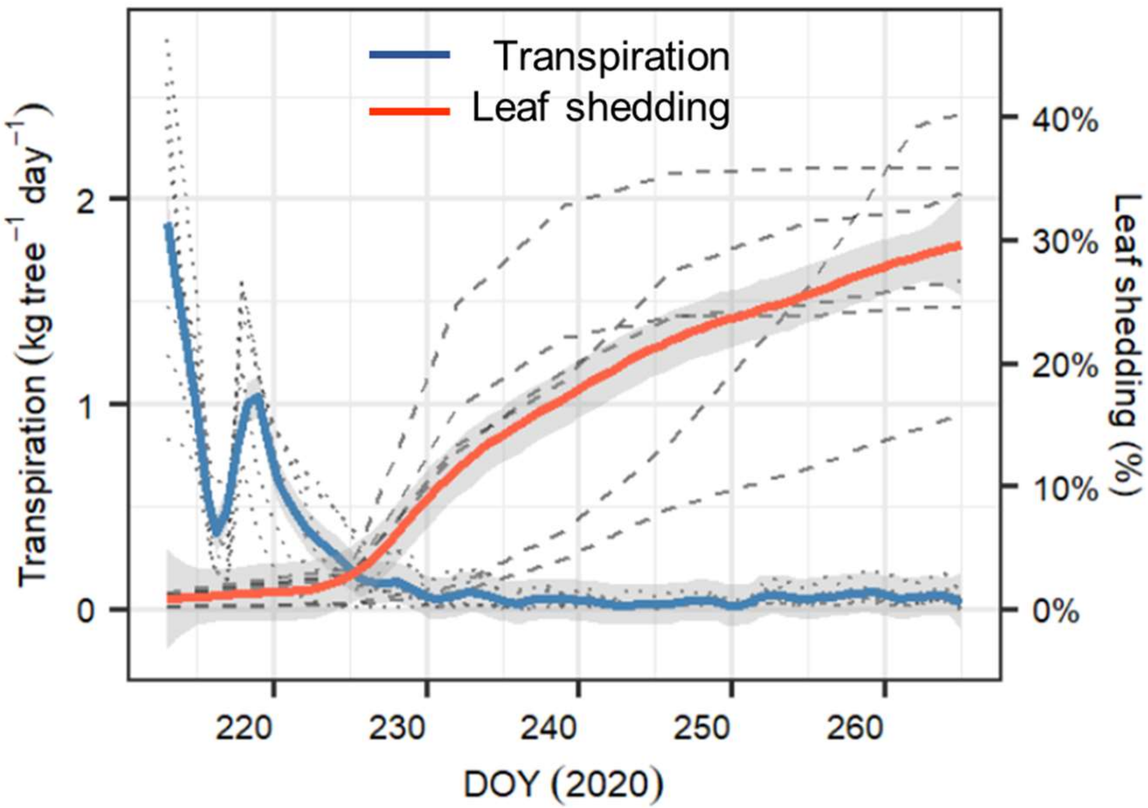
Sustained drought

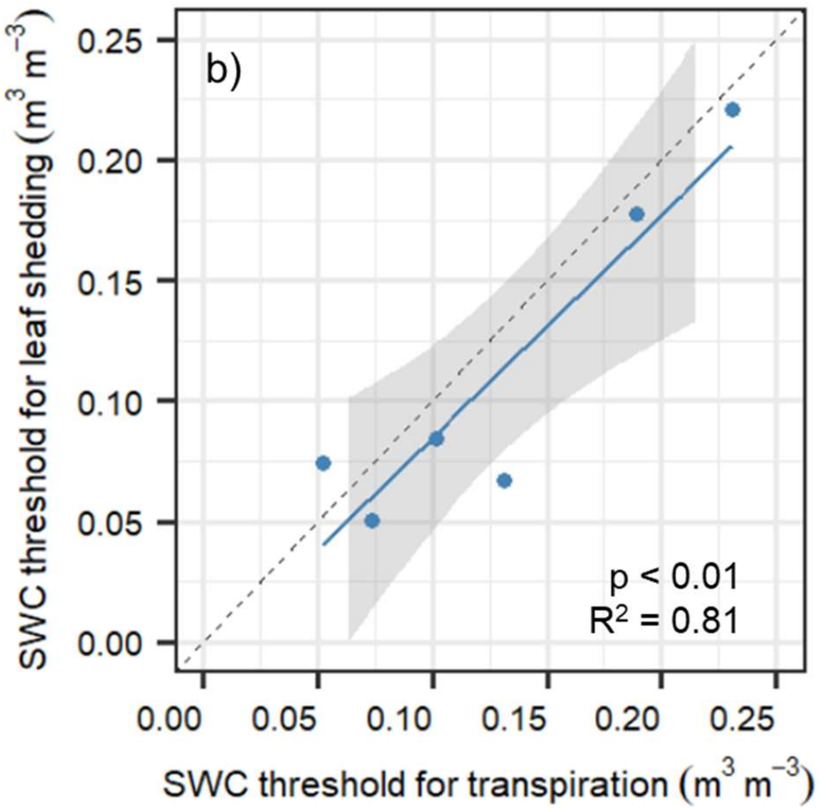
Depletion of soil water
Depletion of tree water storage
Loss of hydraulic function
Leaf shedding
Tree death

Drought stress-induced leaf shedding

P. sylvestris pre drought

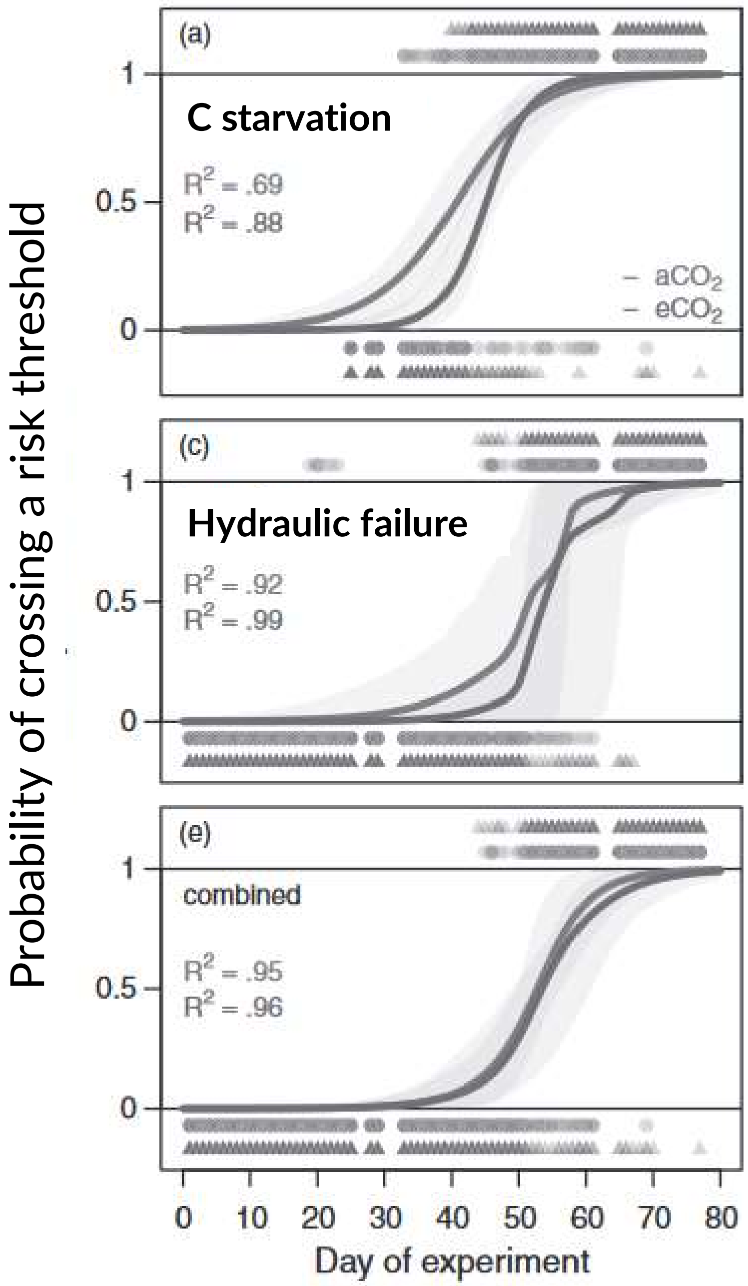
P. sylvestris after drought

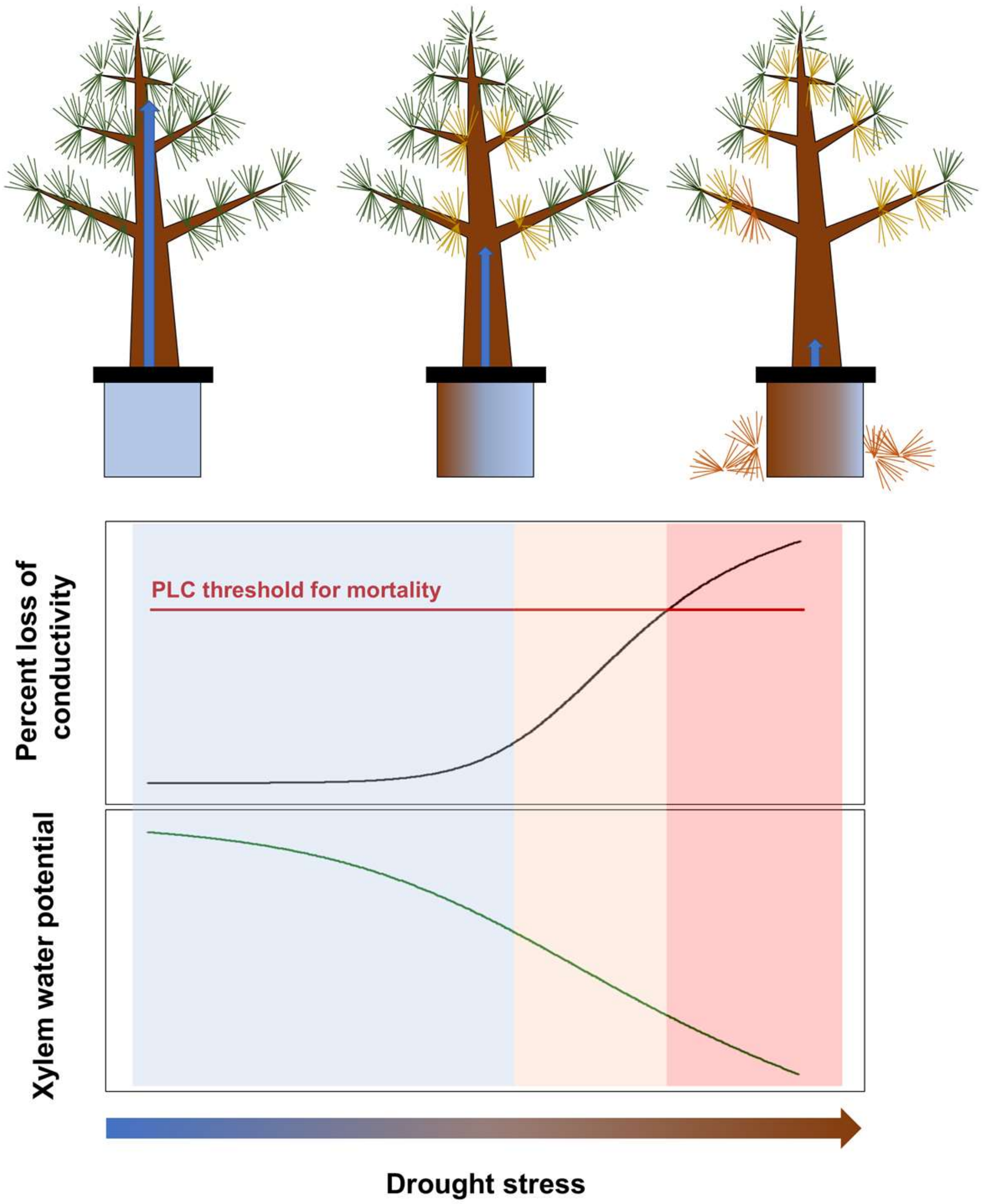




Nadal-Sala et al., (2021)

Dying by drying





Gattmann et al., (2020) Plant, Cell & Environment

Trivia (1’)

Which of the following statements is **true**?

- Intrinsic water use efficiency is reduced as $[CO_2]$ increases
- Drought stress enhances assimilation at global scale
- Intrinsic water use efficiency is the Assimilation / stomatal conductance at leaf level
- Leaf area dynamics do not affect plant desiccation rates

Upscaling fluxes to the canopy

Leaf Area Index (LAI)

LAI stands for Leaf Area Index, and its units are in m^2leaf m^{-2}ground

1 squirrel; LAI = 3

1 m^2 leaf; LAI = 3

1 m^2 leaf; LAI = 2

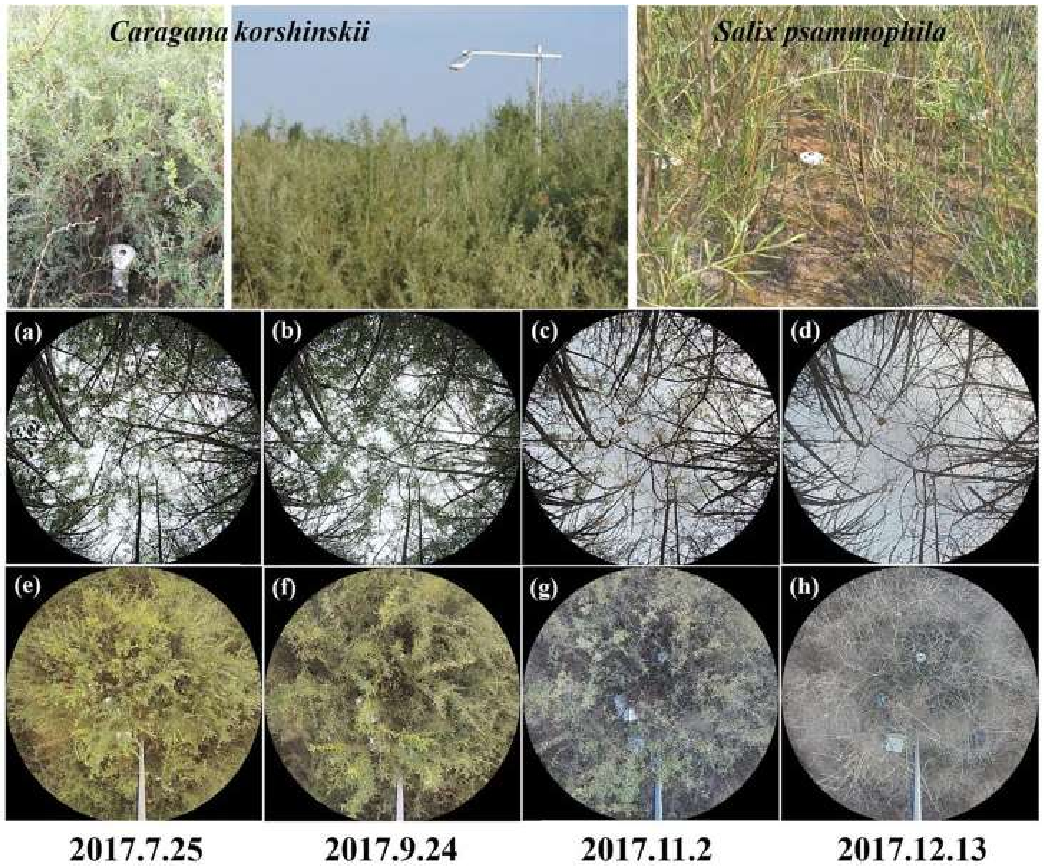
1 m^2 leaf; LAI = 1

1 m^2 ground

But what limits the LAI for the different biomes?

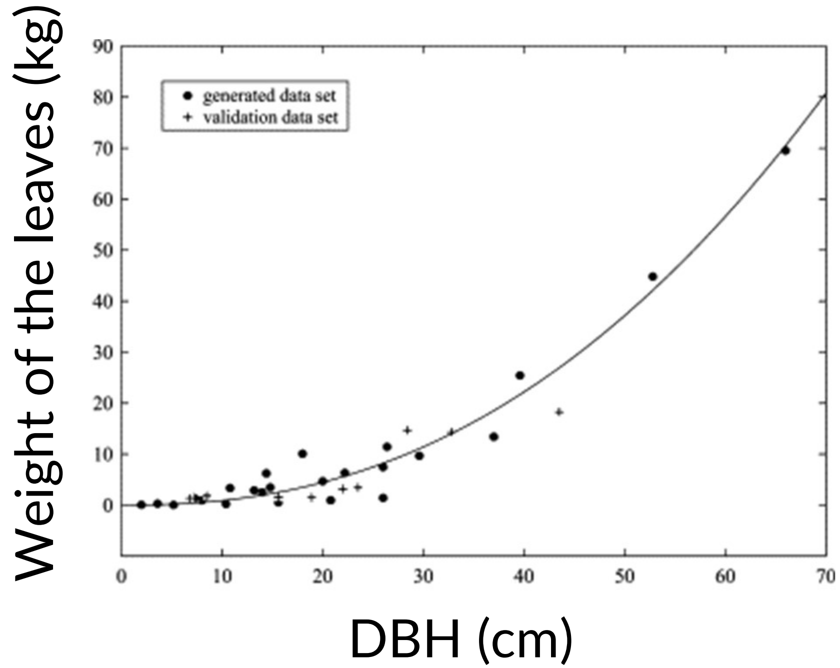
Measuring the LAI

Non-destructive



Destructive

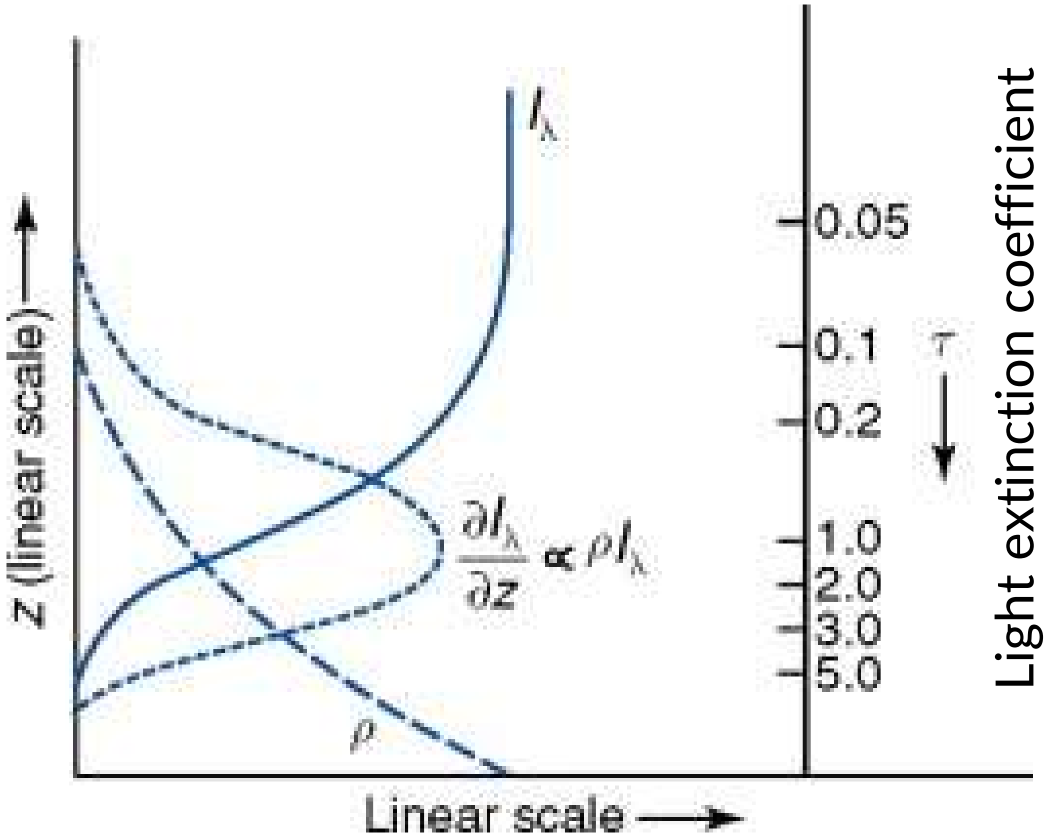
Allometric relationship for white pine (*Pinus strobus*), US

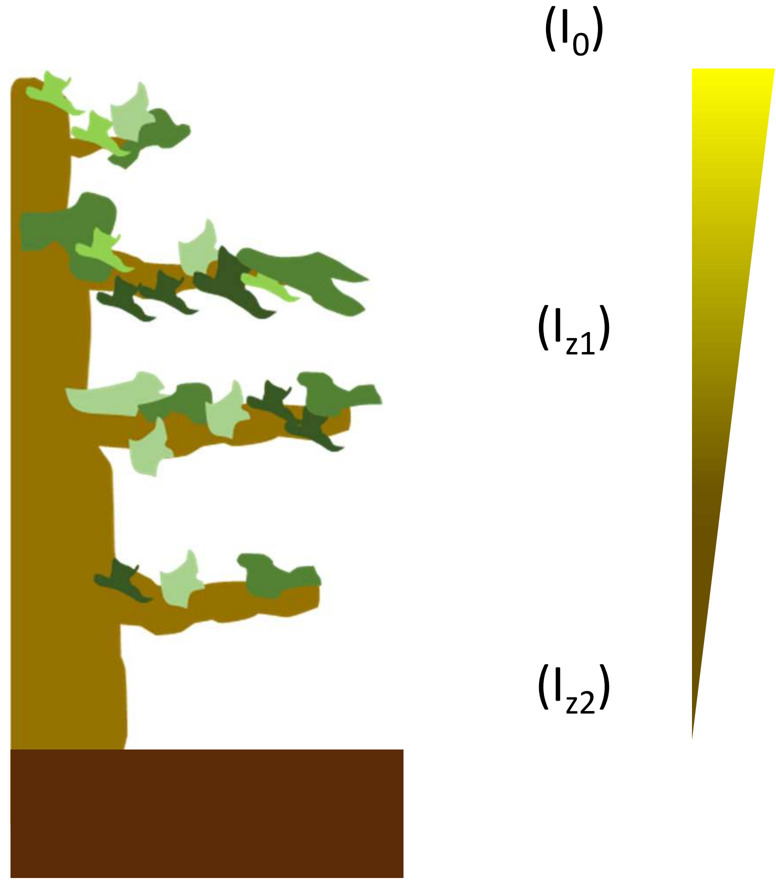


Niu et al., 2021 (Ecological indicators)

Levia Jr., 2008, (FORECOMAN)

Light extinction: the Lambert-Beer law





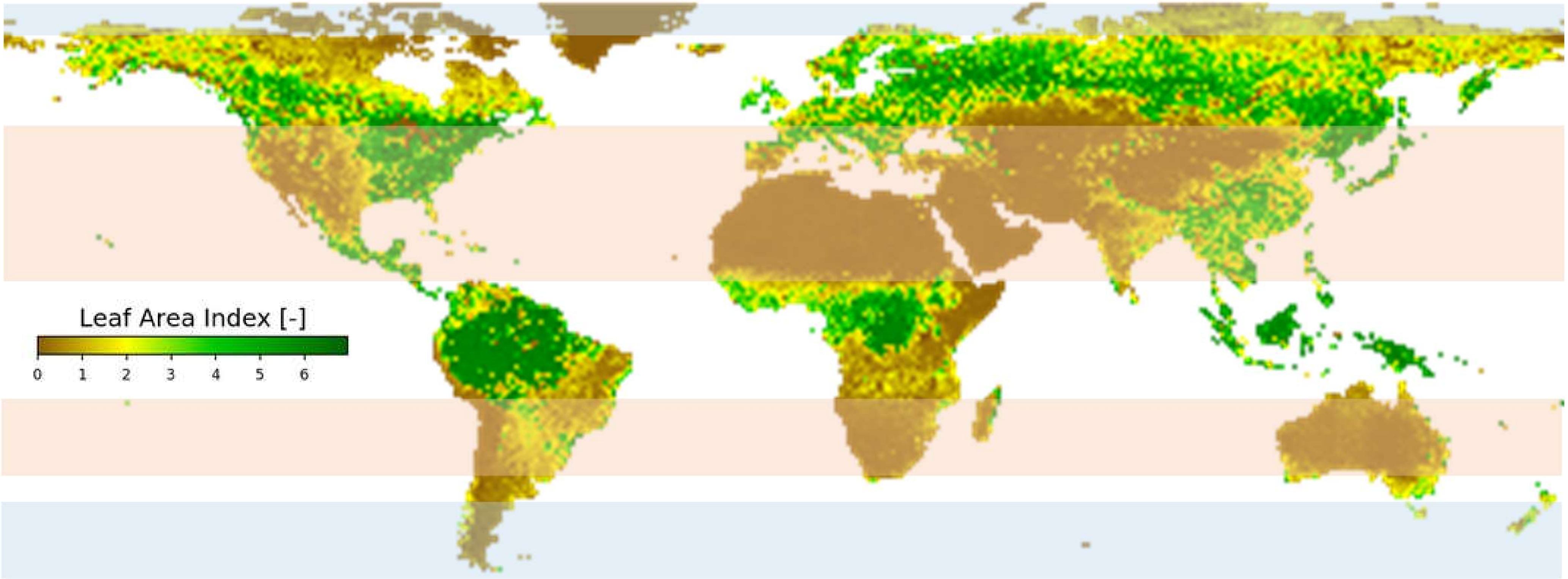
$$I_z = I_0 * e^{-(1-\tau)z}$$

$$I_z = I_0 * e^{-(1-\tau)*LAI}$$

In forests, light extinction depends on the LAI surface rather than canopy depth

Meyers, 2001

Global LAI distribution

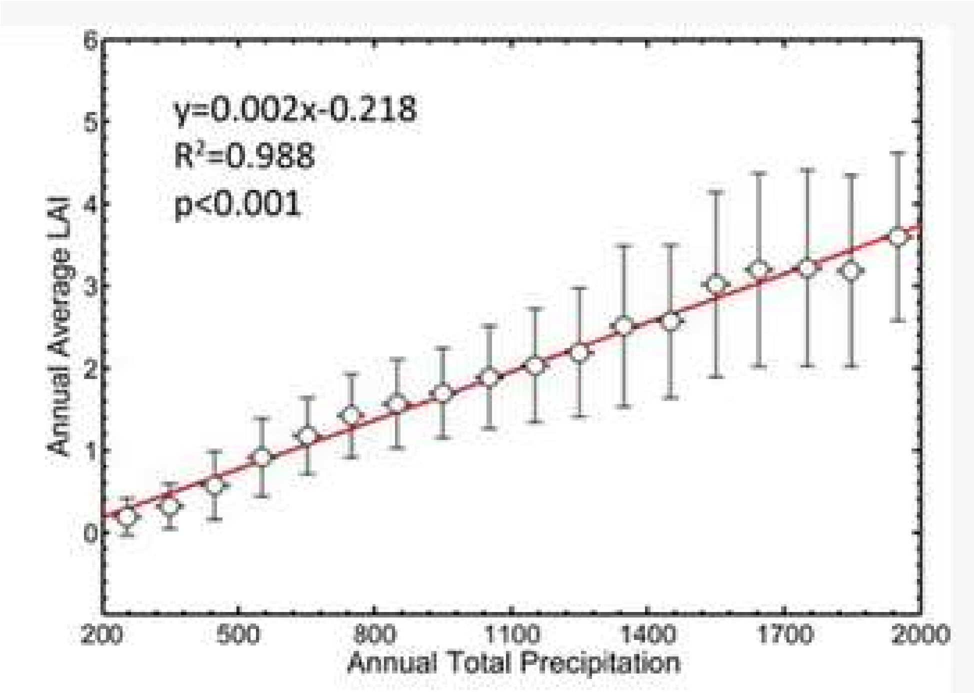


LAI 1x1 km. Copernicus Global Land Service, 2017

Regional differences in LAI due to environmental conditions

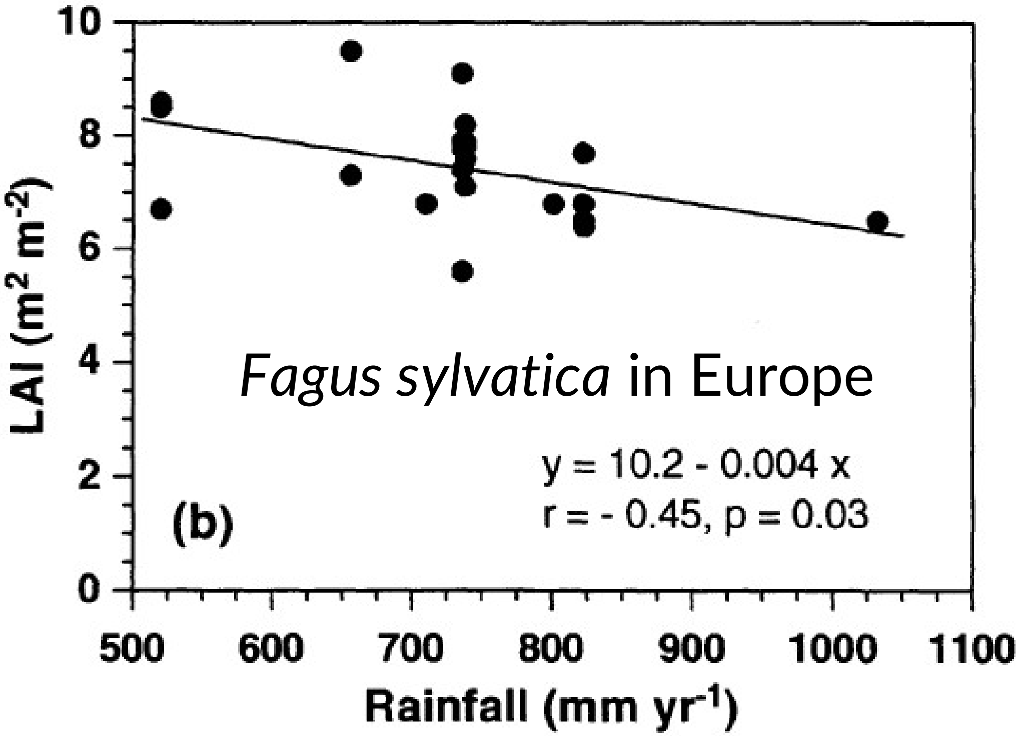
LAI and water availability

Water limitation of LAI



Zhu et al., 2013 (Remote sensing)

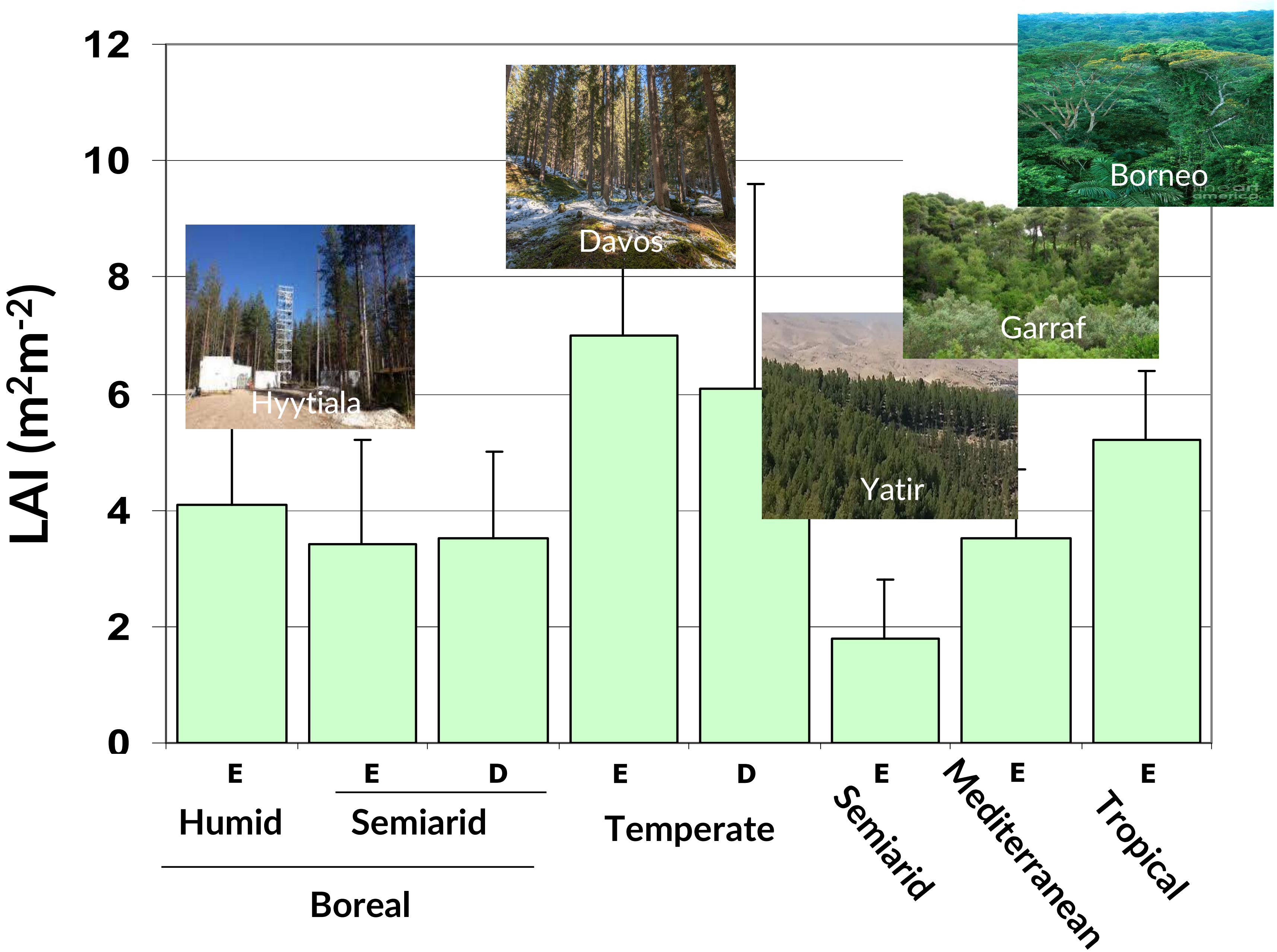
Energy limitation on LAI



Meyer & Leuschner, 2008

LAI dependent on the most limiting factor either (energy or water)

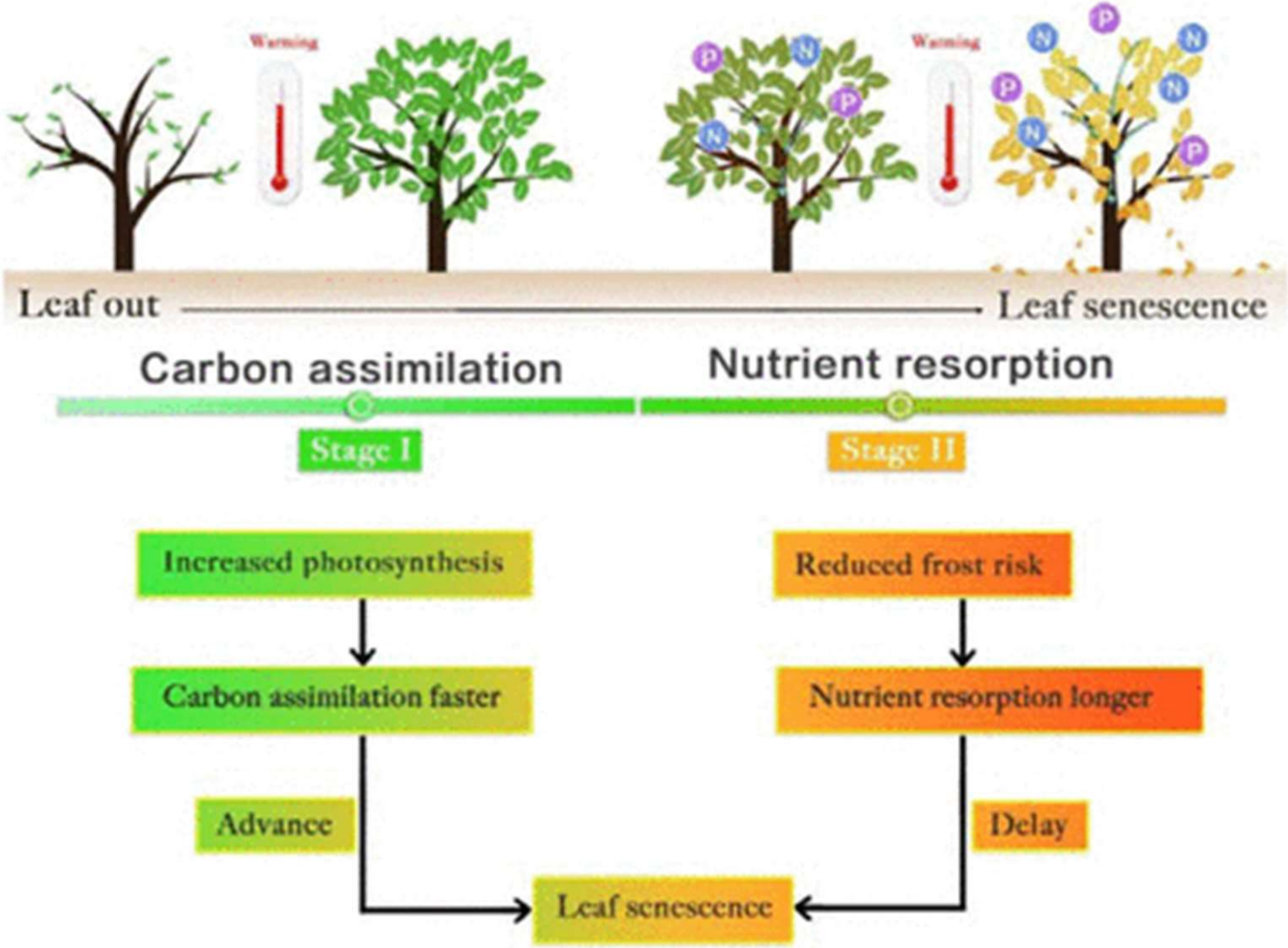
LAI values across the different biomes

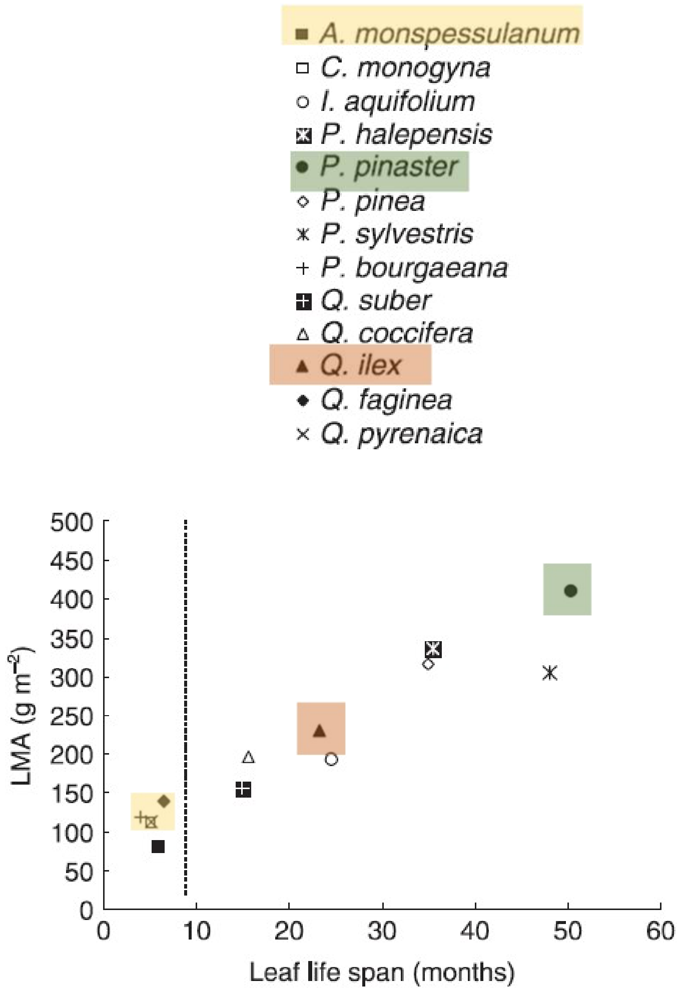


E: evergreen; D: deciduous

Luyssaert, 2008

Leaf senescence

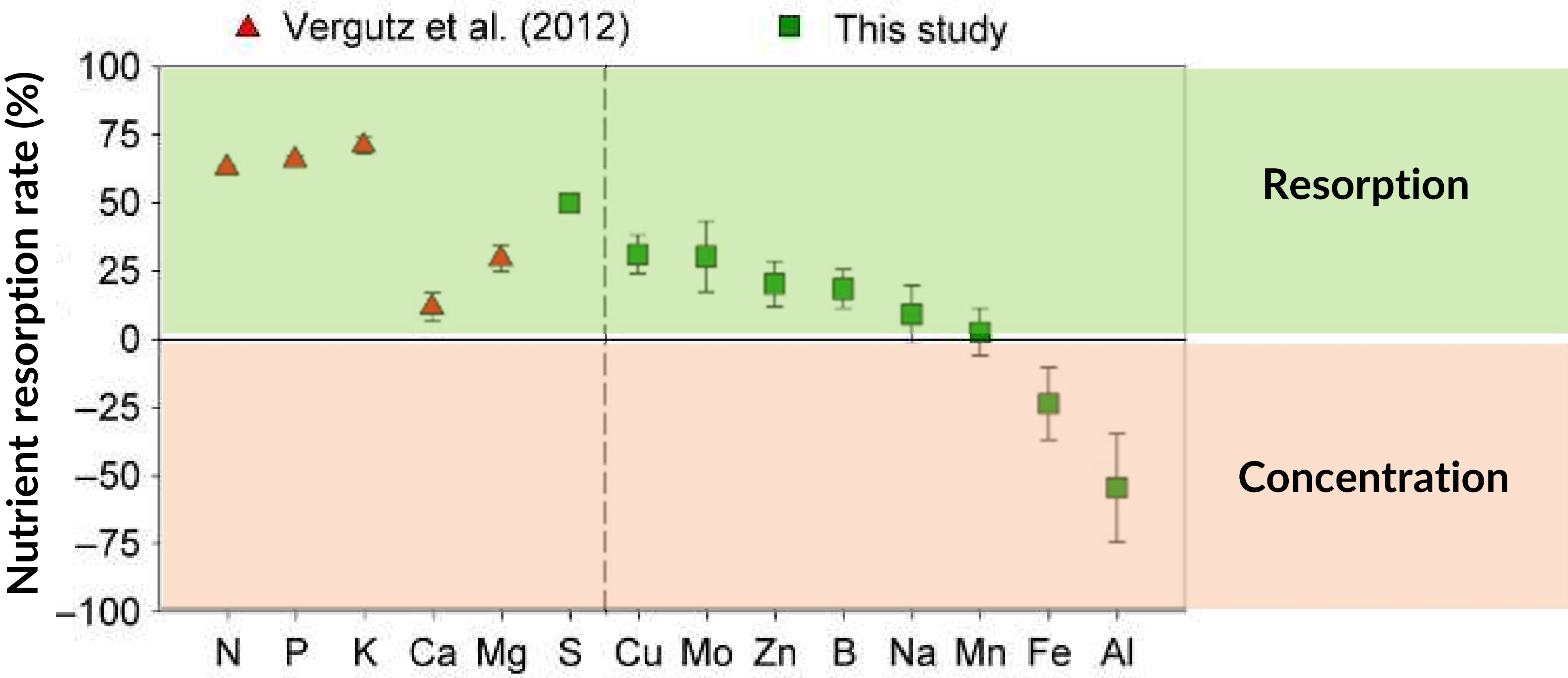




Chen et al, 2021

Mediavila et al, 2008

Leaf nutrient resorption



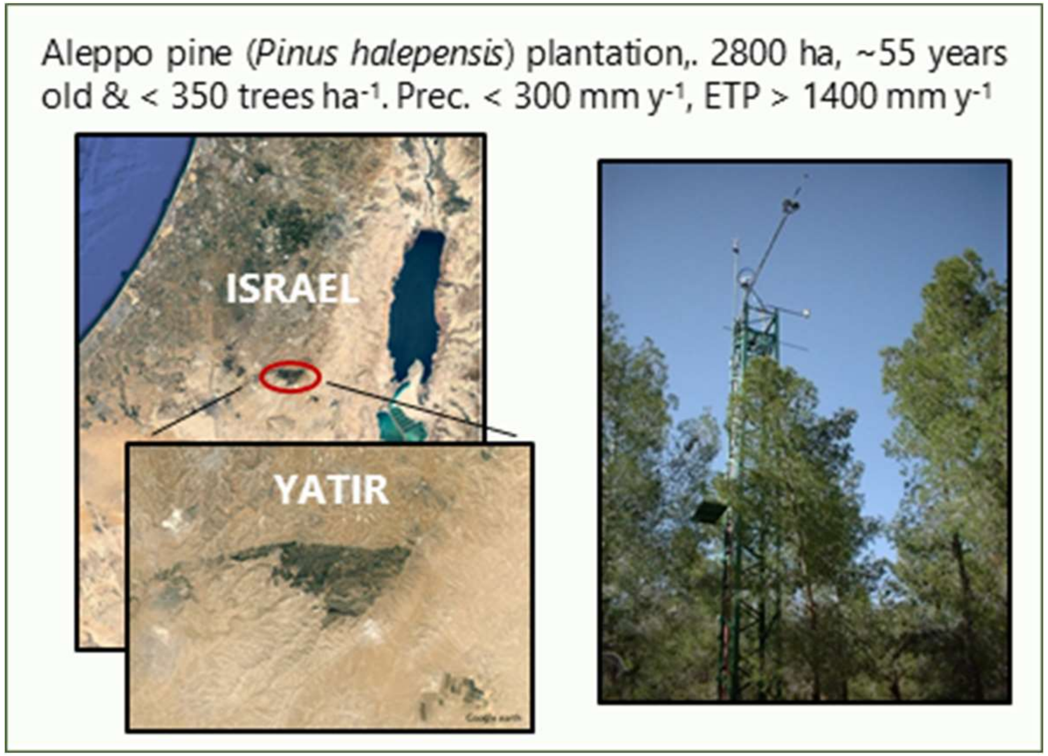
Data from ~ 50 stands across the globe:

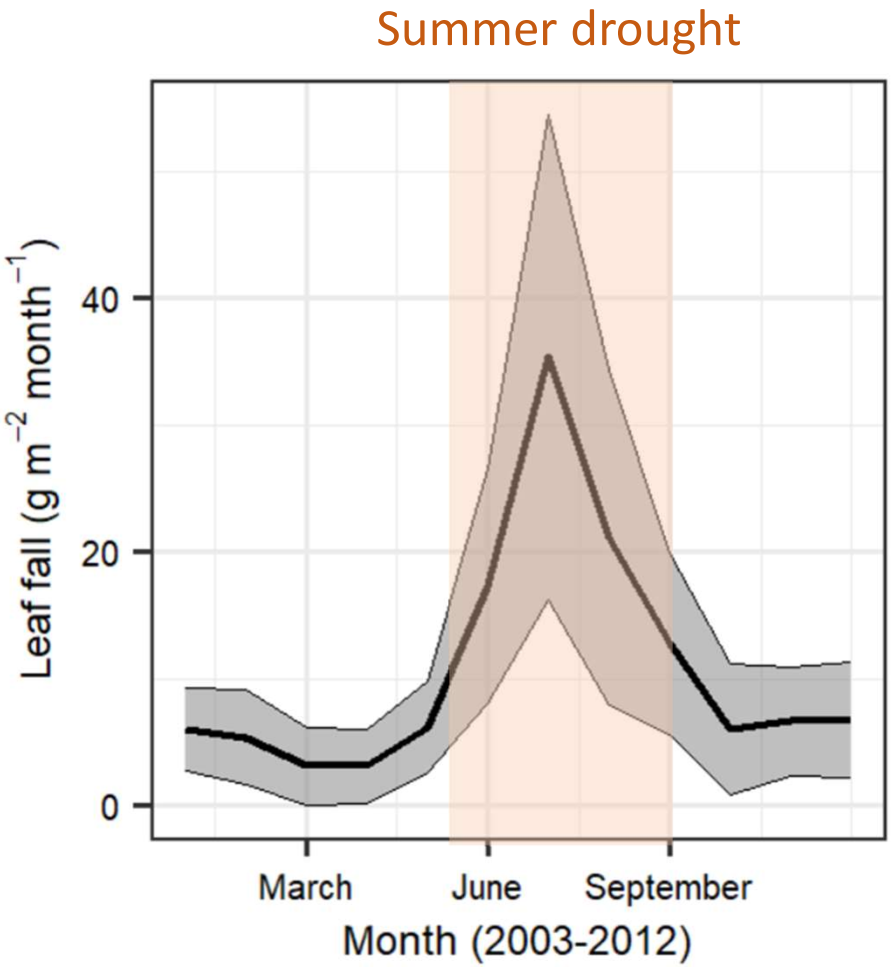
Macronutrients (N, P, S) ↑↑↑ resorption
Trace elements (Mo, Na, Zn) ↑ resorption
Toxic elements (Fe, Al) concentration

Trees resorb nutrients, but also eliminate pollutants with leaf senescence

Chen et al, 2021 (Functional Ecology)

LAI drought-induced seasonality





Nadal-Sala et al., (2024)

Upscaling fluxes to the canopy

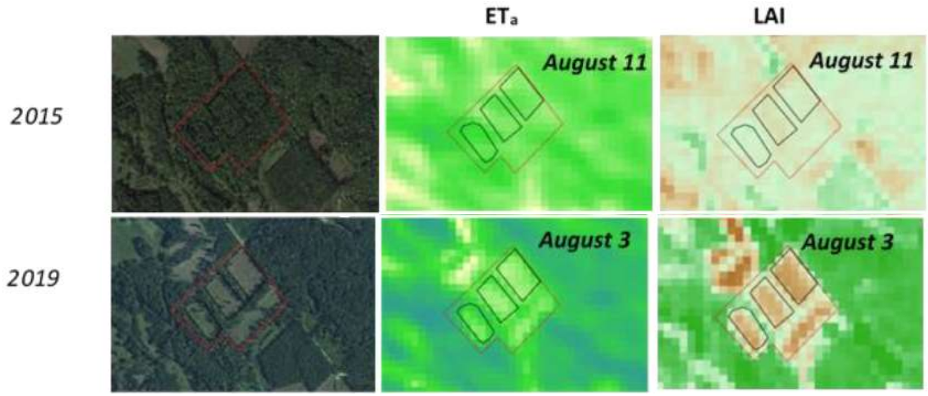
From [flux] * **[leaf surface]$^{-1}$** * [time step]$^{-1}$ to [flux] * **[ground surface]$^{-1}$** * [time step]$^{-1}$

Eddy-covariance tower

We use the LAI (m^2leaf m^{-2}ground)

We can also use Sapwood Area (m^2sapwood m^{-2}ground)

Satellite observations (Czech Republic)



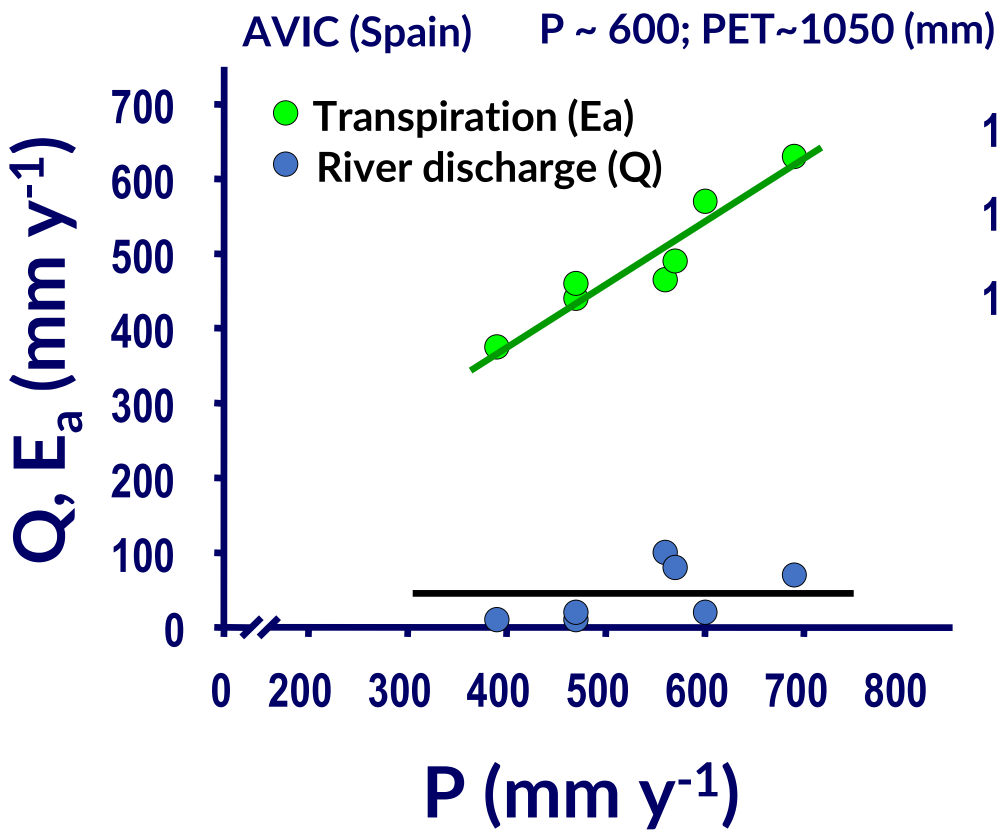
Ghisi et al., 2023 (FORECOMAN)

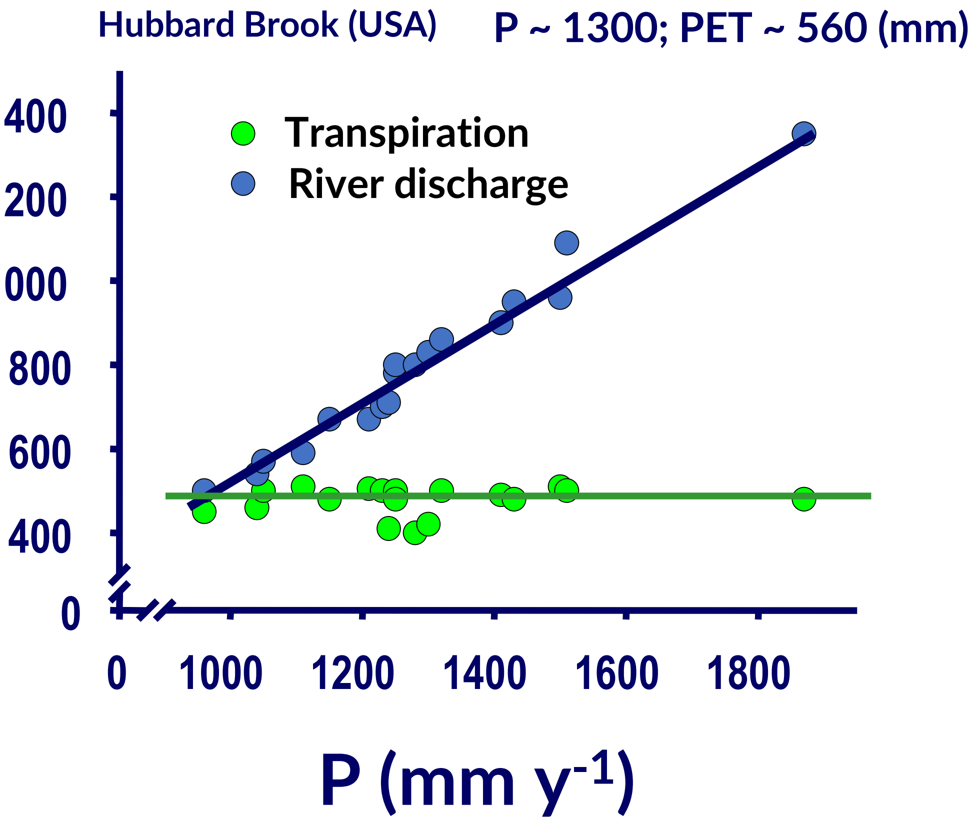
Dendrometer

Arbúcies, Catalunya

Sap flow sensor

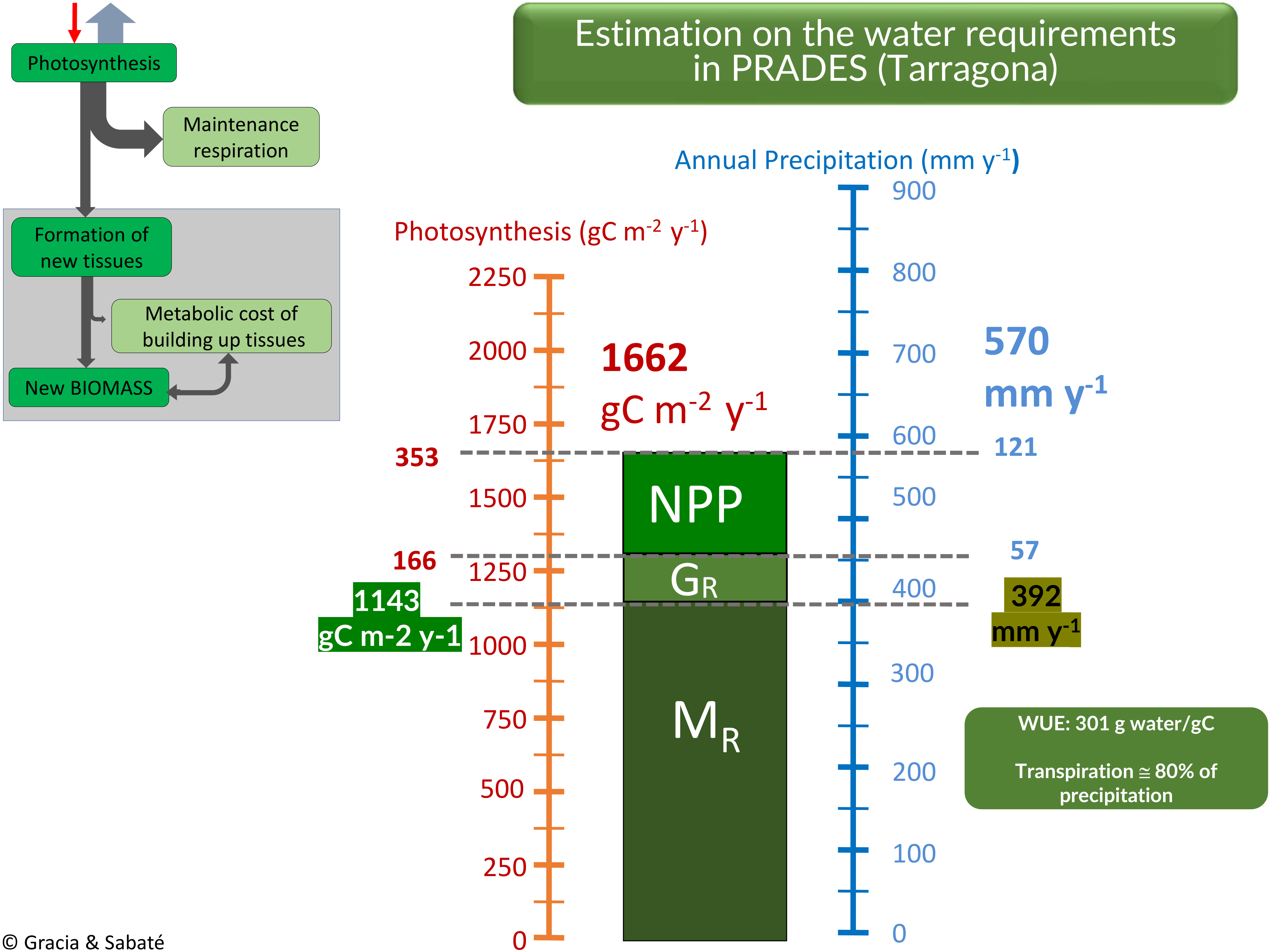
Drainage basin-level water use estimates





From Piñol et al 1991, 1995

Estimation on the water requirements in PRADES (Tarragona)



Trivia (1')

Which of the following statements is **not** true?

As atmospheric [CO_2] increases, stomatal conductance decreases

Maintenance respiration amounts about half of the C assimilated

1 gC provides about 100 kcal of energy, and 1gMO contains about 0.5 gC

Leaf area index is larger in wetter ecosystems

Recommended lectures

Birot, Y., Gracia, C., & Palahi, M. (2011). *Water for forests and people in the Mediterranean region: a challenging balance*. European Forest Institute (EFI).

Cernusak, L. A. (2020). Gas exchange and water-use efficiency in plant canopies. *Plant Biology*, *22*, 52-67.

Keenan, T., Sabate, S., & Gracia, C. (2010). Soil water stress and coupled photosynthesis–conductance models: Bridging the gap between conflicting reports on the relative roles of stomatal, mesophyll conductance and biochemical limitations to photosynthesis. *Agricultural and Forest Meteorology*, *150*(3), 443-453.

Robert A. Meyers (Ed.). 2001. Encyclopedia of Physical Science and Technology. 3rd edition. Academic Press: San Diego, US

Strasburger, E., Schimper, A. F. W., Noll, F., Schenck, K., Sitt, P., Weiler, E. W., ... & Kórner, C. (2004). *Tratado de botánica*. Omega.