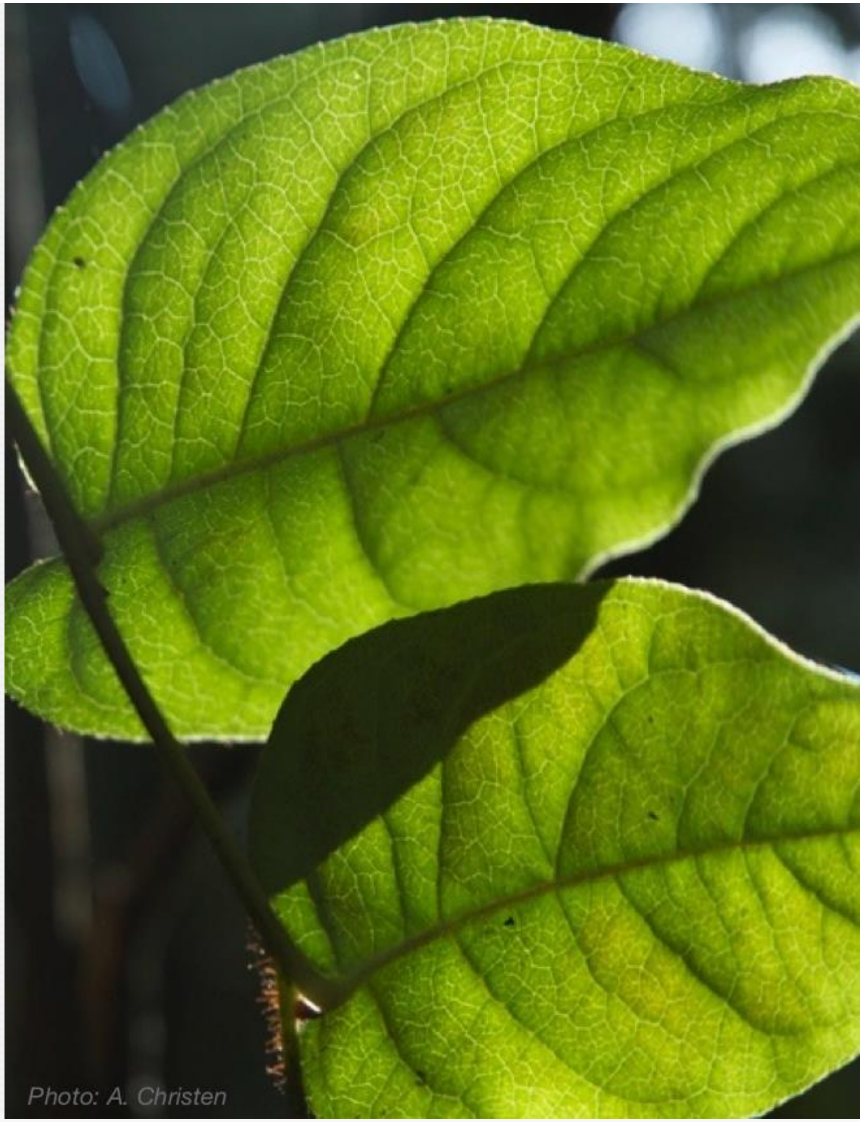
Photo: J. Verfaillie

30 Plant-atmosphere interactions

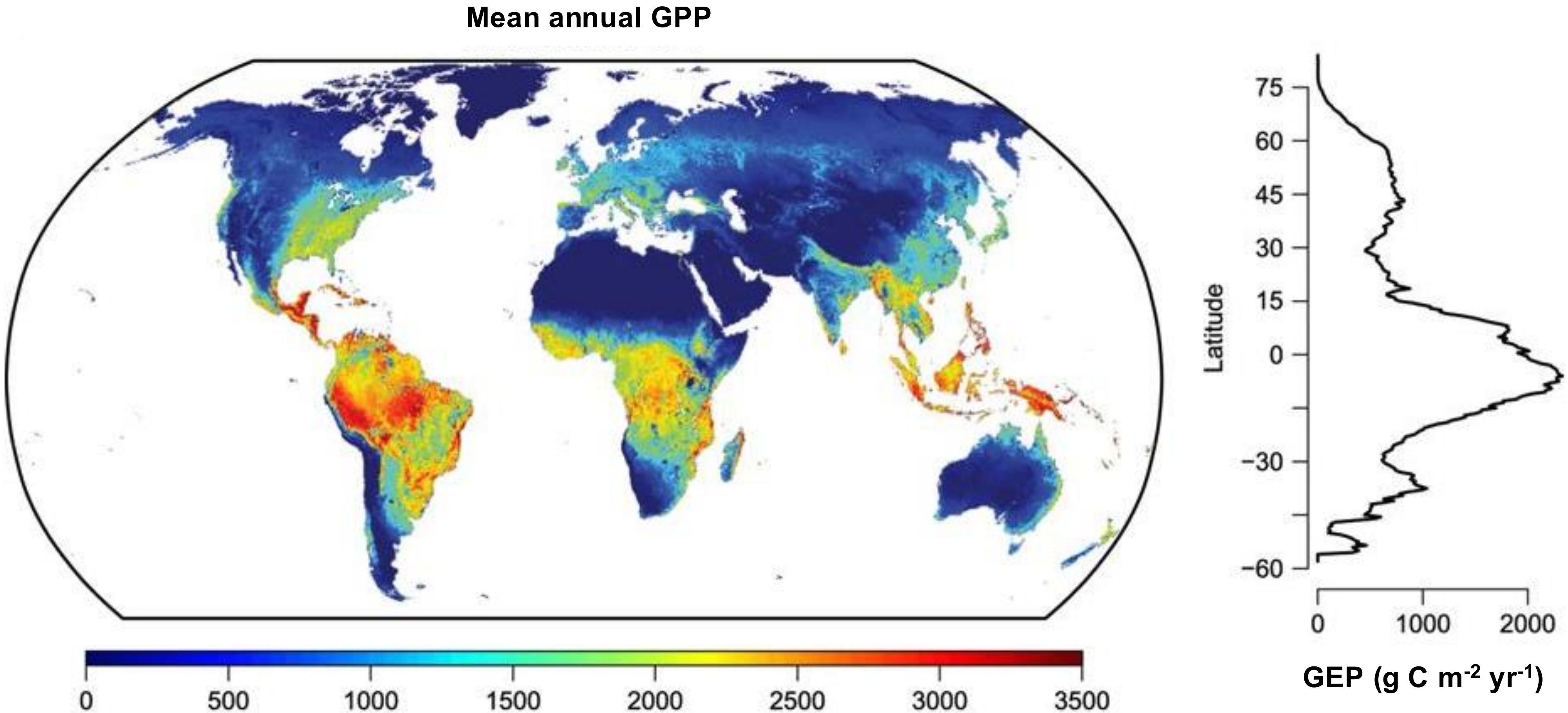
Learning objectives

- 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.

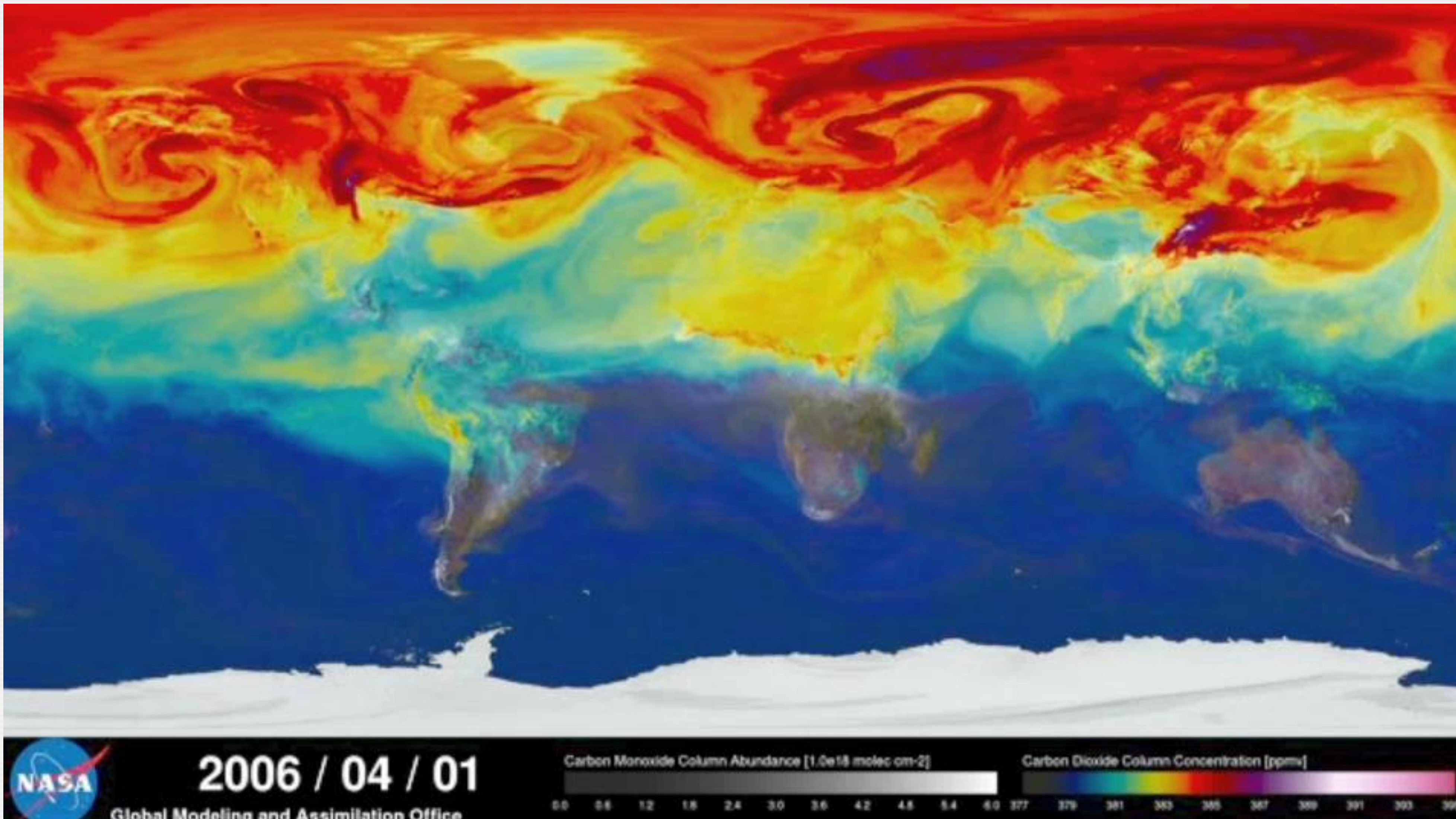


In the beginning there was cyanobacteria

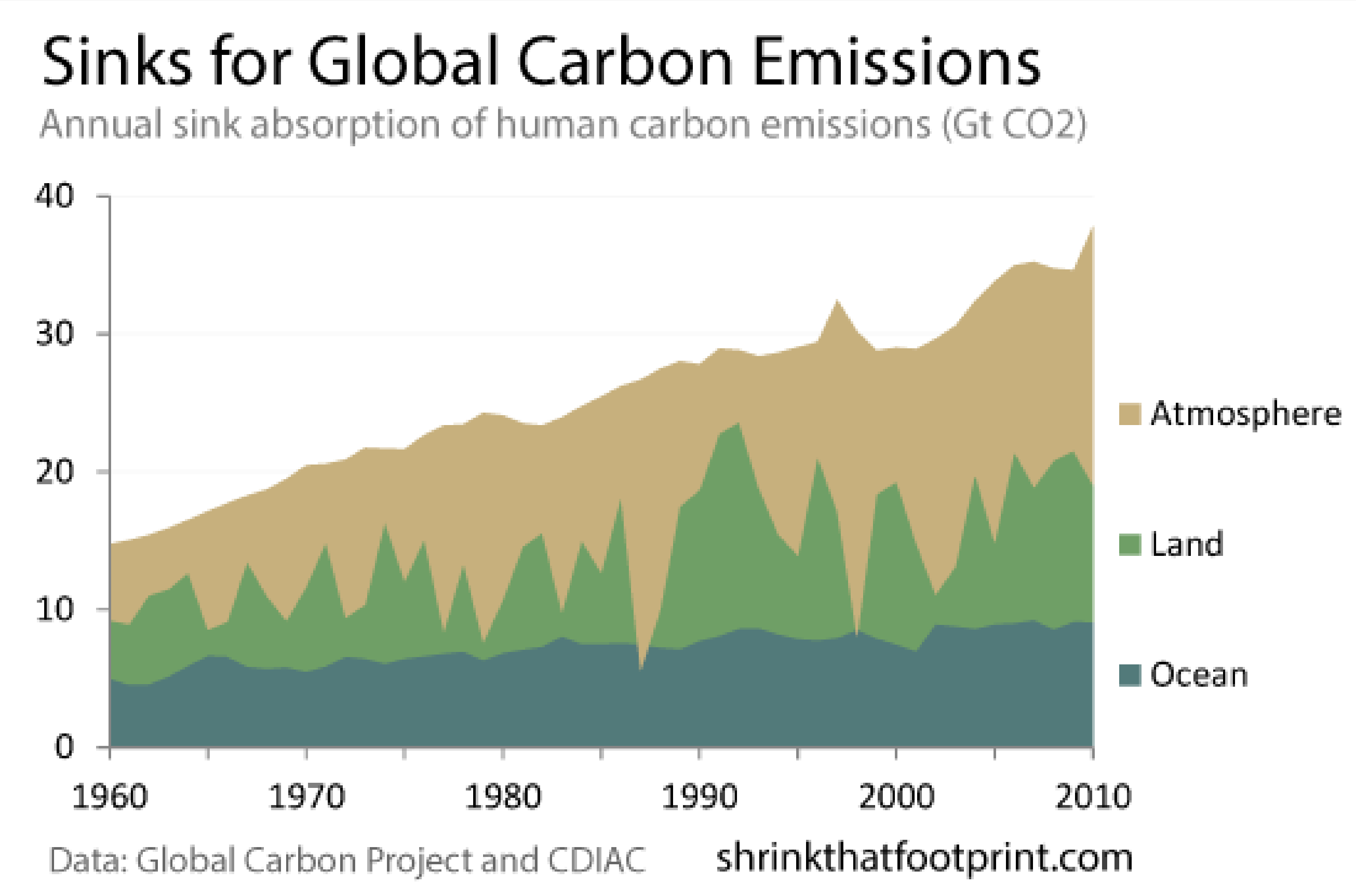
Photosynthesis across the globe

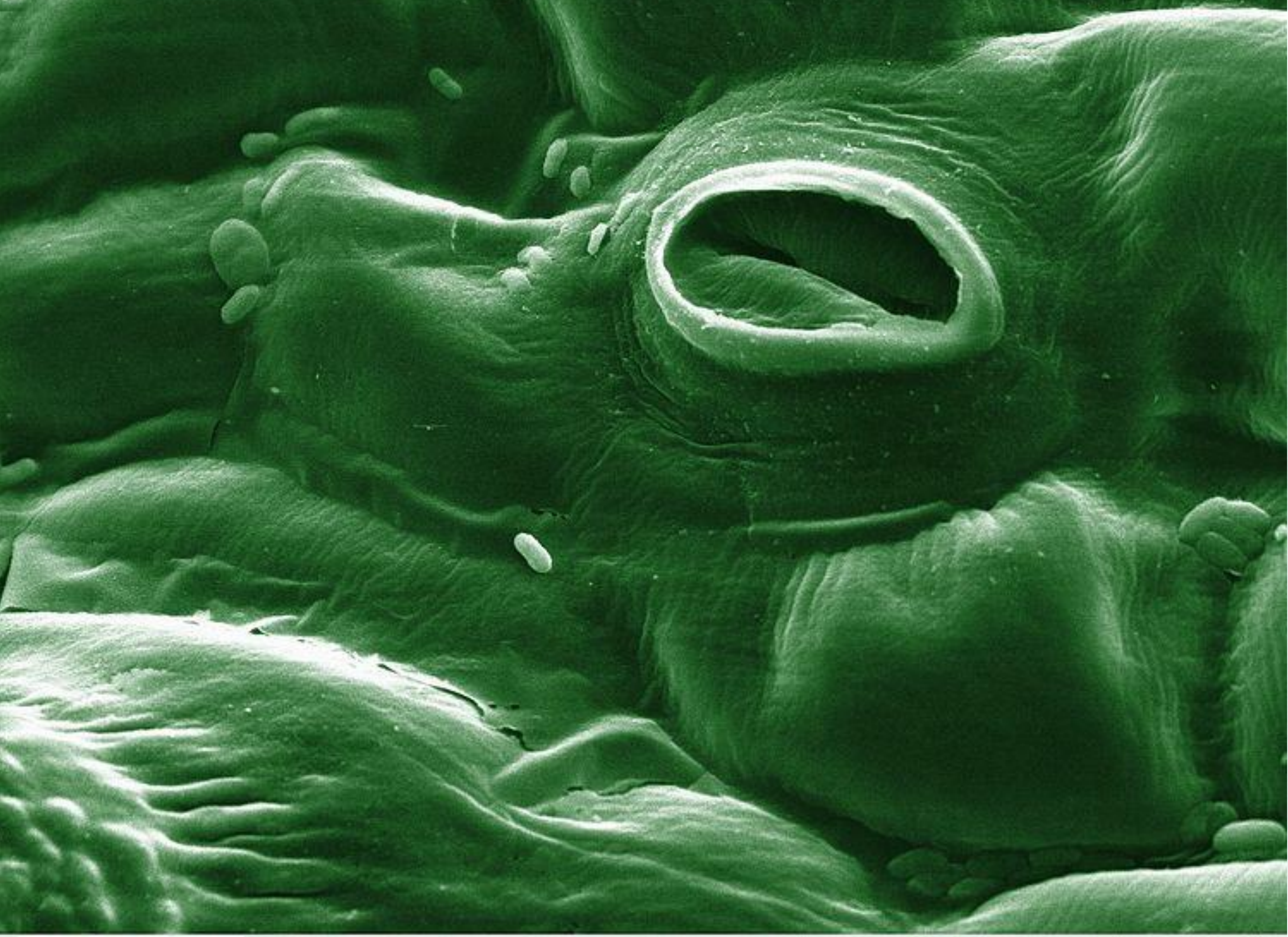


The ‘breathing’ of the biosphere

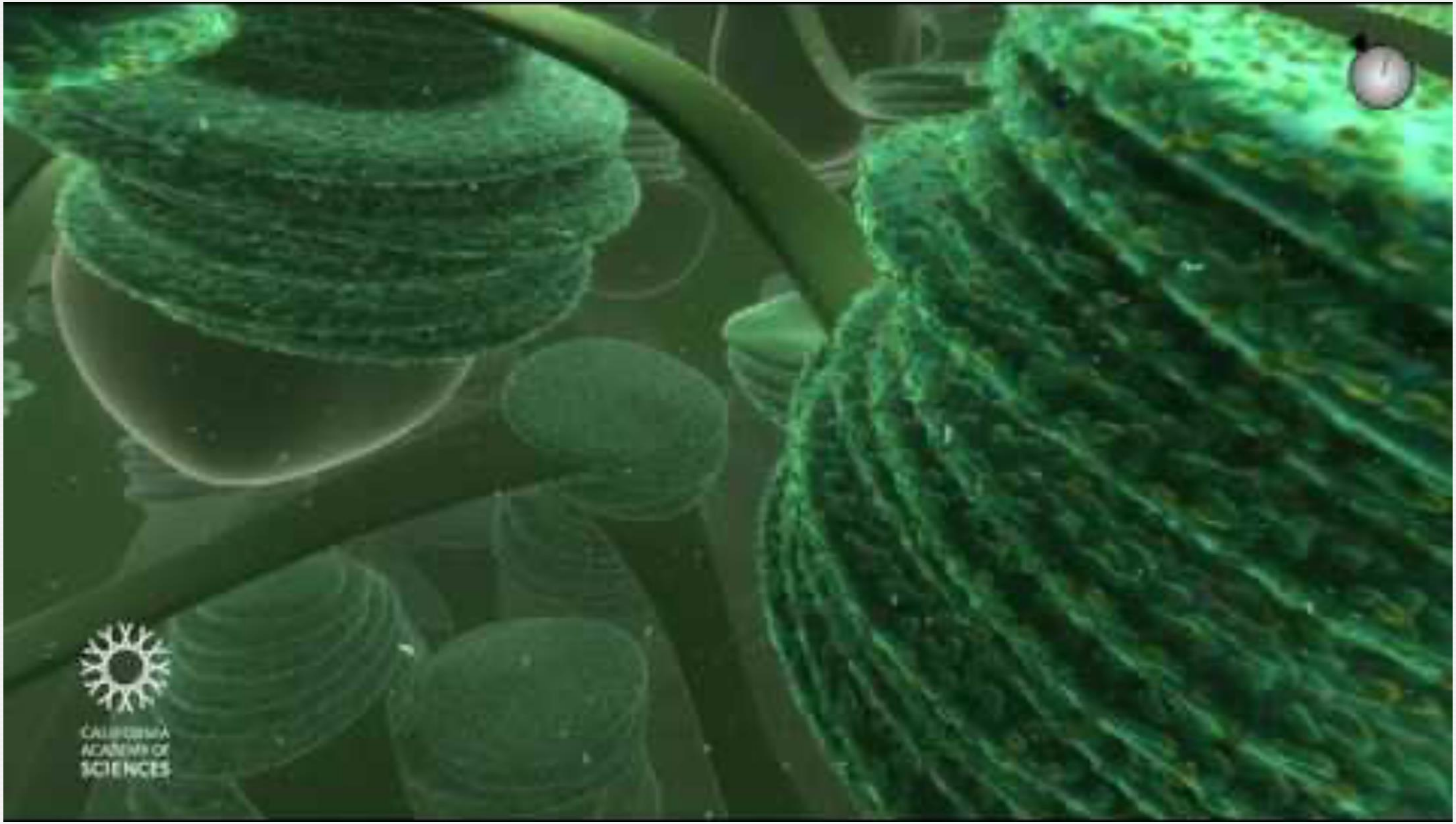


The land sink for CO_2




10 µm

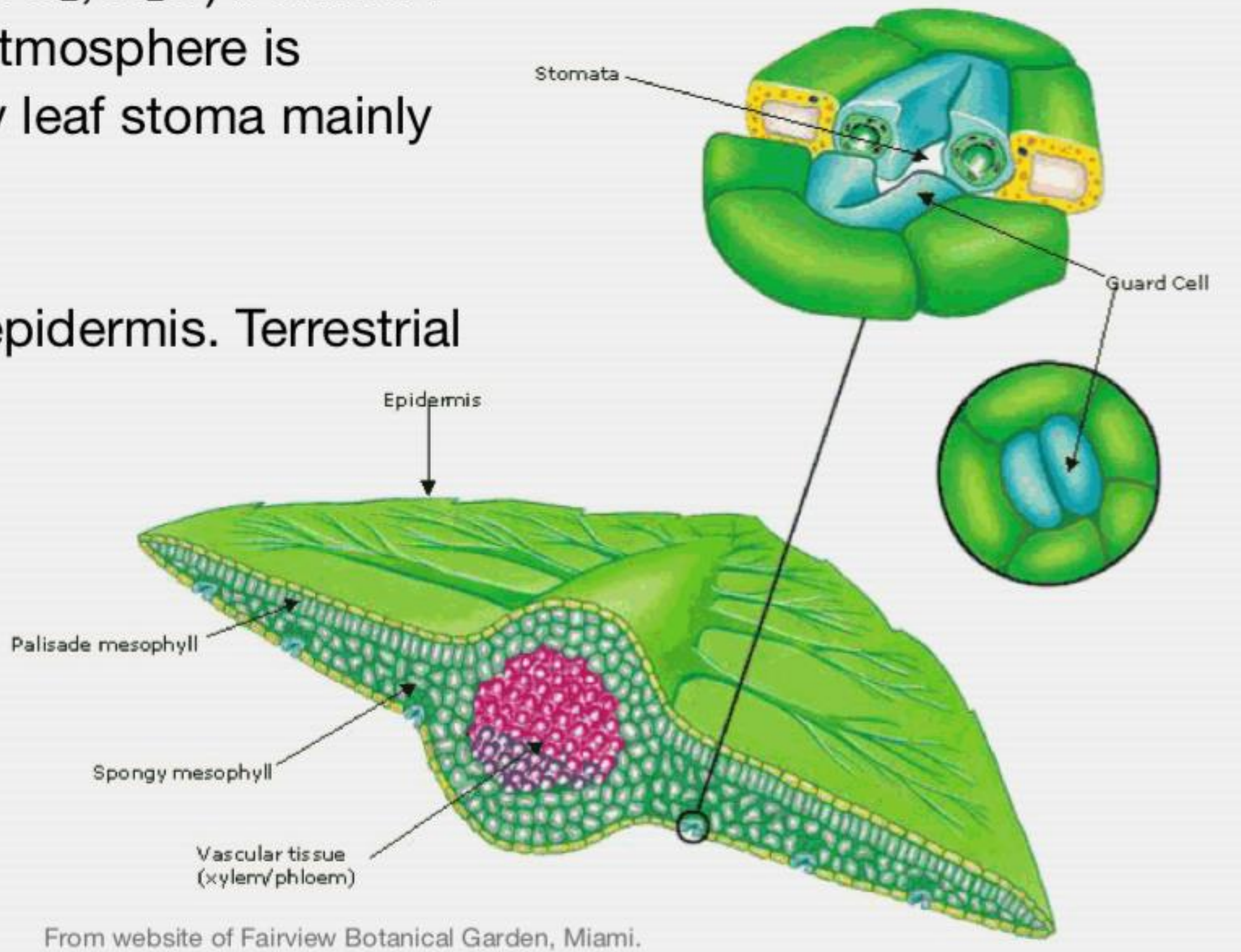
Inside a leaf



Exchange between plants and the atmosphere

The exchange of air (including CO_2, H_2O) 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 CO_2 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:

$$CO_2 + H_2O + h\nu \rightarrow (CH_2O) + O_2$$

PAR Carbohydrates

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:

$$(CH_2O) + O_2 \rightarrow CO_2 + H_2O + \text{Energy}$$

Carbohydrates

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 mol m^{-2} s^{-1} or g m^{-2} s^{-1}):

$$NEP = GPP - ER$$

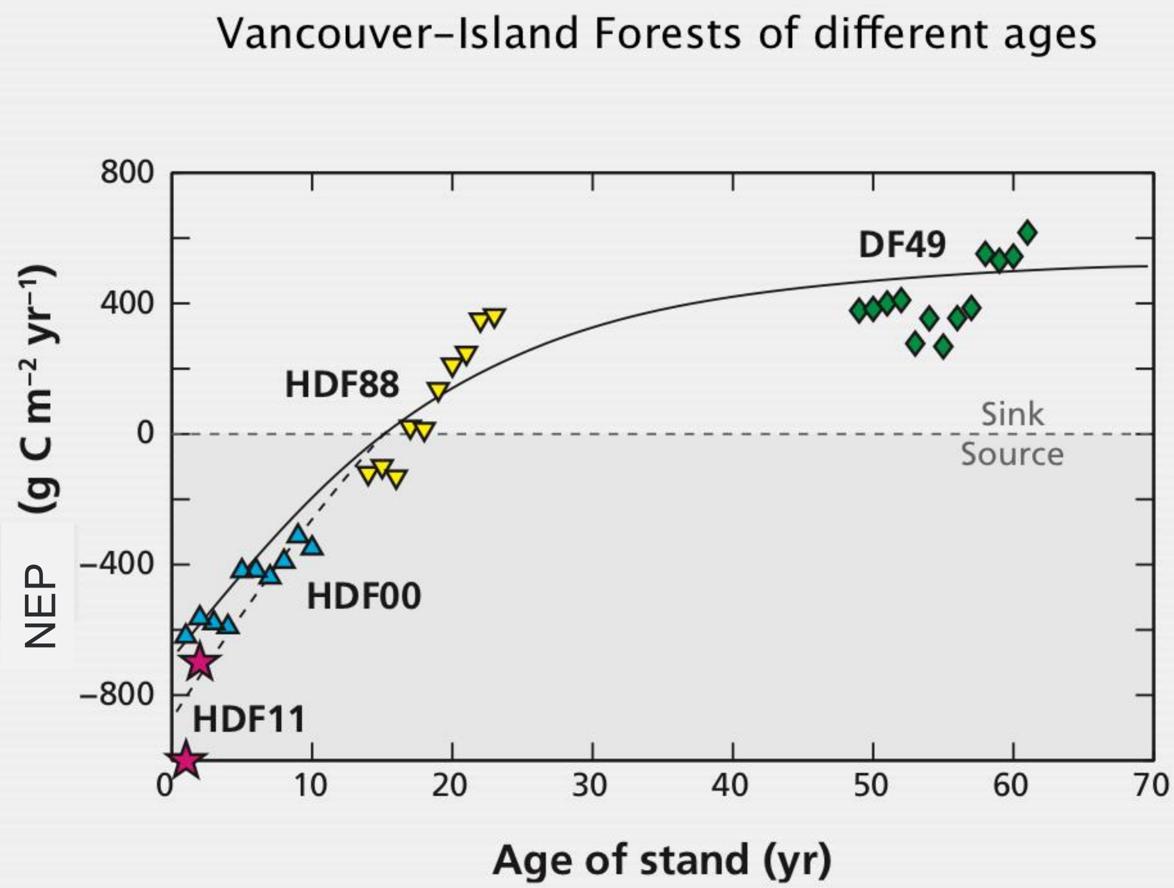
Ecosystem respiration (**ER**) is the total aerobic respiration of CO_2 by an ecosystem:

$$ER = AR + HR$$

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

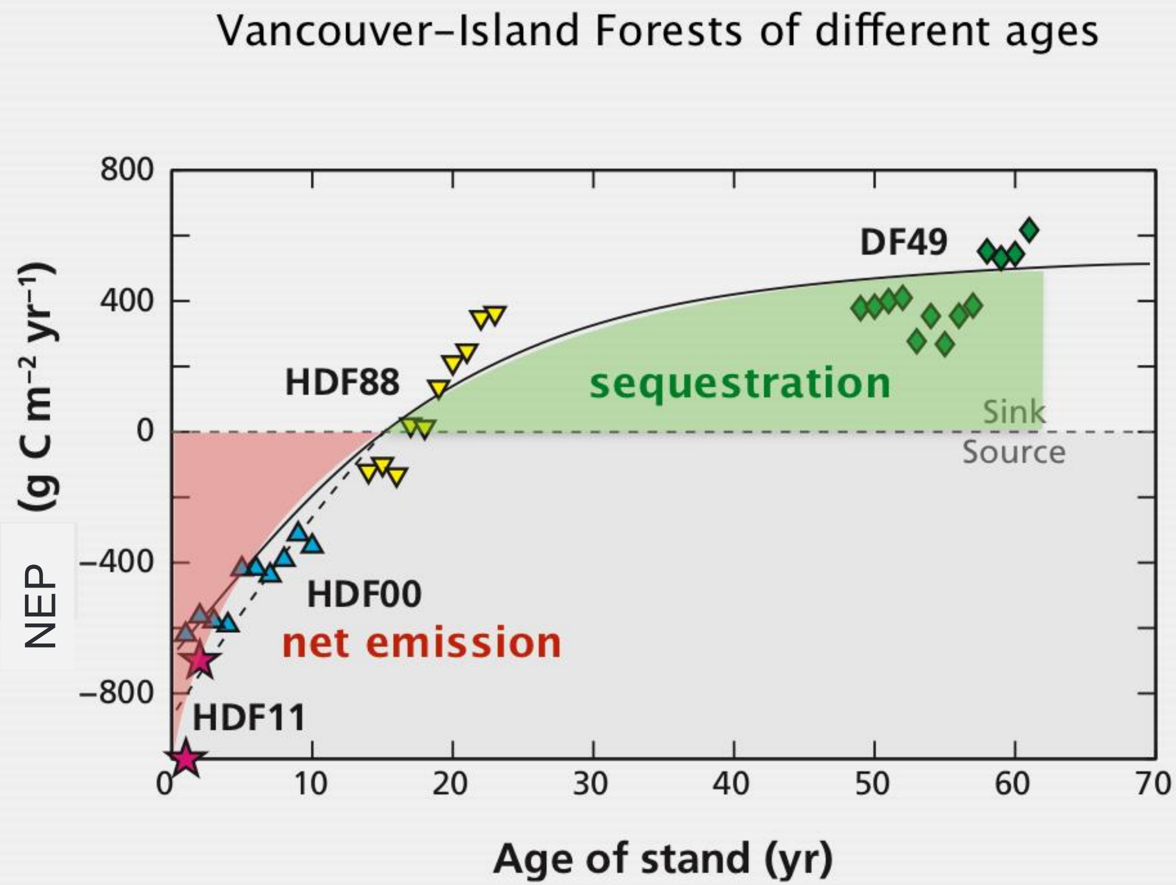
Heterotrophic respiration (**HR**) is CO_2 respired by all other living organisms (i.e., bacteria, animals, fungi). This CO_2 is also derived from GPP, but in a more roundabout way.

Carbon uptake or release from ecosystems?



Paul-Limoges, et al. (2013)

Carbon uptake or release from ecosystems?



Paul-Limoges, et al. (2013)

Join at:
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ID:
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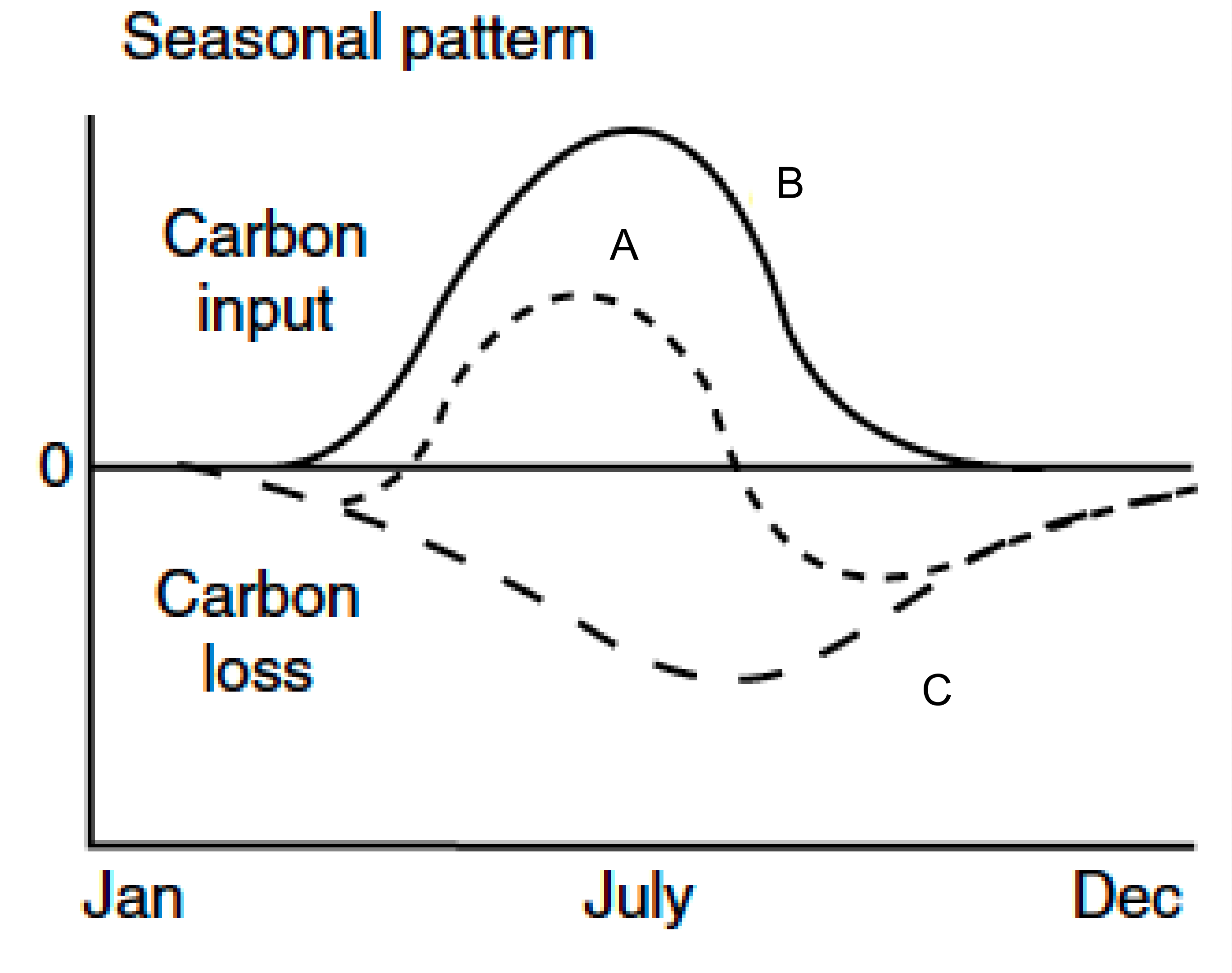
Test your knowledge



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}):

$$\Delta Q_P = \phi NEP$$

where ϕ is the **heat of assimilation of carbon** (1.07 x 10^7 J kg^{-1} or 469 kJ mol^{-1} which corresponds to 3 W m^{-2} per g(CO_2) m^{-2} h^{-1}).

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

Energy balance | *Water mass balance* | *Carbon mass balance*

Precipitation

=

Net all-wave radiation = Sensible heat flux density + Latent heat flux density (evapotranspiration) + Soil heat flux density + Net CO_2 flux (NEP) (ΔQ_P)

+

Runoff

+

Infiltration

+

Water storage

Linked via stomatal control

=

Photosynthesis (GPP)

-

Respiration (ER)

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

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%.

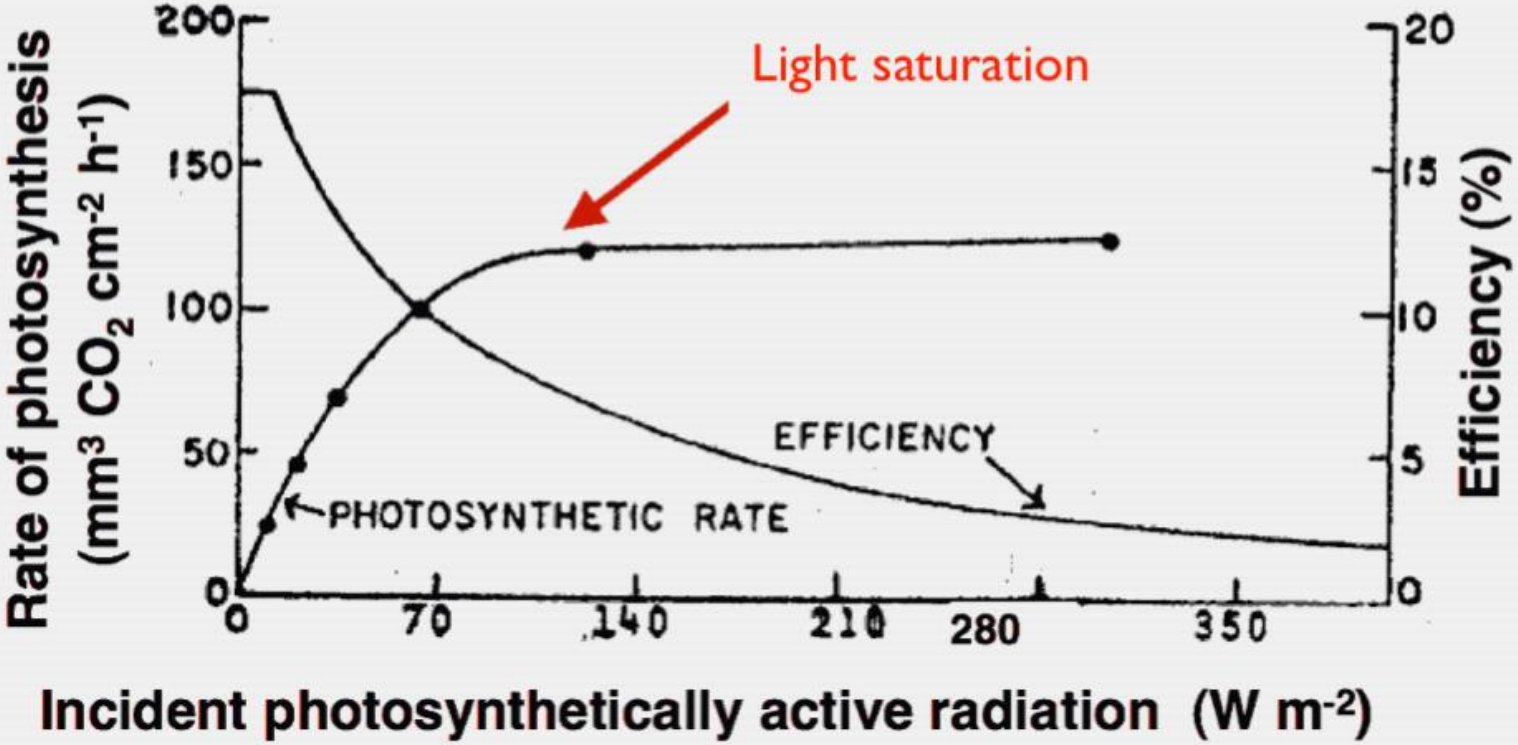
This is called the **potential photosynthesis** - the rate of photosynthesis if the plant is well watered, suffers no other stress.

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
Photo: M. Novak, UBC

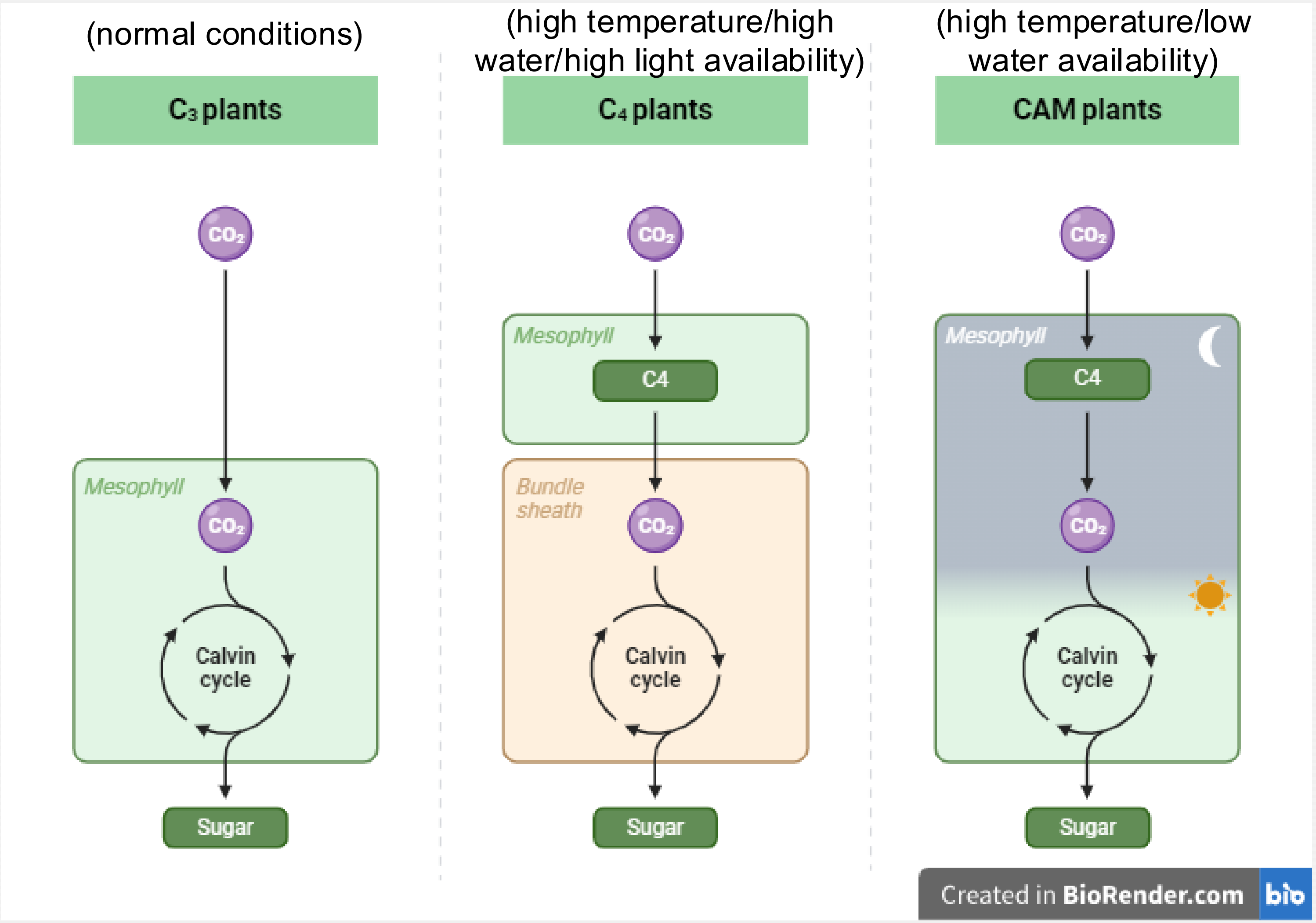
Photo: M. Novak, UBC

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.

Different photosynthetic pathways



Photosynthesis – biochemistry rules efficiency

C_3 is the most common case of photosynthesis (found in of most plants in mid-latitudes). C_4 and CAM are biochemical strategies to reduce the water loss during uptake of CO_2 but are introducing other disadvantages.

	C_3	C_4	CAM
Water loss through transpiration in g H_2O 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	1.5 – 1.8

[a] for nocturnal situation

C_4 (400 – 500): needs high PAR, high temperatures

CAM (1.5 – 1.8): poor efficiency slow growth

U. Lüttge et al. (1994)

CAM = Crassulacean acid metabolism

Temperature response of photosynthesis

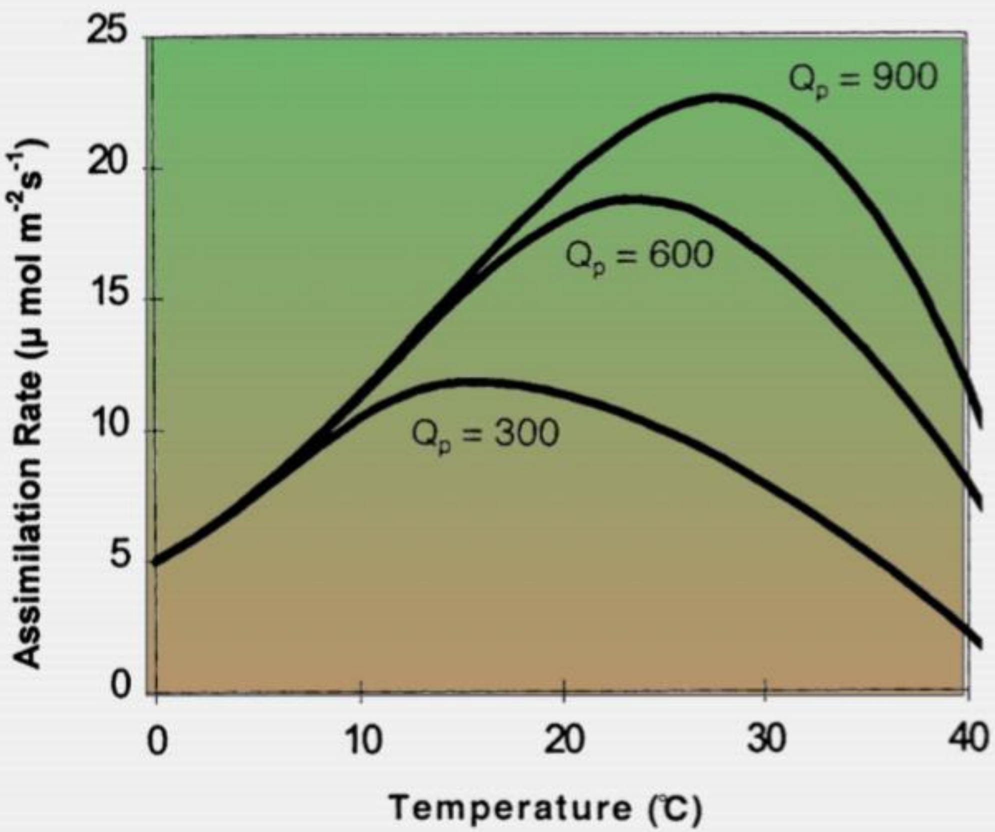
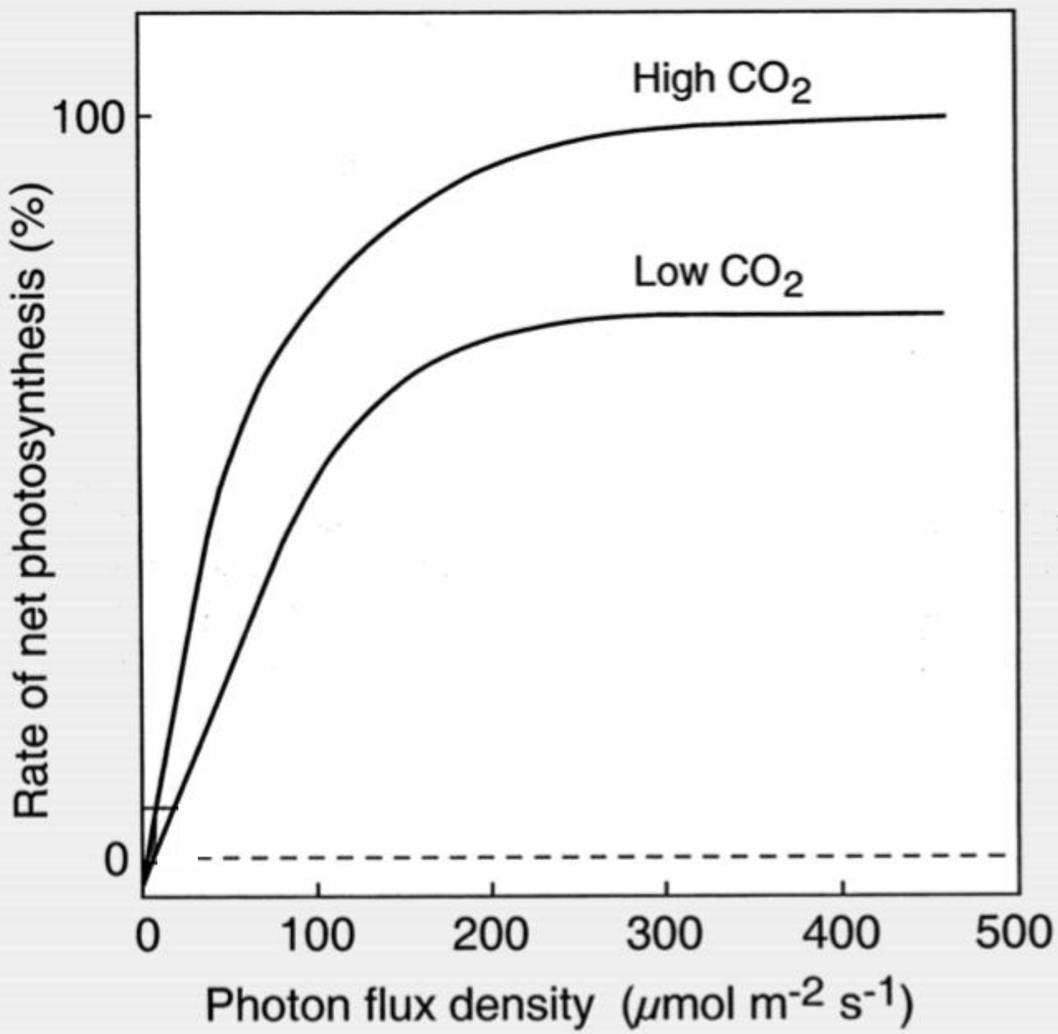


FIGURE 14.5. Temperature response of photosynthesis at three PAR levels for C_{ci} of 240 μmol mol^{-1}.

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

CO_2 response of photosynthesis



CO_2 concentration in stomatal cavity

Resistance approach

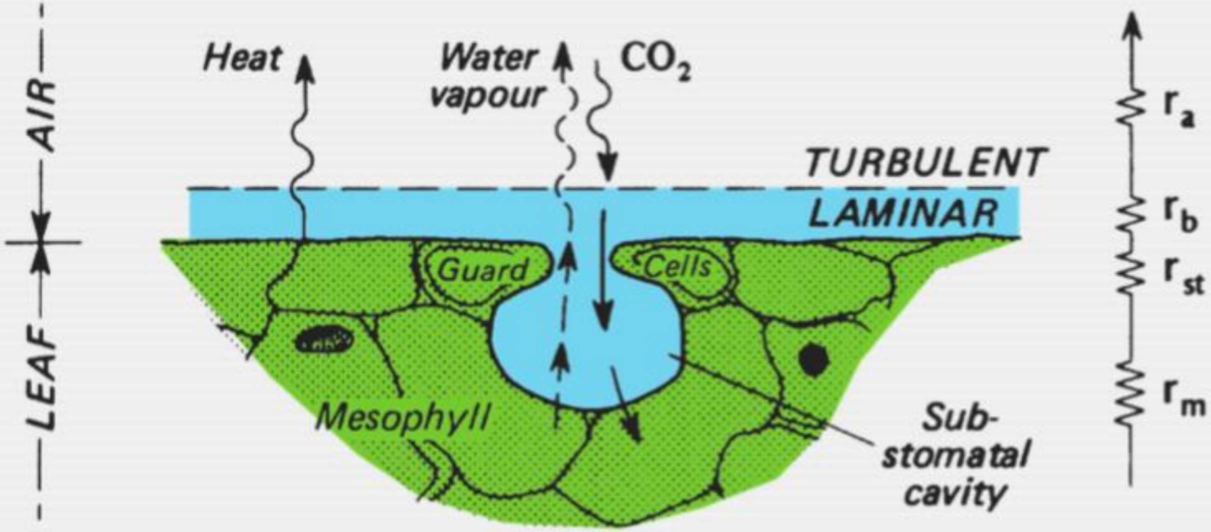
The exchange of CO_2 (and H_2O) between atmosphere and plant interior can be viewed as a resistance network in series:

r_a aerodynamic resistance

r_b LBL resistance

r_{st} stomatal resistance

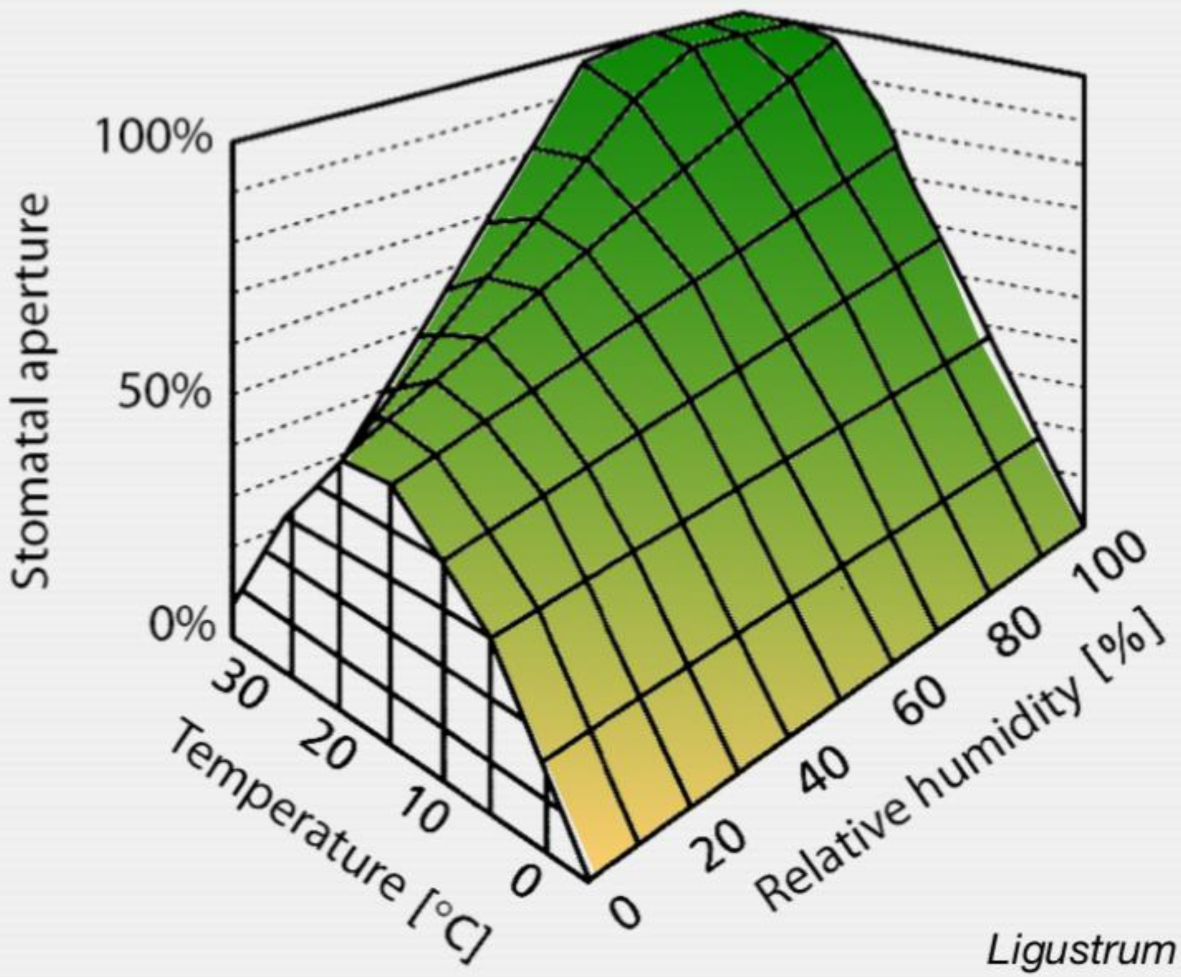
r_m mesophyll resistance



(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

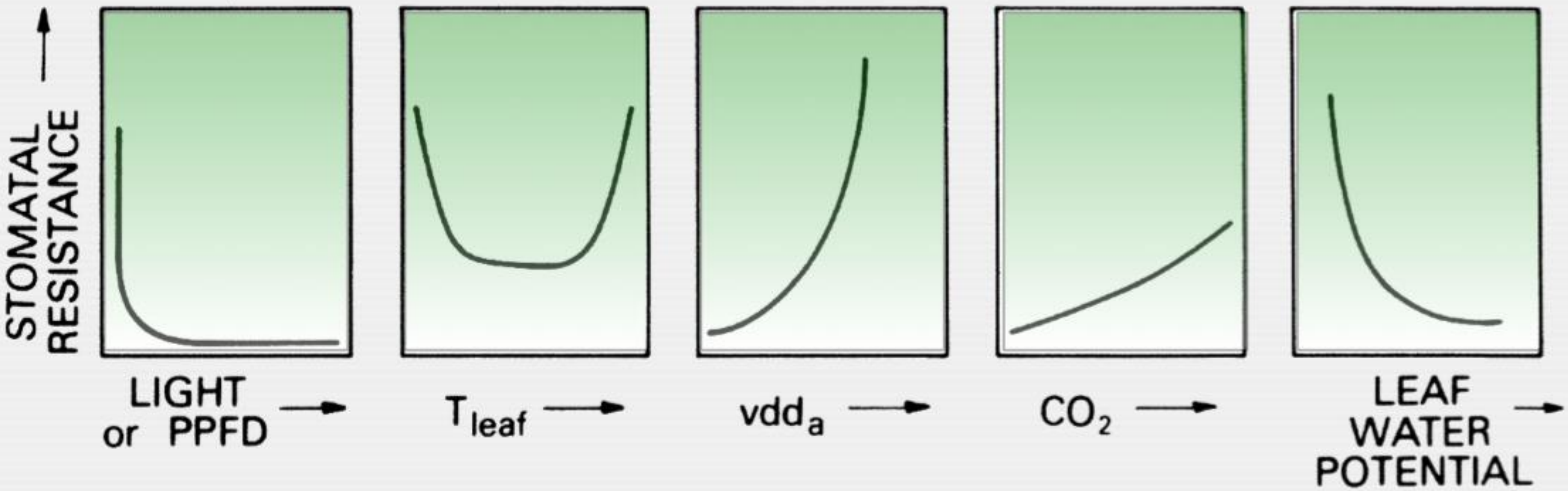
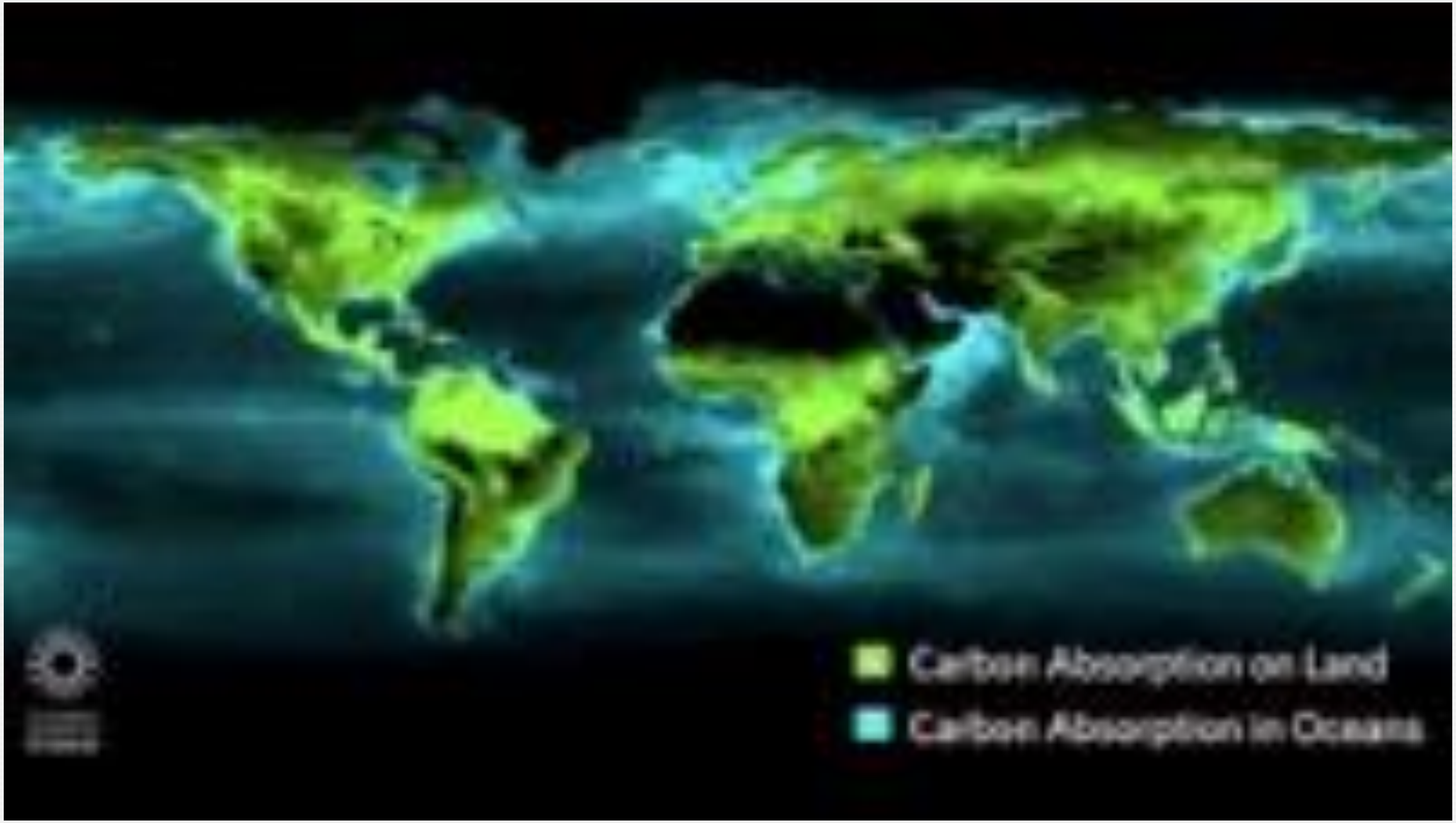


Figure 4.7 Typical response of stomatal resistance (r_{st}) to five variables

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 $\mathbf{Q_E}$ 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.