Photosynthesis
9/11/2003, 9/16/2003

Objectives:
- Review the 3 components of photosynthesis.
- Understand the ecophysiological implications and limitations on each component.
- Understand the Farquahar model, so you can follow the literature.

Readings

1) Jones, Chapter 7.
2) Bonan, GB. 2002. Ecological Climatology. Cambridge University Press. Chapter 9 (partial).

Photosynthesis

$CO_2 + 2\ H_2O + \text{light energy} \rightarrow CO_2 + 4H^+ + O_2 \rightarrow CH_2O + H_2O + O_2$

What are the 3 components of the photosynthetic process?

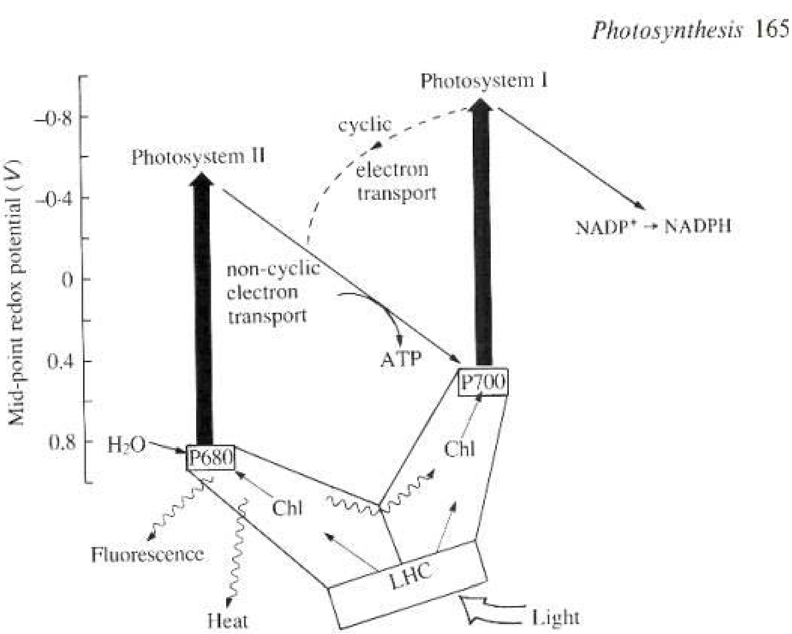


Fig. 7.2. Schematic representation of the photosynthetic electron transport chain showing light trapping by the major chlorophyll-protein antenna complexes and energy transfer to the reaction centres of the two photosystems with fluorescence from PS II, energy transfer to PS I, and dissipation as heat competing with photochemistry at PS II. (LHC = light harvesting complex, Chl = chlorophyll.)

Light Reactions - pigments absorb light energy, water is oxidized, NADPH and ATP are formed

Jones, p 165.

Dark Reactions- enzymes reduce CO_2 using energy in NADPH and ATP Bonan 298

298 Leaves and plants

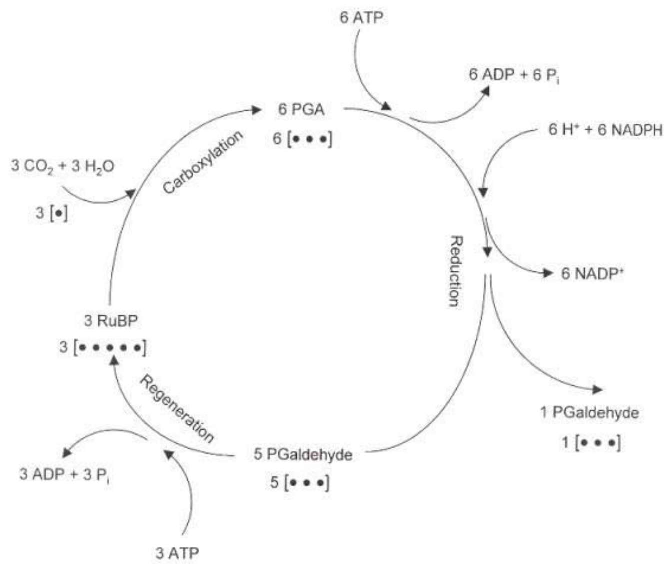


Figure 9.2. Dark reactions of the C_3 photosynthetic pathway. Three turns of the Calvin cycle are depicted. The symbol [•] indicates the number of carbon atoms contained in the compound.

Substrate availability (CO_2), enzyme and pigment amounts, response of photosynthesis to environment.

Light - Limitations: Pigment concentrations, irradiance, temperature.
Efficiency of light reaction is about 27%, quite good, actually
Carotinoids protect from photooxidation.

Dark - very different C_3, C_4, and CAM reactions, but all end up using the C_3 Calvin cycle to reduce CO_2 to sugar. C4 and CAM have reactions up from to fix CO_2 and deliver it to the C3 portion.

Different Dark reaction pathways have very different environmental reactions
Table - sensitivity to CO_2, O_2, temperature. (Jones)
Photorespiration is important in C_3, not C_4

Table 7.1. *Characteristics of the main photosynthetic pathways*
Data collated from a number of sources.

	C_3	C_4	CAM Day	CAM Night
Anatomy				
'Kranz' anatomy (distinct bundle sheath	No	Yes	Succulent	
Frequency of leaf bundles	Low	High	Low	
Leaf air space volume (%)				
monocots.	10–35 %	< 10 %	Low	
dicots.	20–55 %	< 30 %	Low	
Biochemistry				
Early products of ^{14}C fixation	PGA	C_4 acids	PGA	C_4 acids
Primary carboxylase	RuBP	PEP	RuBP	PEP
Discrimination against ^{13}C ($\delta^{13}C$, ‰)	−22 to −40	−9 to −19	C_3-like	C_4-like
Absolute sodium requirement	No	Yes	Only for night fixation	
Physiology				
CO_2 compensation point (vpm)	30–80	< 10	*c.* 50	< 5
Post illumination burst of CO_2	Yes	Slight	Yes	—
Enhancement of $\mathbf{P}_n$ in low O_2	Yes	No	Yes	No
Quantum requirement	15–22	19	—	—
Mesophyll resistance				
r'_m ($m^2\ s\ mol^{-1}$)	7–15	1.2–5	*c.* 20	?
r'_m ($s\ cm^{-1}$)	3–6	0.5–2.0	*c.* 8	?
Relative stomatal sensitivity to environment	Insensitive	Sensitive	Reversed cycle	
Intercellular space CO_2 partial pressure	$\sim 0.7p'_a$	$\sim 0.4p'_a$	$0.5p'_a$	?
Maximum photosynthetic				
rate ($\mu mol\ m^{-2}\ s^{-1}$)	14–40	18–55	6	8
($mg\ CO_2\ m^{-2}\ s^{-1}$)	0.6–1.7	0.8–2.4	0.25	0.3
Optimum day temp (°C)	*c.* 15–30 (Wide acclimation)	25–40	*c.* 35 (Needs low night temperature)	
Light response saturating well below full sunlight	Usually	Rarely	Usually	—

Table 7.1 (*cont.*)

	C_3	C_4	CAM Day	CAM Night
Ecology				
Regions where commonest	Temperate	Tropical, arid	Arid	
Transpiration ratio	High	Low	Medium	Very low
(g H_2O lost per g CO_2 fixed)	450–950	250–350	50–600	< 50
Max. growth rate (g m^{-2} day^{-1})	34–39	51–54	7	
Average productivity (tonne ha^{-1} yr^{-1})	*c.* 40	60–80	Low	

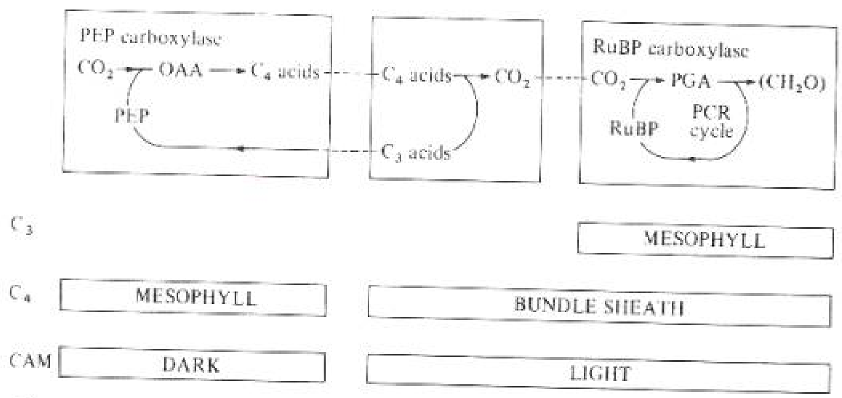


Fig. 7.3. The essential features of C_3, C_4 and CAM photosynthetic pathways, showing the spatial separation of the two carboxylations in C_4 and the temporal separation in CAM.

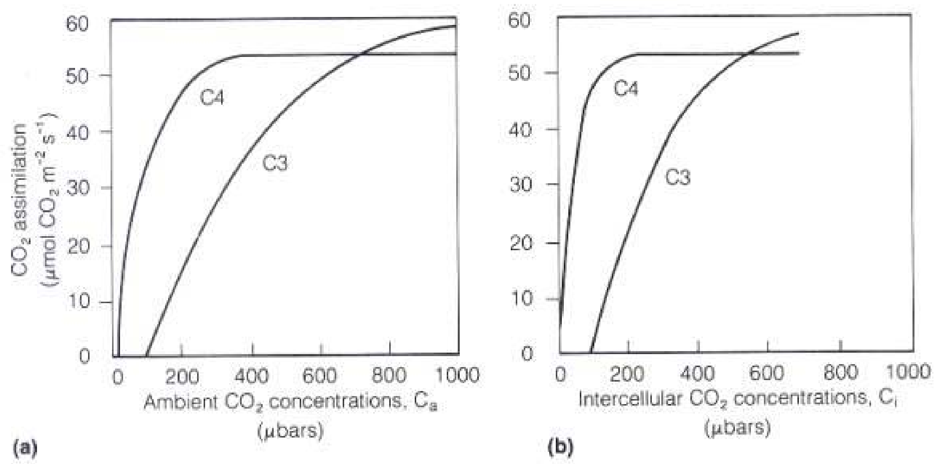


FIGURE 10.10. Changes in photosynthesis as a function of ambient intercellular CO_2 concentrations in *Tidestromia oblongifolia*, a C4 plant, and *Larrea divaricata*, a C3 plant. Photosynthetic rates are plotted against (a) ambient CO_2 concentrations and (b) calculated intercellular CO_2 concentrations inside the leaf (Eq. 10.5). The CO_2 concentration at which CO_2 assimilation is zero defines the CO_2 compensation point. 100 μbar = 1×10^{-5} MPa. (From Berry and Downton, 1982.)

Why aren't all plants C_4?

Interpreting Photosynthetic response curves

A/Ci, A/light

von Caemmerer and Farquahar model of photosynthesis:

3 limitations to photosynthesis (Rubisco amount and activity, rate of electron transport to supply NADPH and ATP to 'regenerate' RuBP, and stomatal conductance):

Overall: $A_n = \min(w_c, w_j, w_p) - R_d$

w_c = Rubisco-limited rate of photosynthesis (related to amount and activity of enzyme)
w_j = light-limited rate of photosynthesis allowed by RuBP regeneration
w_p = limitation by triose phosphate utilization (use of triose phos[-hate for sugar and starch production does not keep pace with production of triose phosphates in the Calvin cycle)—not generally included, but may be important in taller trees where lowe leaf water potential limits sugar export.
R_d = dark respiration in the light.

Rubisco amount and activity:

$$w_c = \frac{V_{max}(c_i - \Gamma^*)}{c_i + K_c(1 + O_i / k_o)}$$

V_{max} = maximum carboxylation rate when enzyme is saturated (μmol CO_2 m^{-2} s^{-1})

c_i = $[CO_2]$ in chloroplast – calculated from $[CO_2]$ outside and stomatal conductance
Γ^* = $[CO_2]$ compensation partial pressure in absence of dark respiration
O_i = ambient partial pressure of O_2
K_c and K_o are Michaelis-Menten coefficients for carboxylation and oxygenation
K_c, K_o, and V_{max} are temperature sensitive.

Electron transport supply NADPH and ATP to 'regenerate' RuBP:

$$w_j = \frac{J(c_i - \Gamma^*)}{4(c_i + 2\Gamma^*)}$$

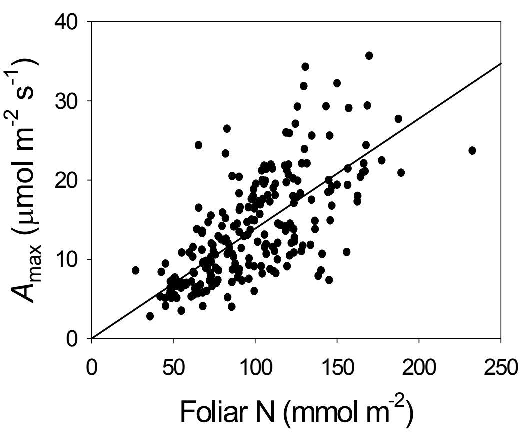
J = potential rate of electron transport (related to irradiance and maximum rate)
J is the smaller of the two roots of the equation:
$0.7J^2 - (J_{max} + 0.385\phi)J + 0.385J_{max} = 0$

J_{max} = maximum potential rate of electron transport (μmol electrons m^{-2} s^{-1})

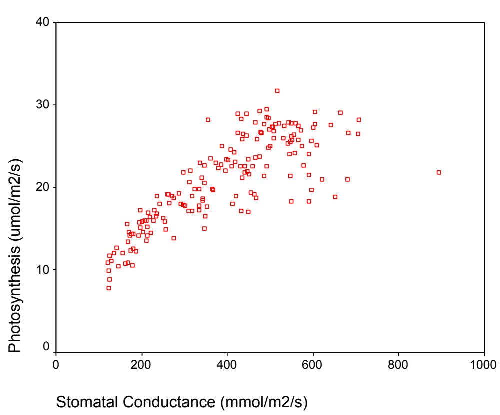
Stomatal conductance

$c_i = (c_a - A)/g_{CO2}$

Ecophysiology of Photosynthesis



Nutrition, position within the canopy (light environment), and species determines photosynthetic capacity.



Stomatal opening, light, and temperature determine photosynthetic performance.

Light, humidity, water availability, temperature, and hydraulic conductance determine stomatal opening.

All factors are generally coordinated – high photosynthetic capacity would be associated with high light, high water availability, high humidity, favorable temperatures, and high stomatal conductance. See Fig. 9.10, p310 in Bonan.

Homework (Due Tuesday, 9/16)

1) Calculate the volume of air needed to supply the CO_2 needed by 1 m^2 of leaves that are photosynthesizing at 10 µmol $m^{-2\ s-1}$ to support their photosynthesis over 8 hours. Assume that ambient CO_2 concentration is 370 µmol/mol. What assumptions did you make in estimating this volume?

> Assumptions: 1) 20°C and 1 atmosphere; 2) CO_2 is depleted by 10 µmol/mol by photosynthesis.
>
> 1) CO_2 used: 1 m^2 leaves * 10 µmol m^{-2} s^{-1} * 8 h * 3600 s/h * 10^{-6} 10 µmol/mol = 0.288 mol CO_2 used.
>
> 2) Volume of air containing 0.288 mol CO_2: 0.288 mol / [370 umol/mol * 1 mol/22.414 L at STP * 273/(273+20) * 10^{-6} mol/µmol] = 0.288 mol / [1.54 *10^{-5} mol/L * 0.001 m^3/L] = 18.7 m^3
>
> 3) Depleted by by 10 µmol m^{-2} s^{-1} by photosynthesis: 18.7 m^3 * 370 /10 = 692 m^3.

2) In an open photosynthesis system, we are measuring the photosynthesis of 5 cm^2 of leaf area. CO_2 concentration entering the chamber is 360 µmol/mol, exiting the chamber is 340 µmol/mol, and the flow rate is 300 ml/minute. What is the photosynthesis rate in µmol m^{-2} s^{-1}? What assumptions did you make in estimating this rate?

> Assumptions: 20°C and 1 atmosphere; Flux = [Co2 in – co2out] * molar flow
>
> 20 µmol CO2/mol air * 300 ml/min * 1 mol/22424 ml * 273/(273+20) * 1 min/60s * [1/5 * 10-4 m^2 leaf area] = 8.31 µmol m^{-2} s^{-1}

3) Photosynthesis at the canopy top in full sun is 10 µmol m^{-2} s^{-1}? Assuming that light attenuation follows Beers law, and photosynthesis declines linearly with light, what would the photosynthesis rate be for a leaf at the bottom of a canopy with LAI = 4? What assumptions did you make?

> Assumption: k = 0.5
> $I = I_0$ e –kLAI. For LAI of 4, I = 0.135 $I_{0;}$ 10 µmol m^{-2} s^{-1} * .135 = 1.35 µmol m^{-2} s^{-1}