



Photo: J. Verfaillie

30 Plant-atmosphere interactions

Learning objectives

- Explain why plant processes are important for the atmosphere.
- Assess the importance of the energy absorbed in photosynthesis or heat released by respiration.
- Describe what controls the exchange of water and carbon between a leaf and the atmosphere.

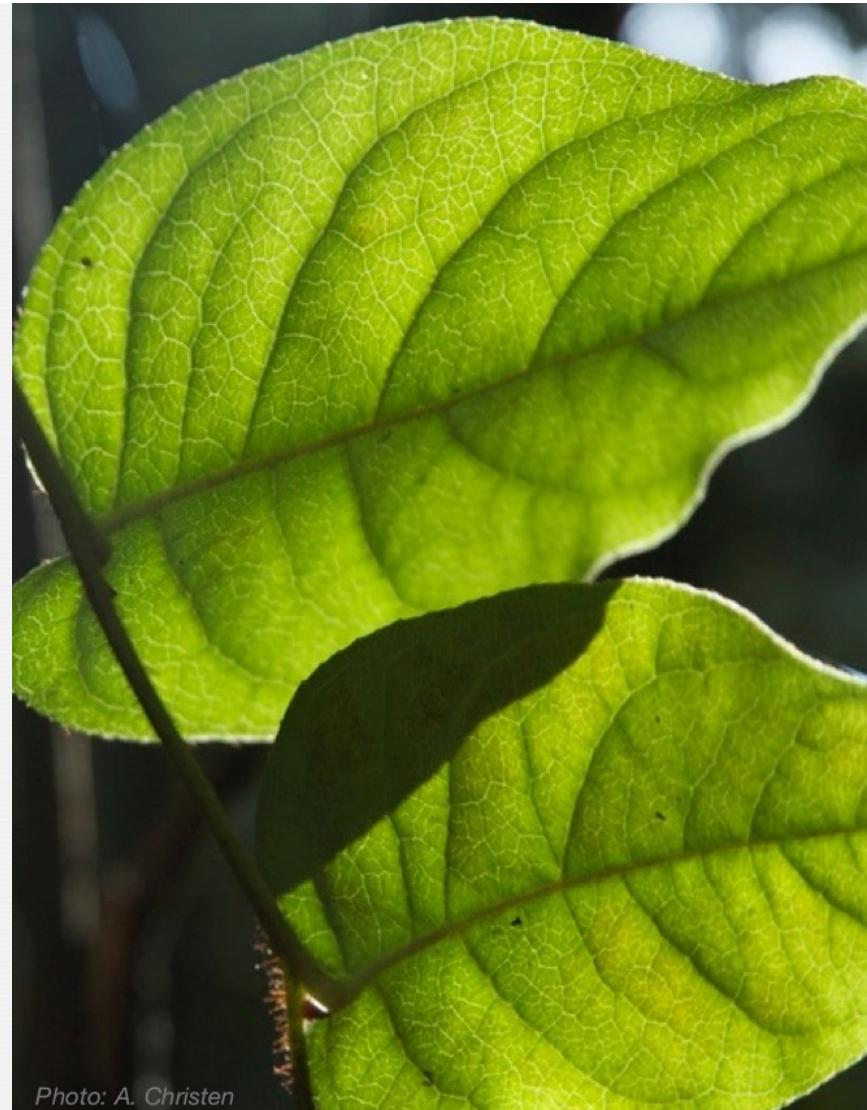
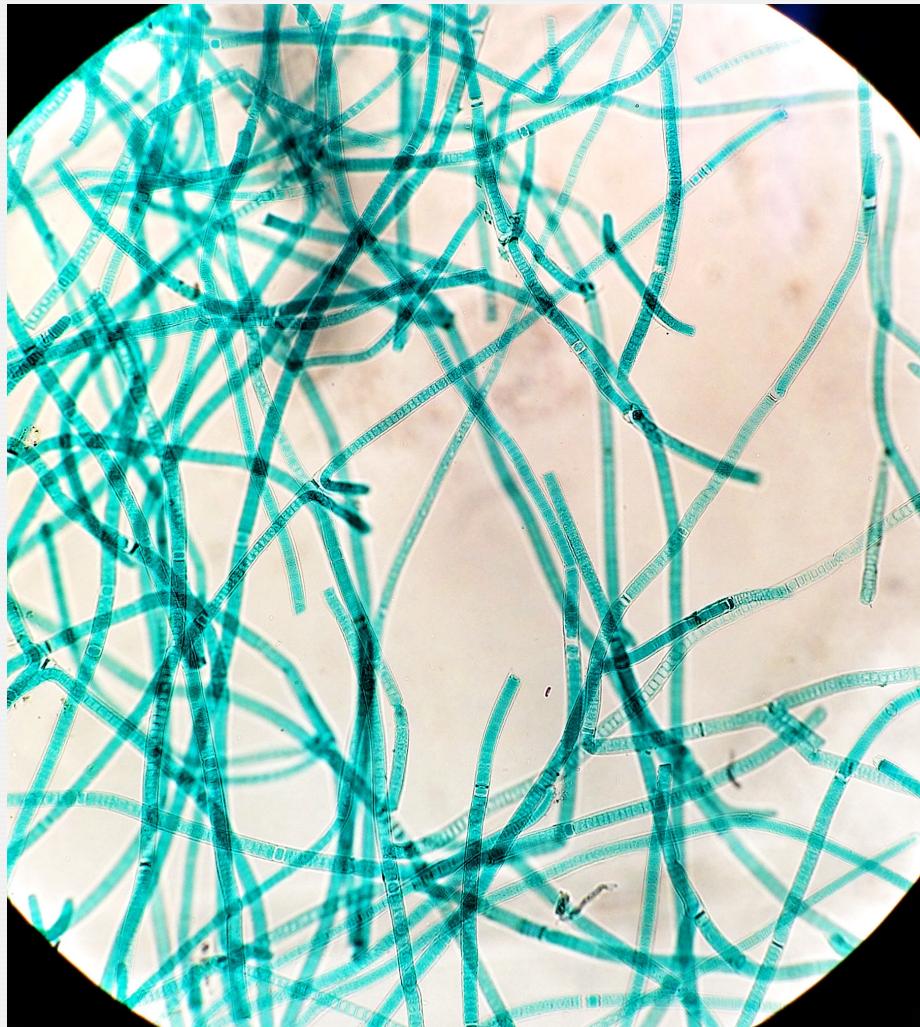


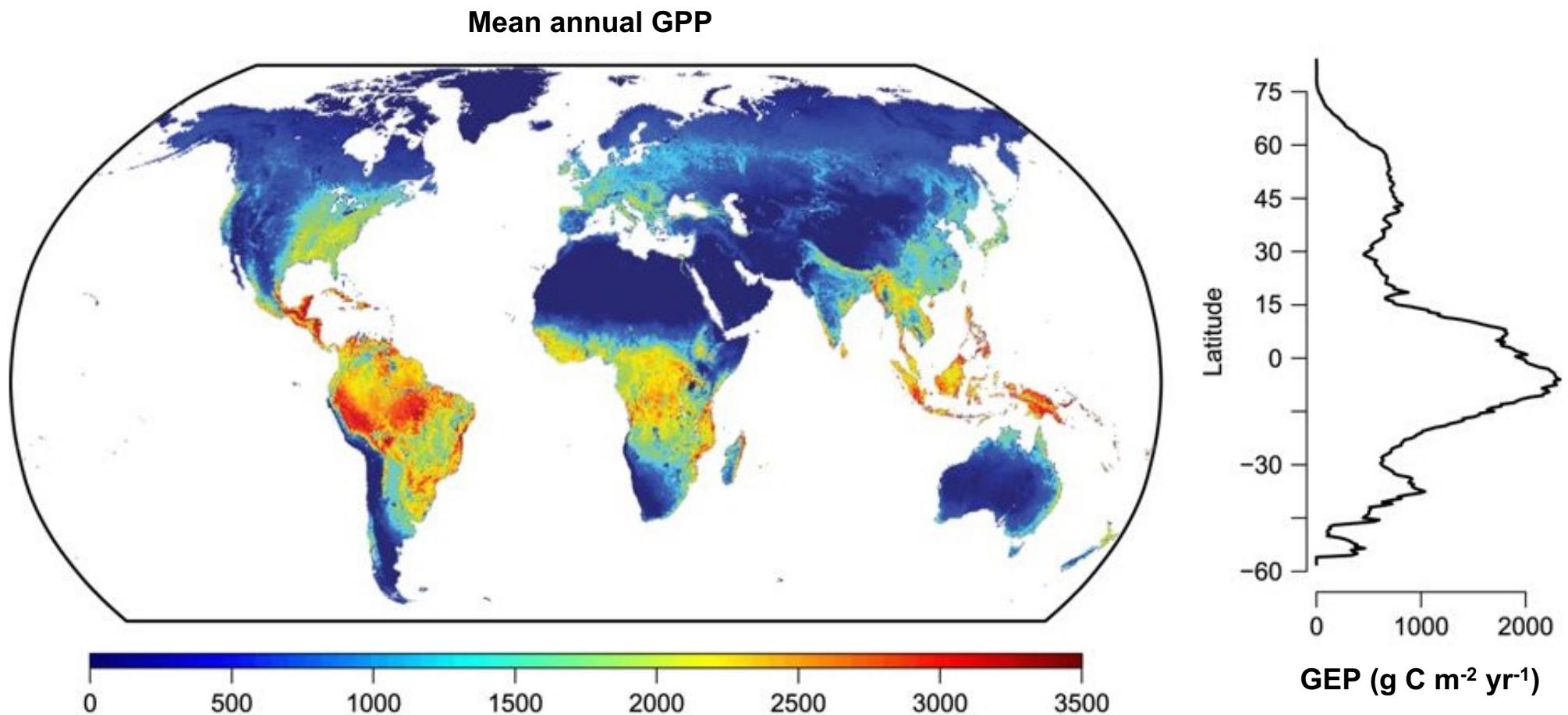
Photo: A. Christen



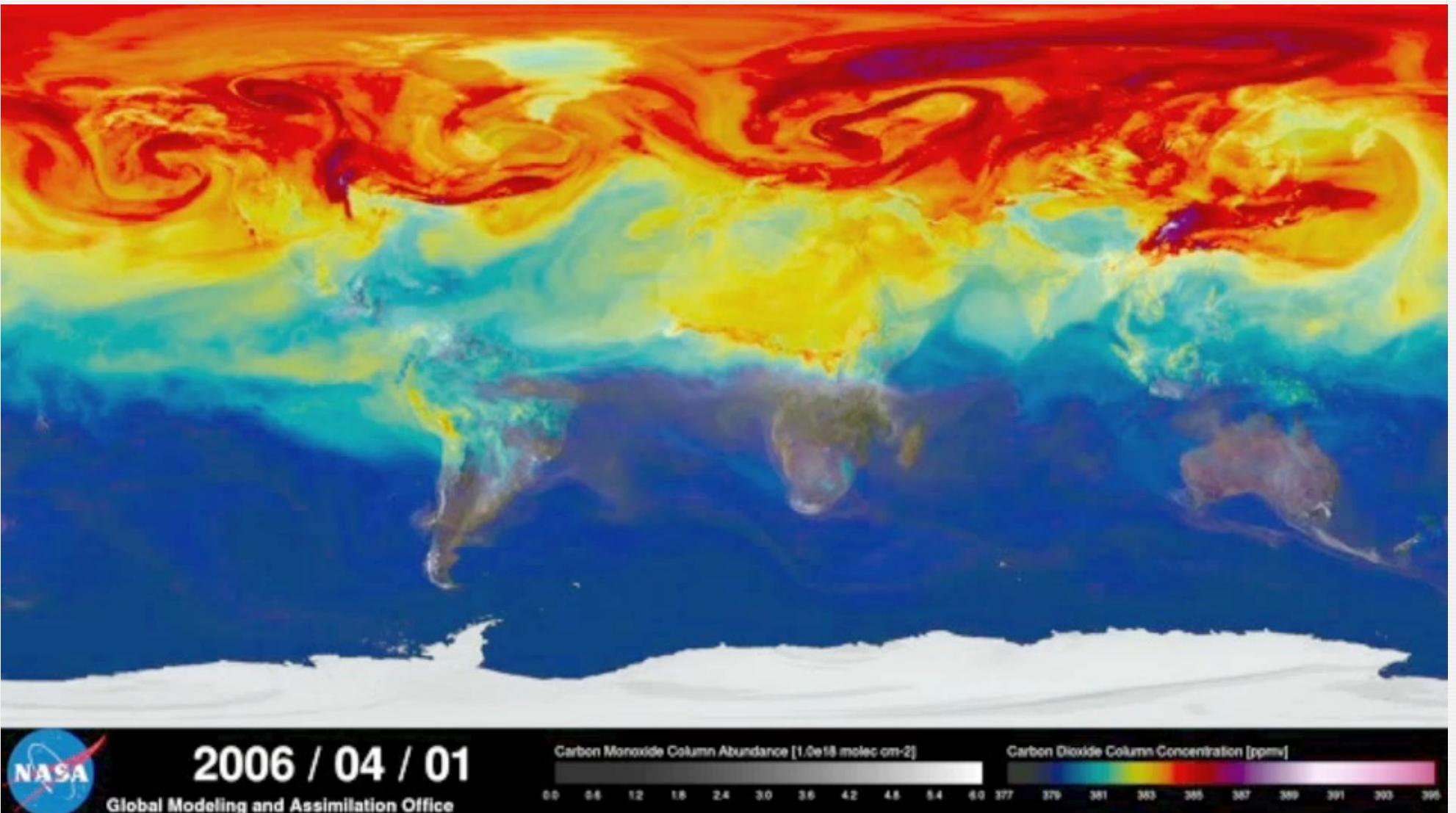
In the beginning there was cyanobacteria



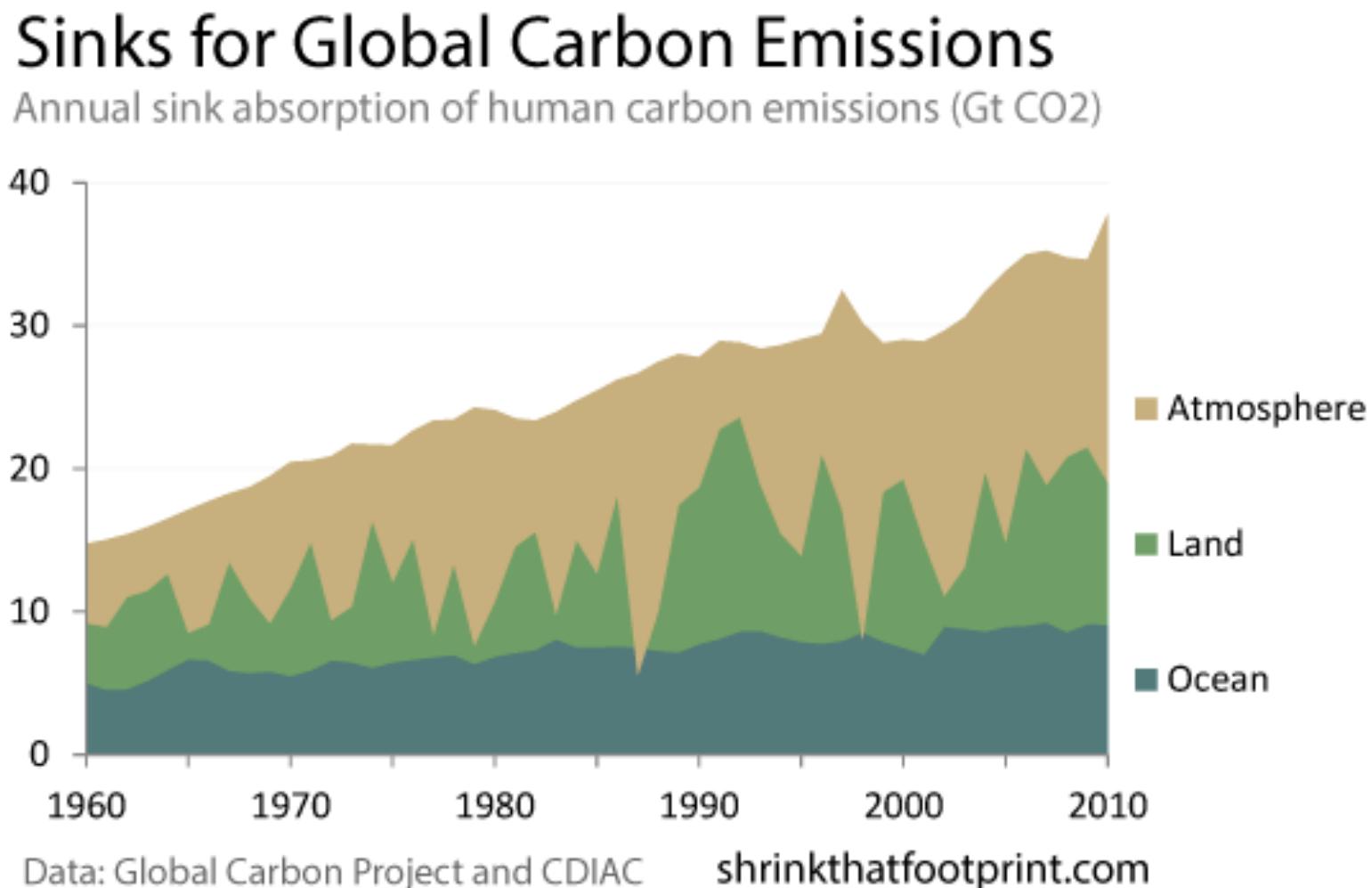
Photosynthesis across the globe

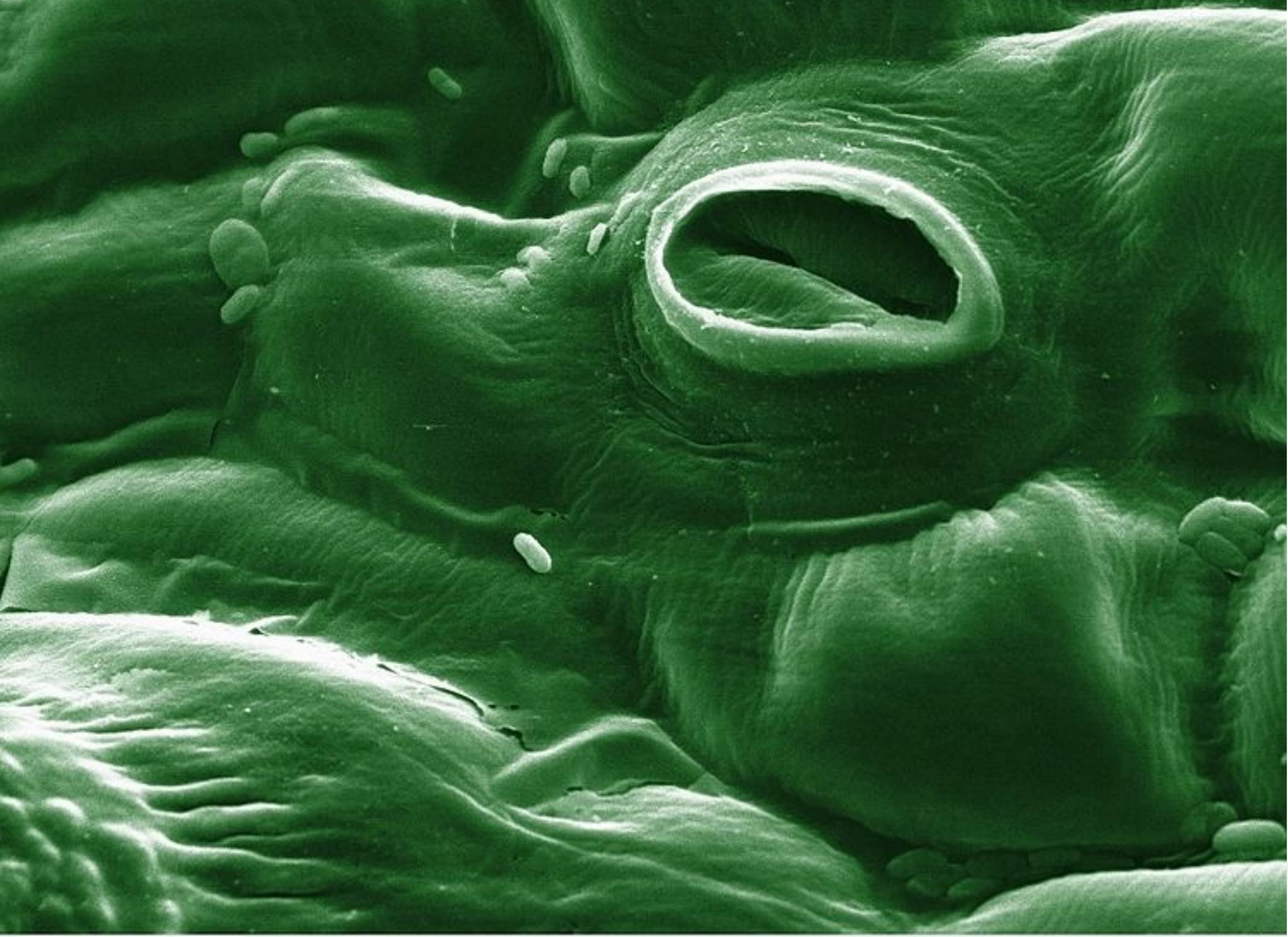


The ‘breathing’ of the biosphere



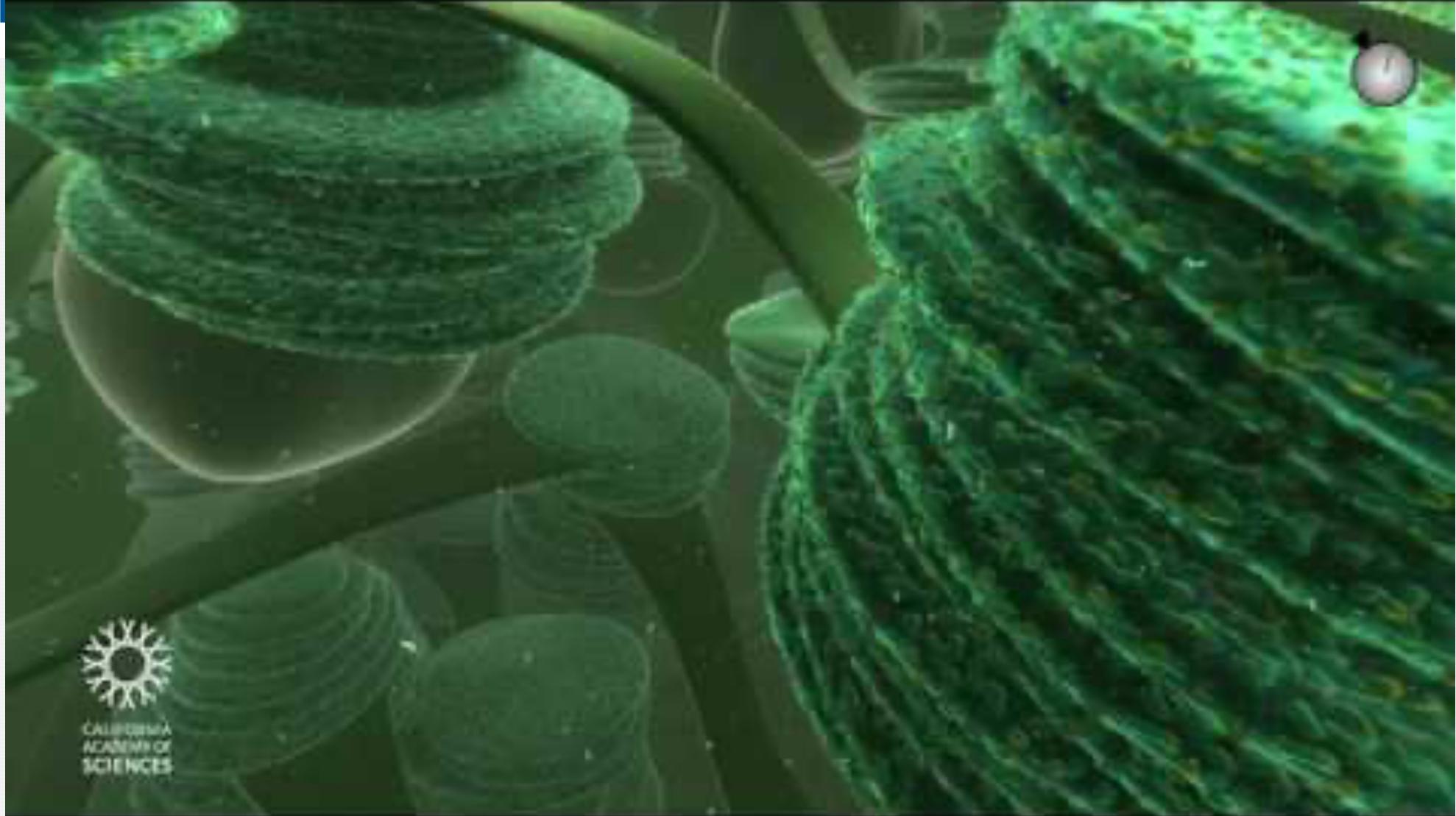
The land sink for CO₂





10 μ m

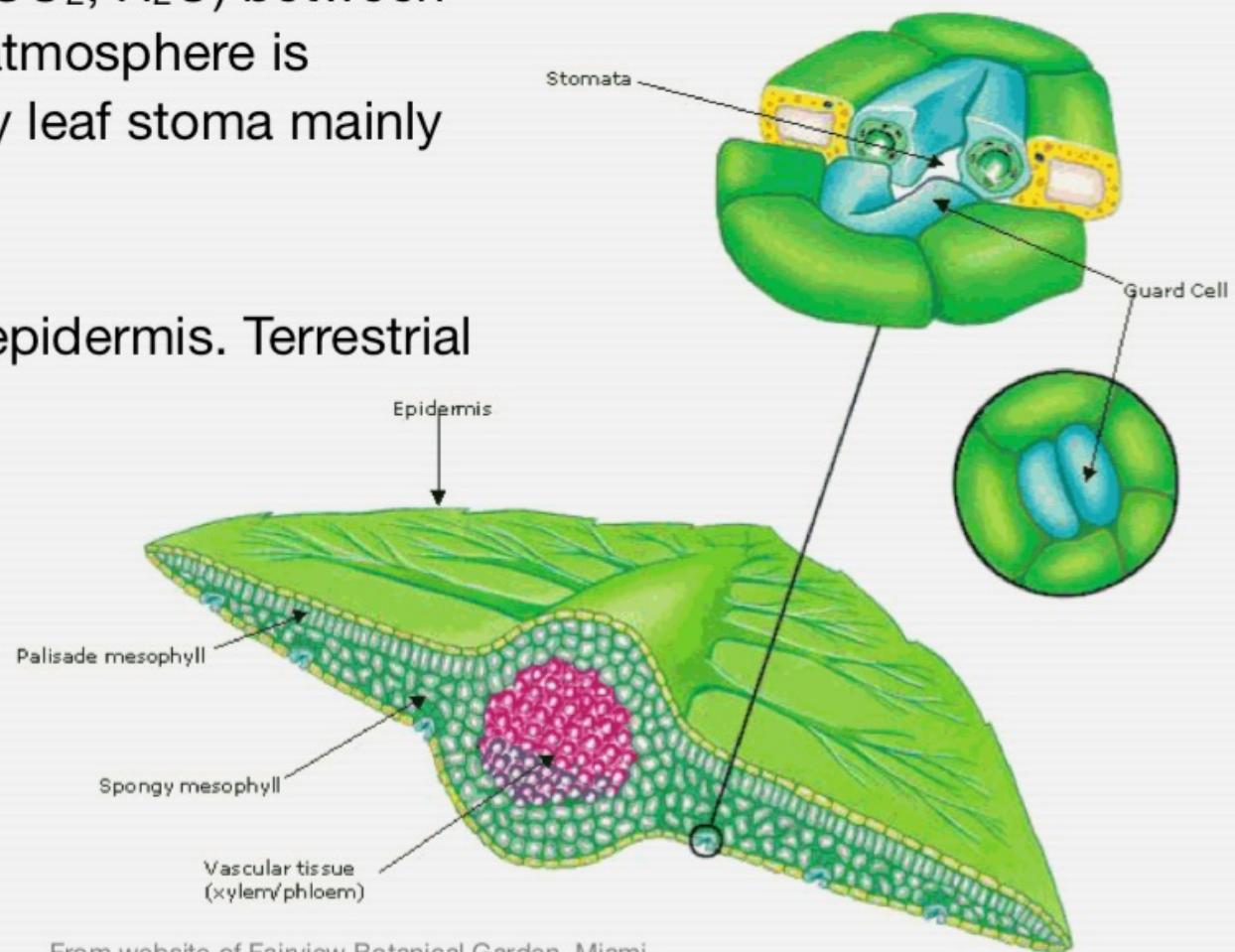
Inside a leaf



Exchange between plants and the atmosphere

The exchange of air (including CO₂, H₂O) between the plant's interior and the atmosphere is physiologically controlled by leaf stoma mainly through **guard cells**.

Stomata are found on the leaf epidermis. Terrestrial plants have them usually on the underside of the leaf. Stomata are typically open during day to capture CO₂ needed in photosynthesis.



From website of Fairview Botanical Garden, Miami.

Photosynthesis and respiration



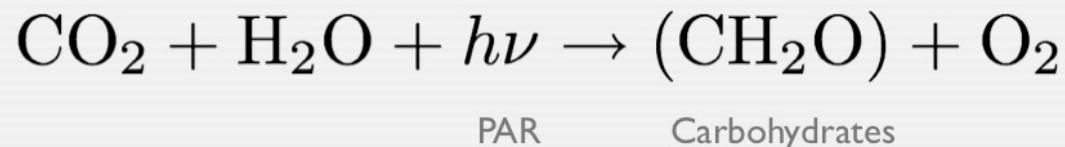
Photosynthesis - The formation of carbohydrates from H_2O and CO_2 in the chlorophyll-containing tissues of plants exposed to **photosynthetically active radiation, PAR, 400-700 nm**)

Respiration -The oxidation of carbohydrates with the **release of energy**, occurs continuously to provide energy for other plant processes and energy for microbes by decomposing organic material.

Photos: A. Christen

Gross chemical processes

The chemical sum equation for **gross photosynthesis** is:



There are 469 kJ of PAR stored in form of chemical energy in each mole of carbohydrate produced.

Respiration is the reverse process (oxidation) releasing energy. The gross chemical equation for the overall process is:



Energy gain for plants: 42% is put into other biochemical processes, 58% is put into sensible heat.

Net ecosystem productivity (NEP)

Net ecosystem productivity (NEP) is the primary component of the carbon balance in most terrestrial ecosystems. It is defined as the difference between **ecosystem scale photosynthesis** (or **Gross Primary Productivity; GPP**) and **ecosystem respiration (ER)** (units are generally in $\text{mol m}^{-2} \text{ s}^{-1}$ or $\text{g m}^{-2} \text{ s}^{-1}$):

$$\text{NEP} = \text{GPP} - \text{ER}$$

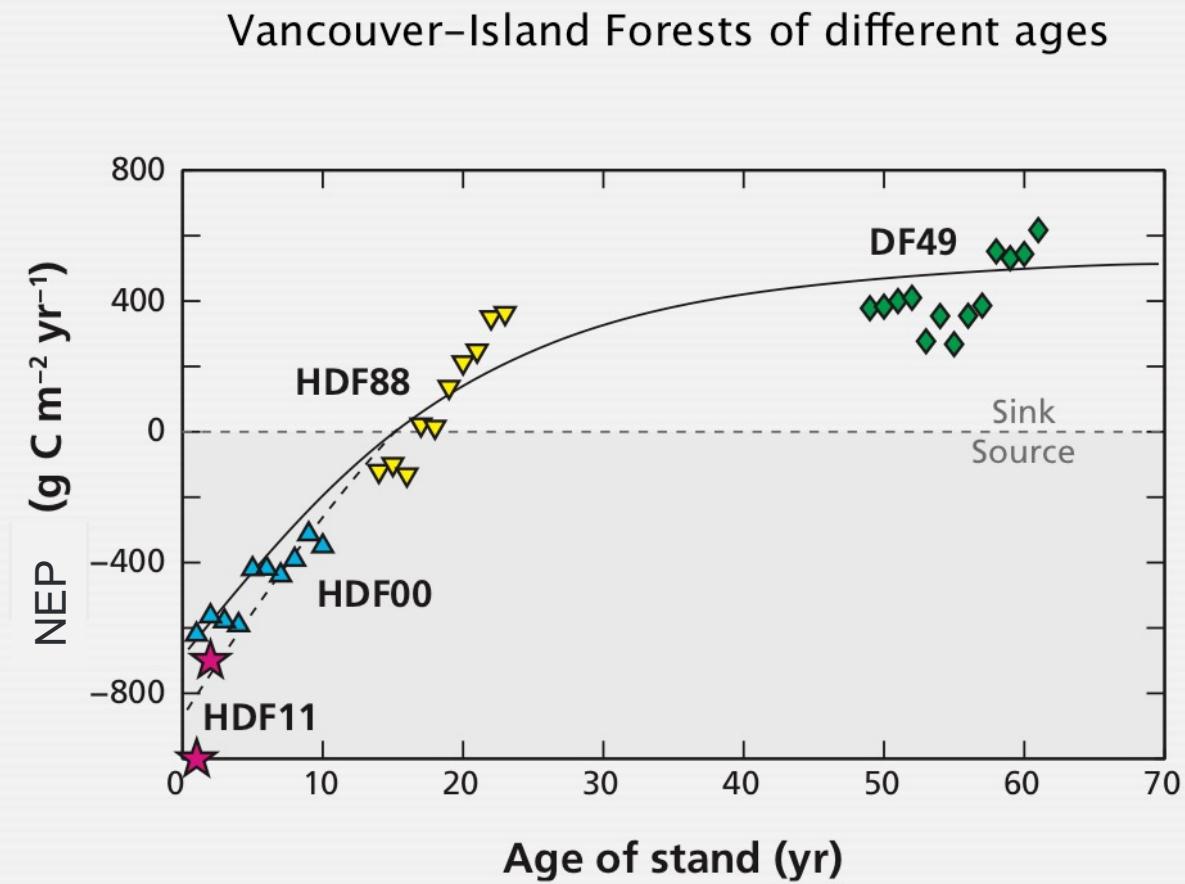
Ecosystem respiration (ER) is the total aerobic respiration of CO_2 by an ecosystem:

$$\text{ER} = \text{AR} + \text{HR}$$

Autotrophic respiration (**AR**) is CO_2 respired by primary producers (i.e., plants)

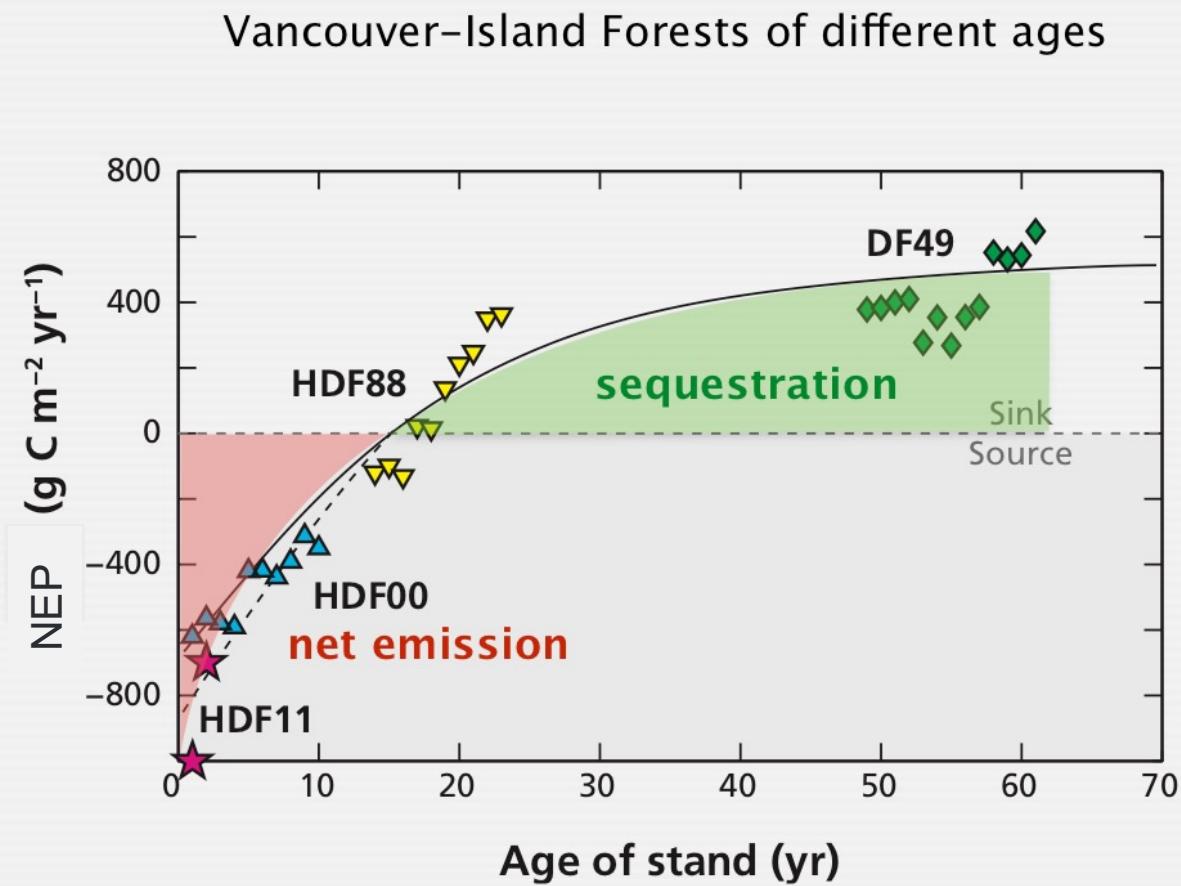
Heterotrophic respiration (**HR**) is CO_2 respired by all other living organisms (i.e., bacteria, animals, fungi). This CO_2 is also derived from GPP, but in a more roundabout way.

Carbon uptake or release from ecosystems?



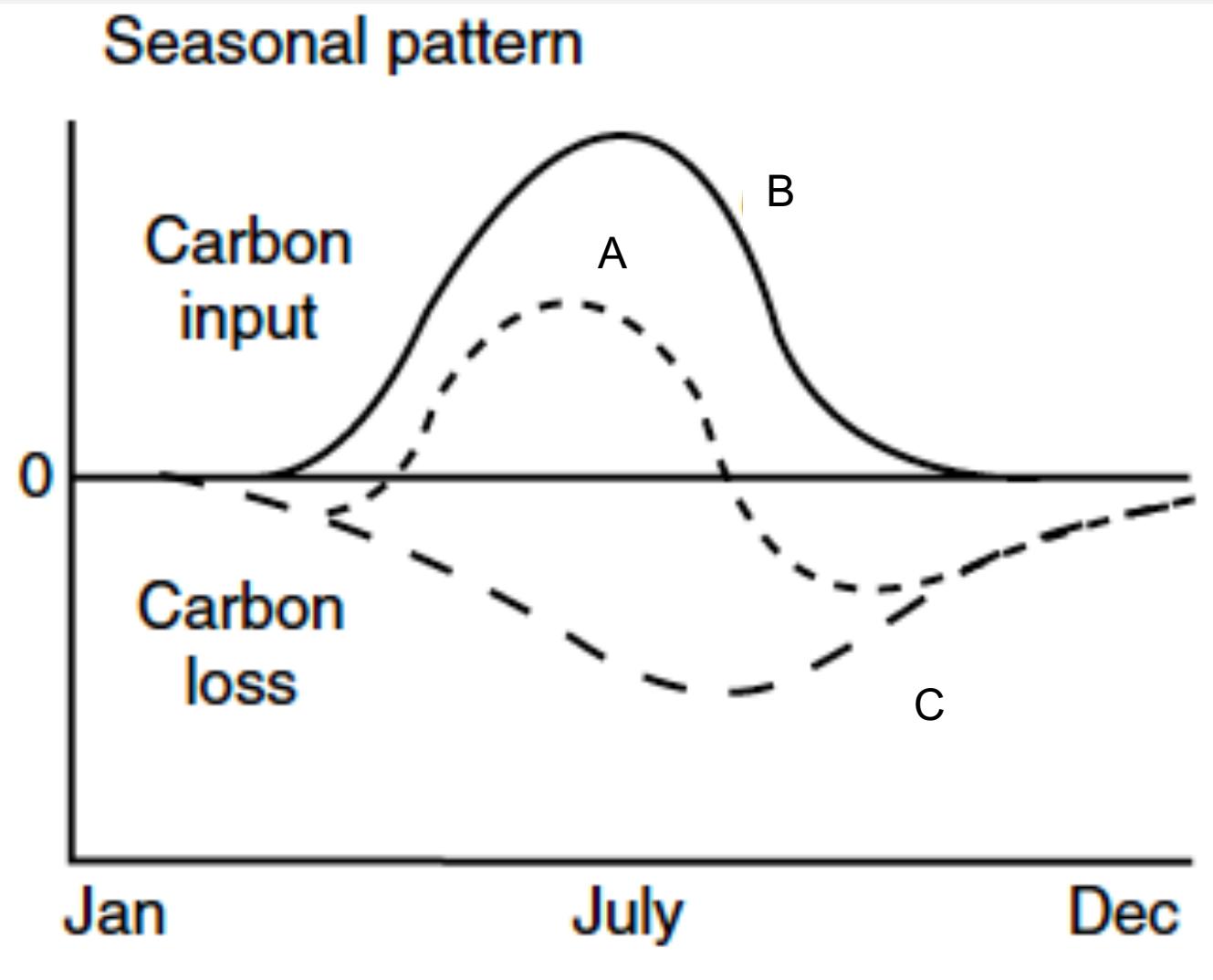
Paul-Limoges, et al. (2013)

Carbon uptake or release from ecosystems?

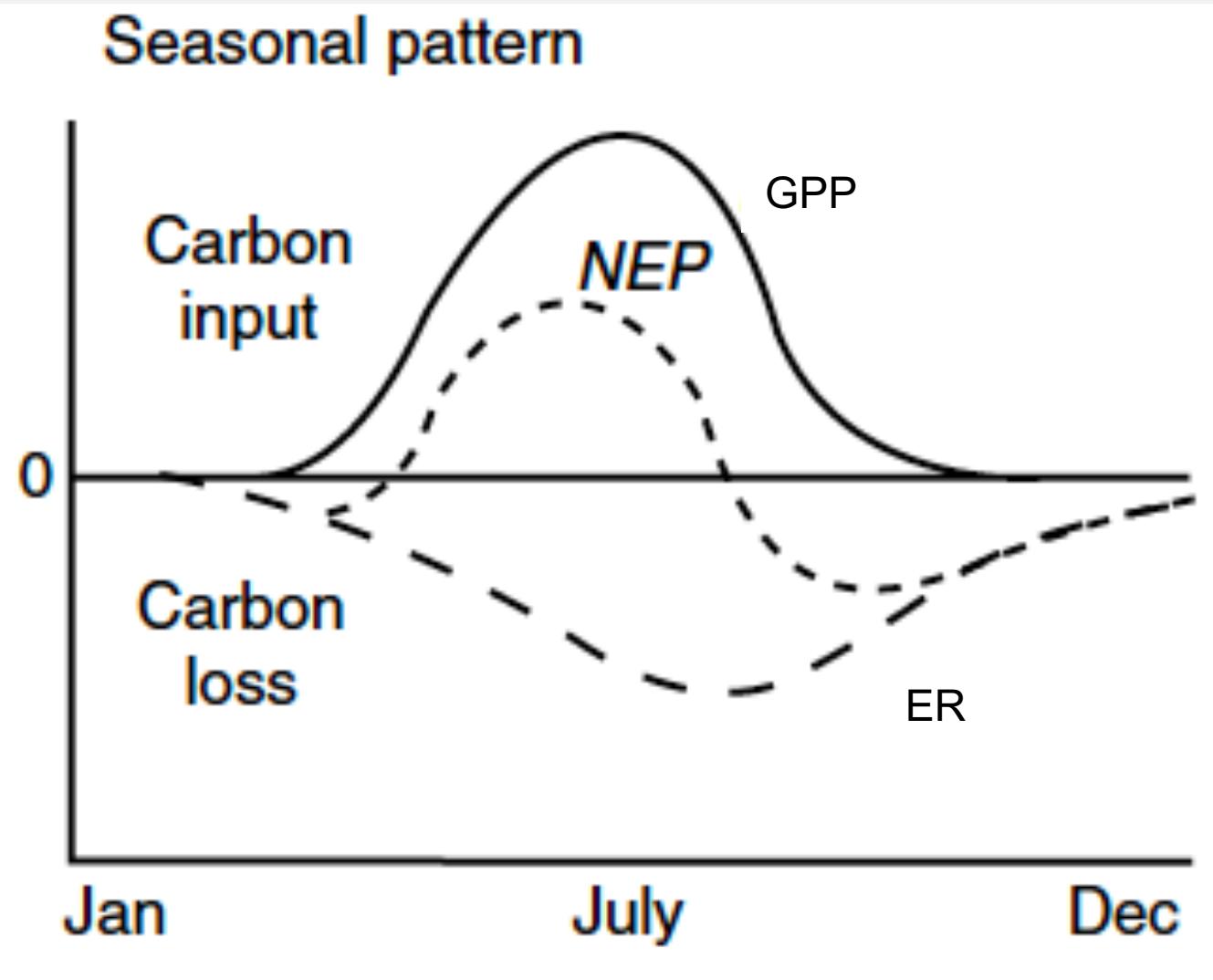


Paul-Limoges, et al. (2013)

Test your knowledge



Test your knowledge



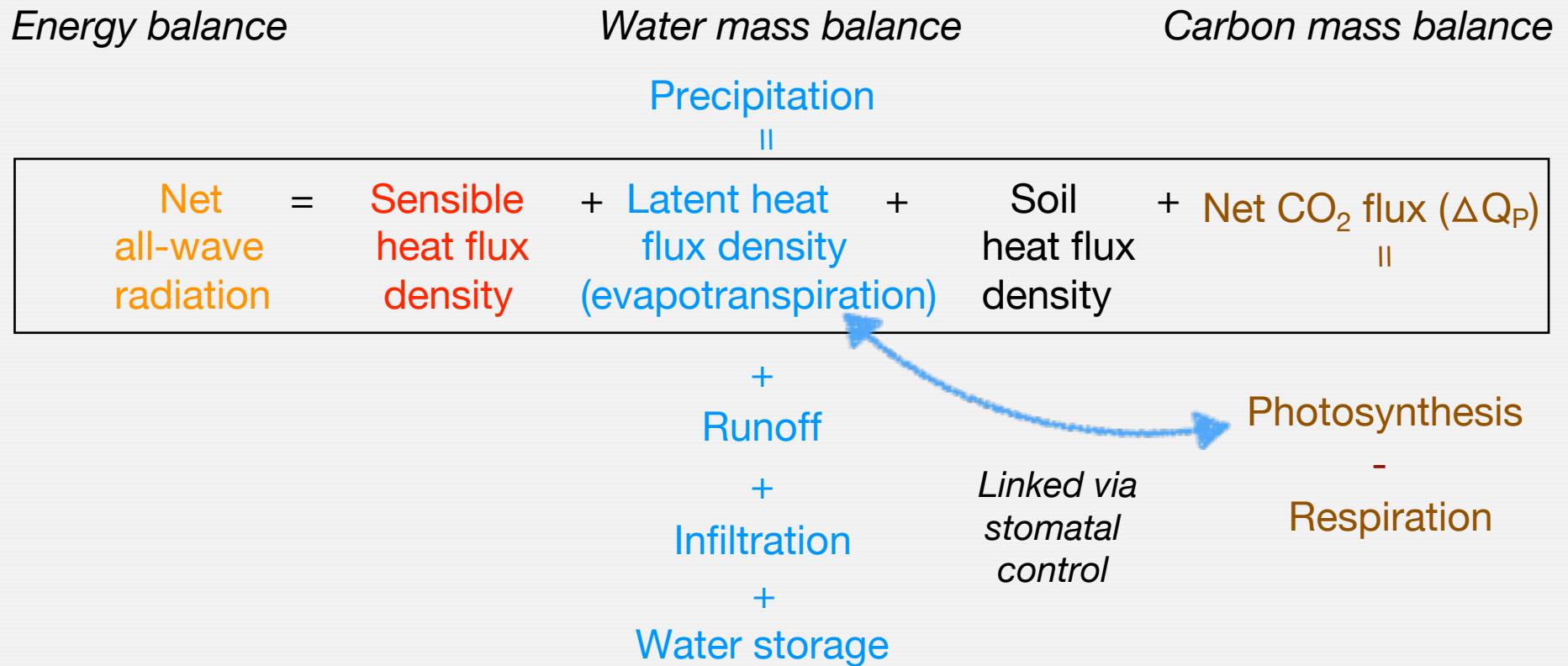
Energy associated with NEP

Energy absorbed in photosynthesis or heat released by respiration can be expressed as a storage energy flux density (in W m^{-2}):

$$\Delta Q_P = \phi \text{NEP}$$

where ϕ is the **heat of assimilation of carbon** ($1.07 \times 10^7 \text{ J kg}^{-1}$ or 469 kJ mol^{-1}) which corresponds to 3 W m^{-2} per $\text{g(CO}_2\text{)} \text{ m}^{-2} \text{ h}^{-1}$.

ΔQ_P is so small that it is often neglected in the energy balance (but NEP is key to the carbon balance!)



Much more relevant in the **surface energy balance** of a land-atmosphere interface is the stomatal control of **transpiration**.

Exchange of water through plants

If stomata are open - they expose their moist interior. Then plants can take up carbon dioxide but are simultaneously losing water vapour. This is known as **transpiration**. Transpiration is a physiologically controlled process.



▲ Electron microscope image of a stoma

Evaporation vs. transpiration



Evaporation - the process by which liquid water is transformed into water vapour from open water, wet soils, surface wetness (without physiological control).



Transpiration - the process by which liquid water is transformed into water vapour within and on plant tissues which is physiologically controlled.

The sum of both together is called **evapotranspiration E** (in mm per time)

Photos: A. Christen

Conversion efficiency of sunlight to chemical energy



Photo: A. Christen

PAR (0.4 to 0.7 μm) covers only about 50% of the short-wave radiation (0.15 to 3 μm). If the efficiency of absorbed PAR flux densities is about 20% (this occurs only at low PAR flux densities), the overall efficiency to convert sunlight to chemical energy is not more than 10%.

This is called the **potential photosynthesis** - the rate of photosynthesis if the plant is well watered, suffers no other stress.

This is an upper limit. Data indicate that in real environments ordinary crops/forests convert less than 1% of the energy of the incident short-wave radiation over the growing season.



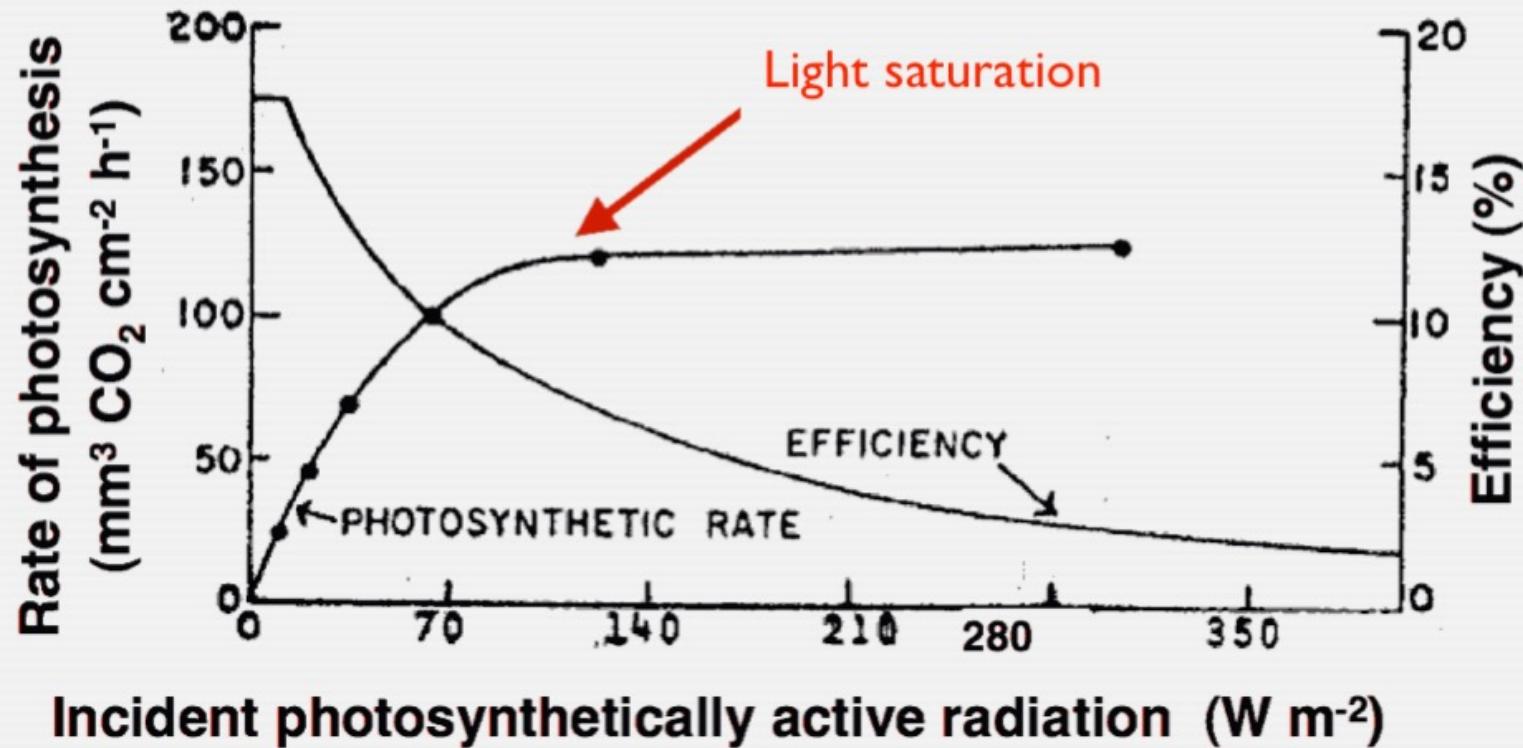
Leaf Cuvette

to CO₂ Analyzer

PAR sensor



Light response curve & light saturation



In this example (sugar beet leaf) the maximum conversion efficiency of incident PAR is about 17% and this occurs at low PAR flux densities. Photosynthesis initially increases linearly with increasing PAR flux density. Then the process becomes virtually light saturated.

Photosynthesis – biochemistry rules efficiency

C₃ is the most common case of photosynthesis (found in most plants in mid-latitudes). C₄ and CAM are biochemical strategies to reduce the water loss during uptake of CO₂ but are introducing other disadvantages.

	C ₃	C ₄	CAM
Water loss through transpiration in g H ₂ O per g C assimilated	450 – 950	250 – 350	18 – 100 ^a
Potential photosynthesis (high PAR) in mg CO ₂ m ⁻² (leaf area) s ⁻¹	0.4 – 1.1	1.1 – 2.2	0.03 – 0.36
Maximum growth rate in g dry mass m ⁻² (leaf area) d ⁻¹	50 – 200	400 – 500 ↑ needs high PAR, high temperatures	1.5 – 1.8 ↑ poor efficiency slow growth

^a for nocturnal situation

U. Lüttge et al. (1994)

CAM = Crassulacean acid metabolism

Temperature response of photosynthesis

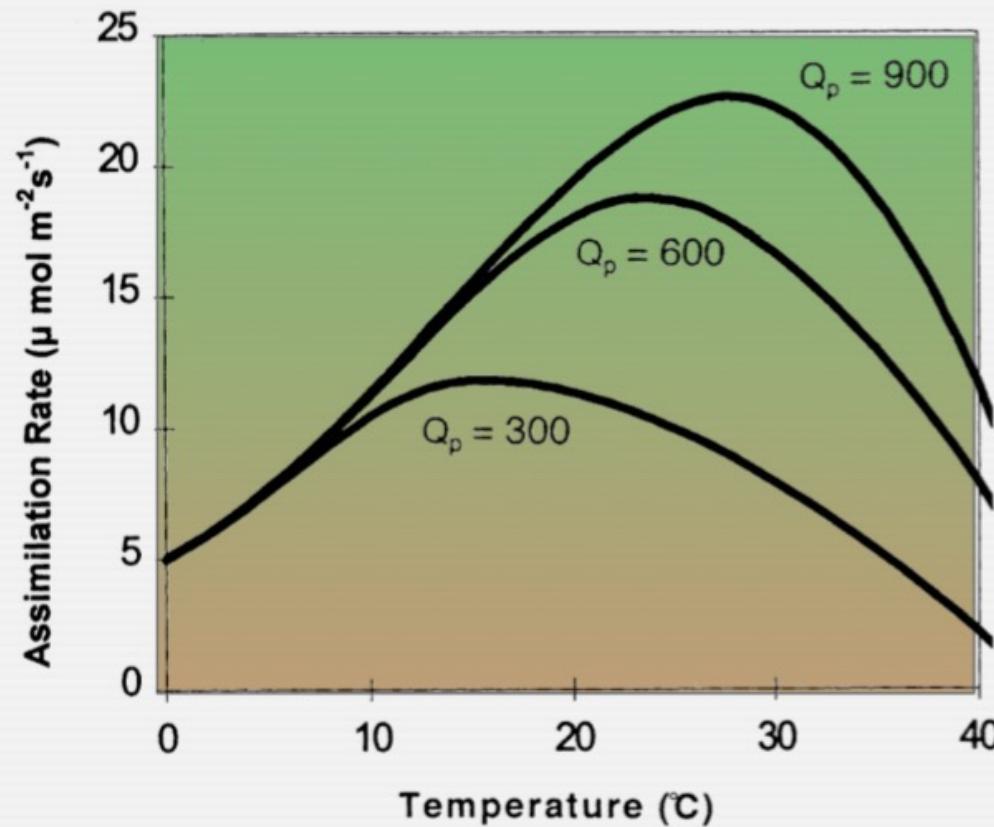
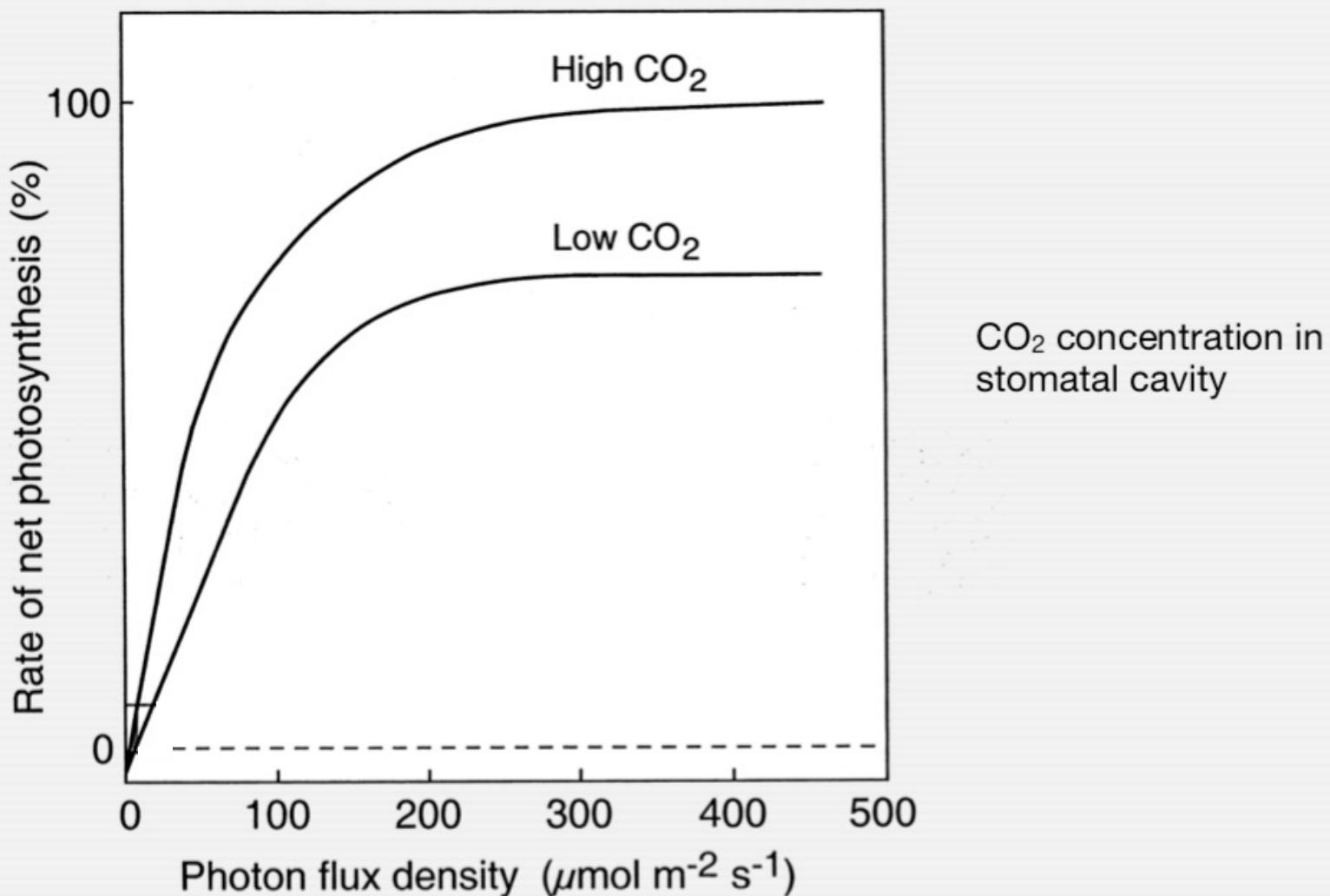


FIGURE 14.5. Temperature response of photosynthesis at three PAR levels for C_{ci} of $240 \mu\text{mol mol}^{-1}$.

G.S. Campbell and J. M. Norman (1998): 'Environmental Biophysics' 2nd Edition.

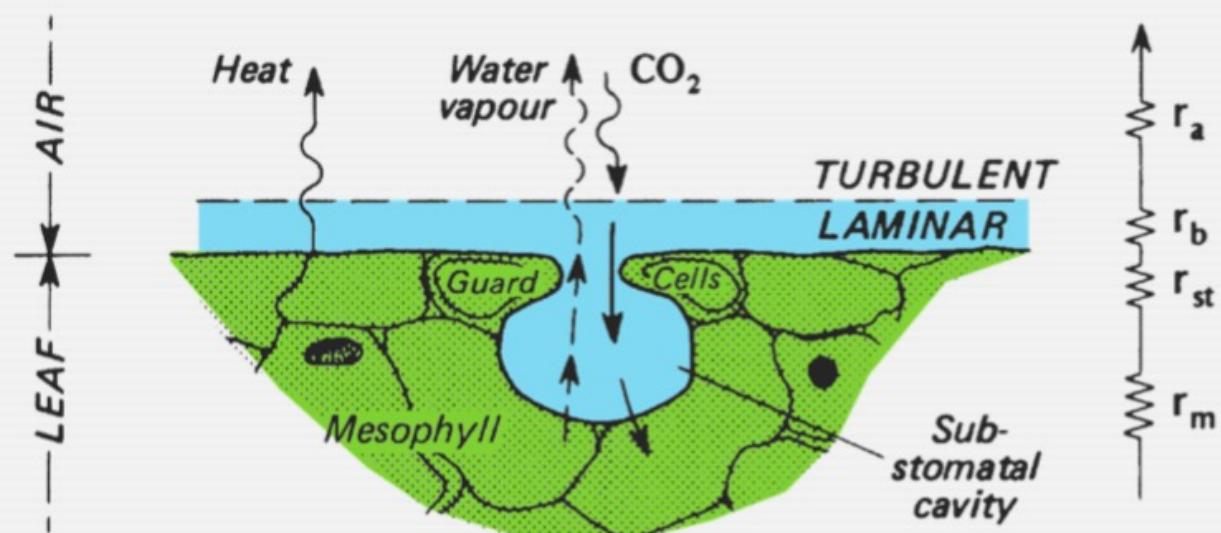
CO_2 response of photosynthesis



Resistance approach

The exchange of CO_2 (and H_2O) between atmosphere and plant interior can be viewed as a resistance network in series:

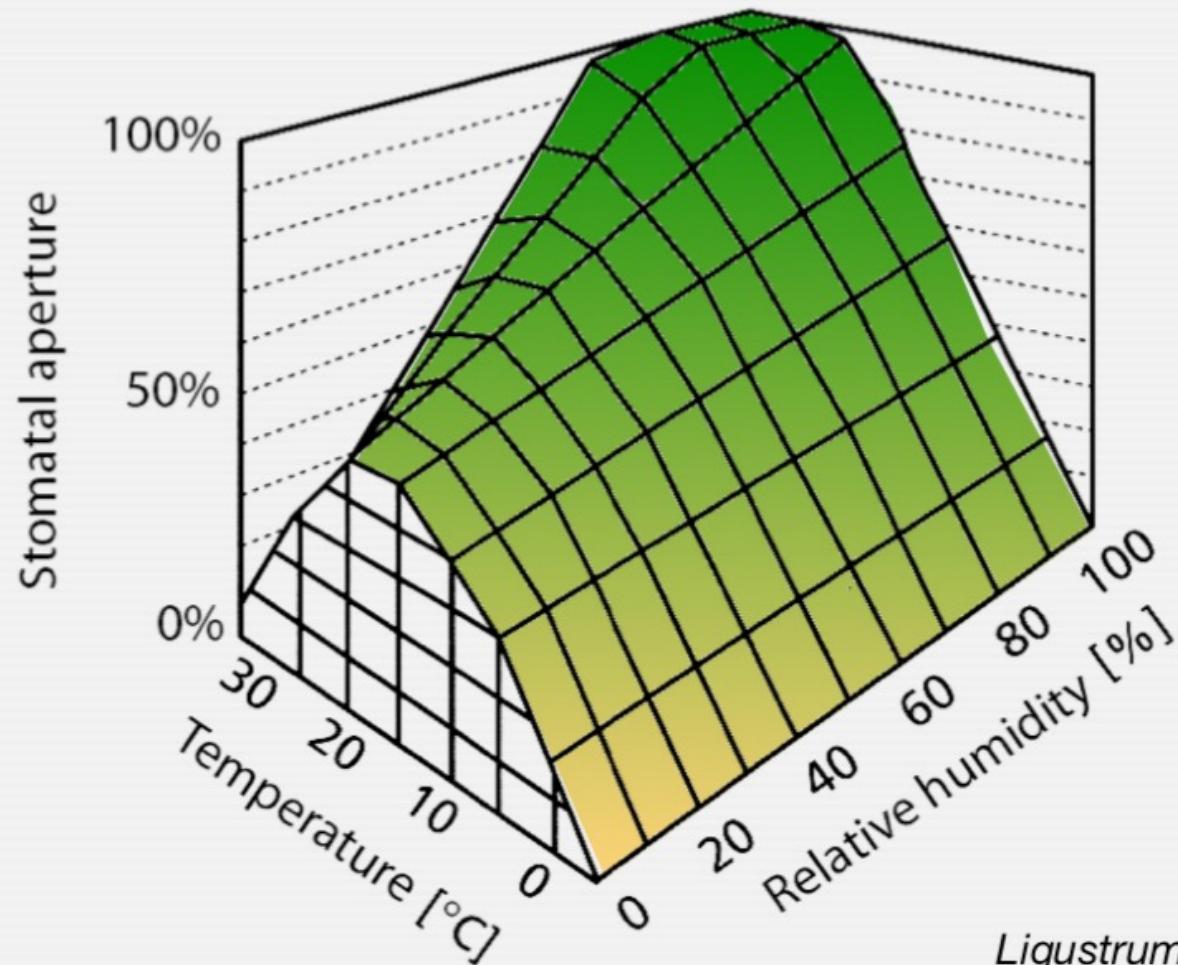
- r_a aerodynamic resistance
- r_b LBL resistance
- r_{st} stomatal resistance
- r_m mesophyll resistance



(b) Schematic cross-section through a portion of a leaf illustrating the exchanges of water vapour and CO_2 through a stomate, and of heat from the leaf exterior.

T.R. Oke (1987): 'Boundary Layer Climates' 2nd Edition.

Stomatal response to humidity and temperature



Larcher W. (2001) 6th Ed.

Ligustrum japonicum (Laboratory)

Stomatal resistance – response to environmental variables

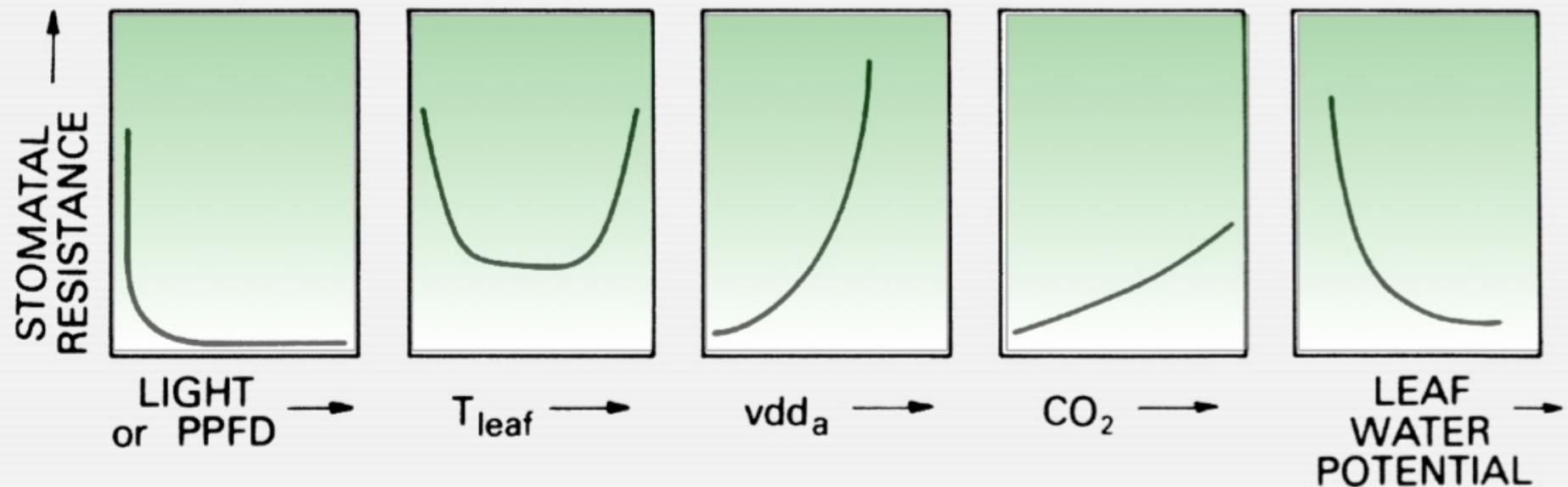
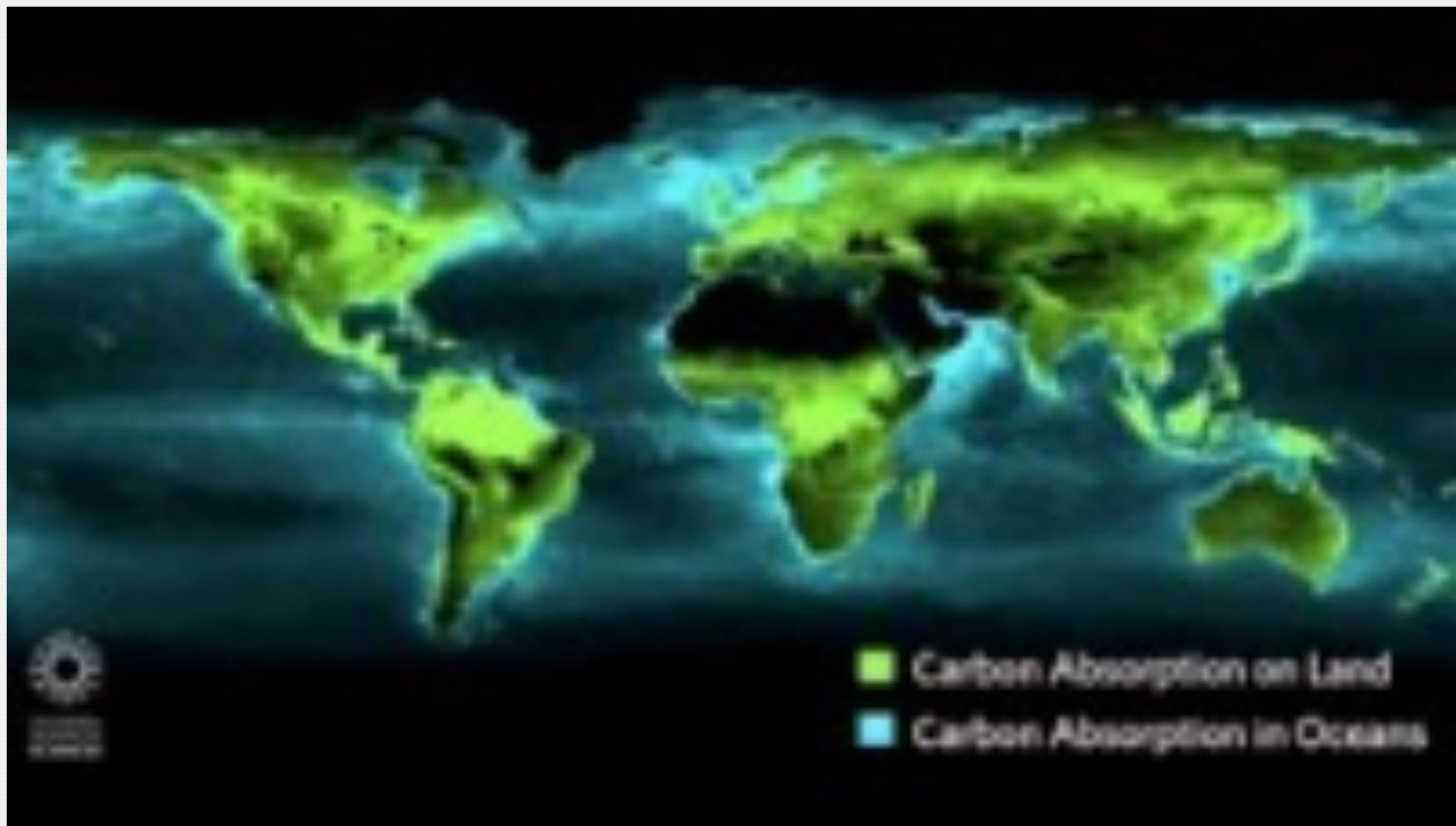


Figure 4.7 Typical response of stomatal resistance (r_{st}) to five variables

To open stomata **all** conditions must be simultaneously fulfilled: (1) PAR and (2) temperature within range and (3) no water stress (vdd_a = vapour density deficit) and (4) low CO_2 concentration in stomatal cavity and (5) enough leaf water potential.

Timelapse: photosynthesis from space



Take home points

- Ecosystems by the process of **photosynthesis** take up carbon-dioxide, and release it by **respiration**.
- The **energy** used for photosynthesis and released by respiration is **minor**, and not more than ~3% of Q^* .
- However the plant physiological responses (stomatal resistance) is very important for the climate as it controls **transpiration** and hence energy partitioning into **Q_E** and **Q_H** .
- A proper description / modelling of the physiological controls on **stomatal resistance** (function of PAR, water stress, temperature, vdd , and carbon-dioxide) is essential in weather or climate models.