Bioenergy:

Potentials and limitations

EPS-Summer School

July 17 to 23, 2014

E D Schulze

MPI Biogeochemie

I will organize my 2 lectures as following

Saturday, July 19:

The physiology and ecology of photosynthesis and growth

Monday, July 21:

Land-use and Bioenergy

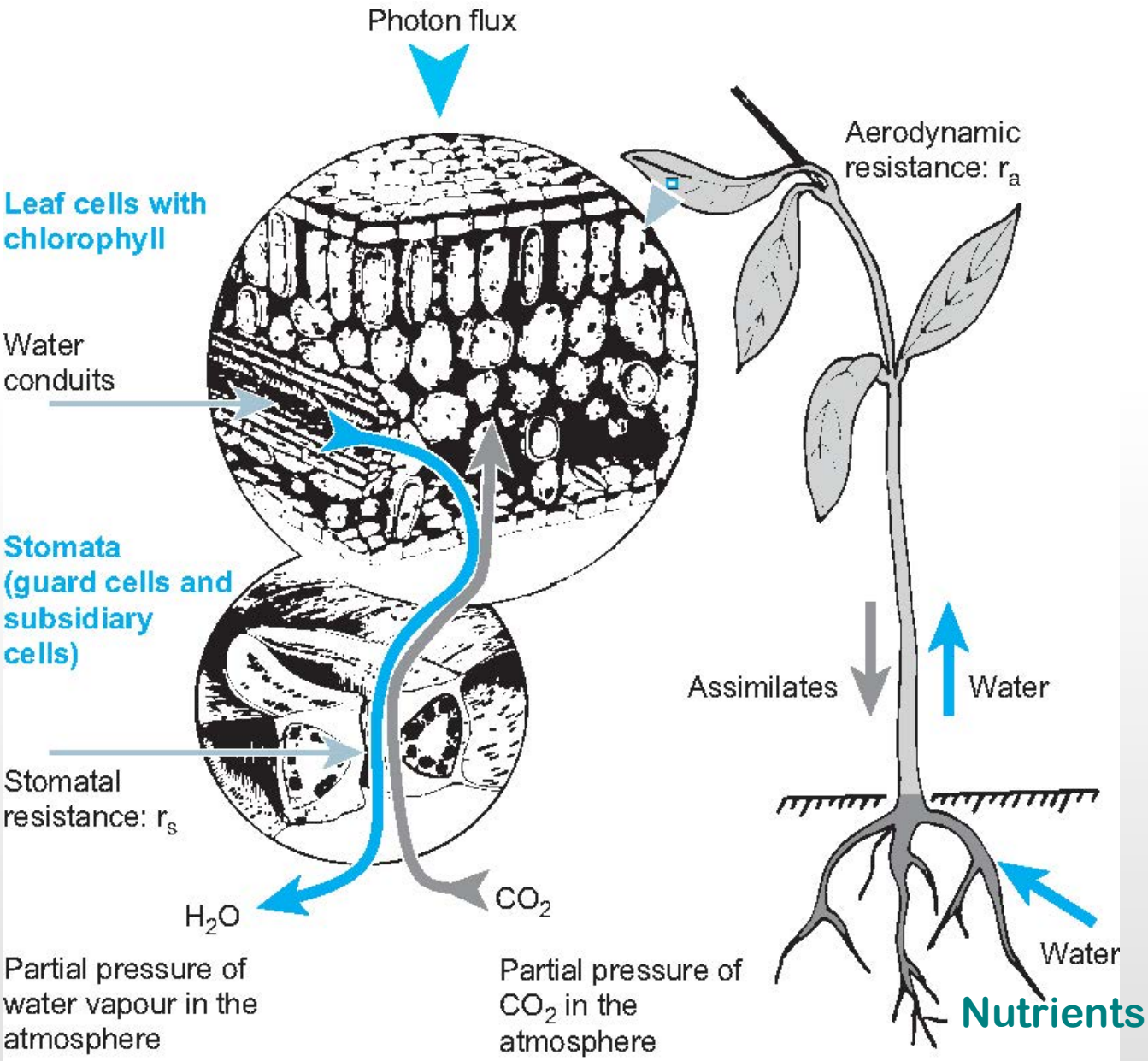
Physiolgy and Ecology of photosynthesis and growth

- The functioning of a plant
- Biochemistry of Photosynthesis
- Carbon fixation
- Respiration
- Gas exchange
- Growth and yield

- The following will contain several “biochemical pathways”
- It is not my aim to teach you biochemistry, but you should learn some principles about plant functioning:
  - The regeneration of substrates in closed reaction cycles
  - The use of chemical energy via redox-systems
  - The importance of membranes to separate charges

- Literature
  - Straßburger: Lehrbuch der Botanik
  - Schulze et al: Plant Ecology
  - Larcher: Plant Eco-Physiology
  - Lambers et al: Plant physiological Ecology

- **The functioning of a plant**


Photon flux
Leaf cells with chlorophyll
Water conduits
Stomata (guard cells and subsidiary cells)
Stomatal resistance: r_s
H_2O
CO_2
Partial pressure of water vapour in the atmosphere
Partial pressure of CO_2 in the atmosphere
Aerodynamic resistance: r_a
Assimilates
Water
Water
Nutrients
Flower and fruits
Leaves
Shoot
Root


Sphagnum squarrosum


Agatis australis

Why is water use such a problem for plants?

Diffusivity of CO_2 in air: $0.14\ 10^{-4}\ m^2s^{-1}$

in water: $0.16\ 10^{-8}\ m^2s^{-1}$

Membrane: no membrane permeable for CO_2 and not for H_2O: Mol. weight: 44/18

Plants

CO_2 Gradient air/plant interior: 100 ppm

H_2O Gradient air/plant interior: 12000 ppm

Water use (incl diffusivity): 12000x1.6/100= 192 H_2O/CO_2

Animals

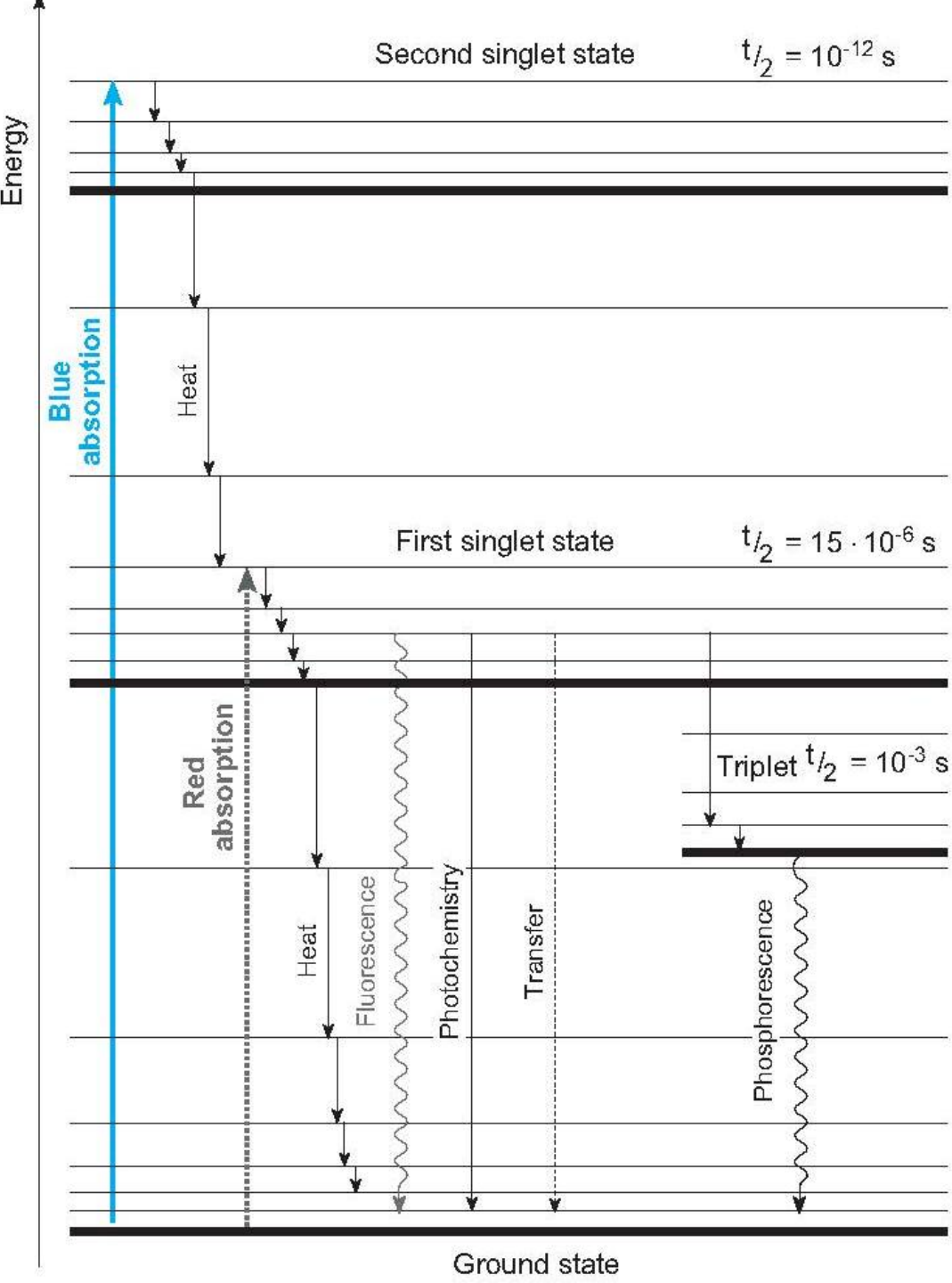
O_2 Gradient air/lung: 50000 ppm

H_2O Gradient lung/air: 50000 ppm

Water use: 1 H_2O/O_2 (warm blooded)

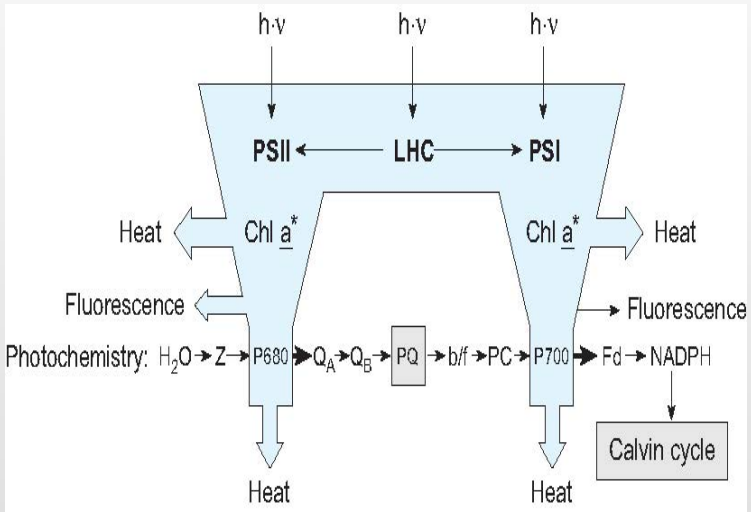
0.2 H_2O/O_2 (cold blooded)

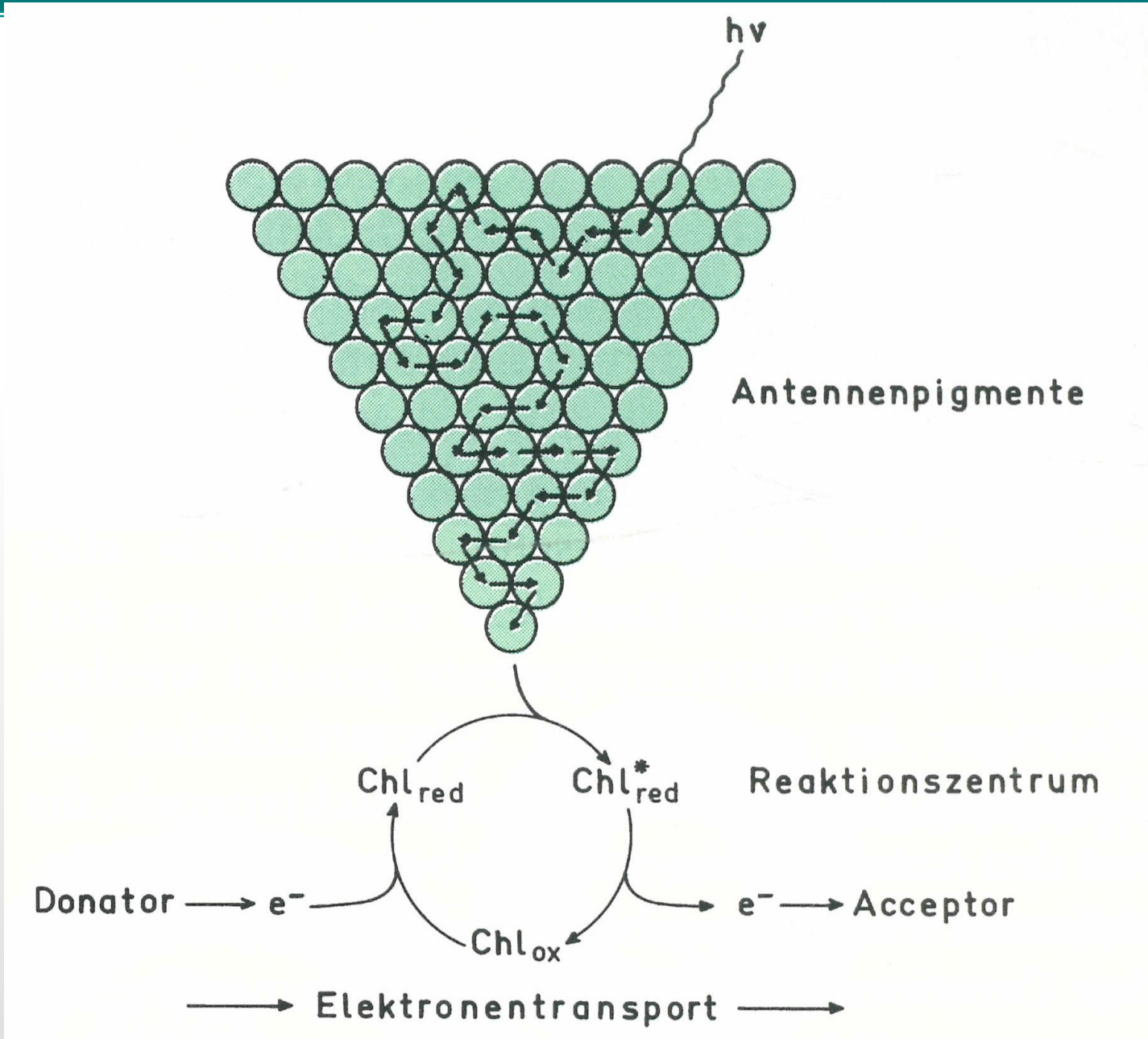
- **Biochemistry of Photosynthesis**

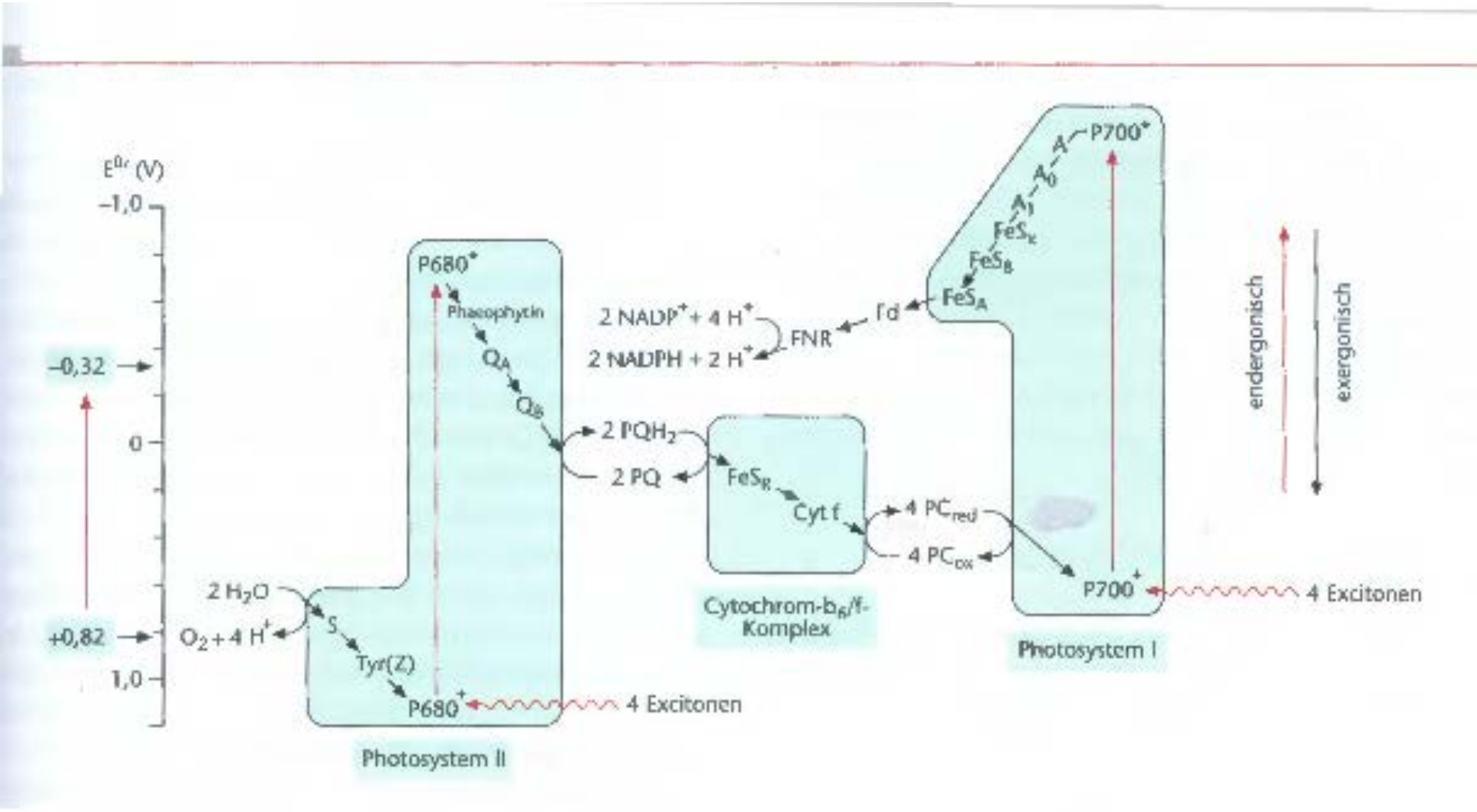


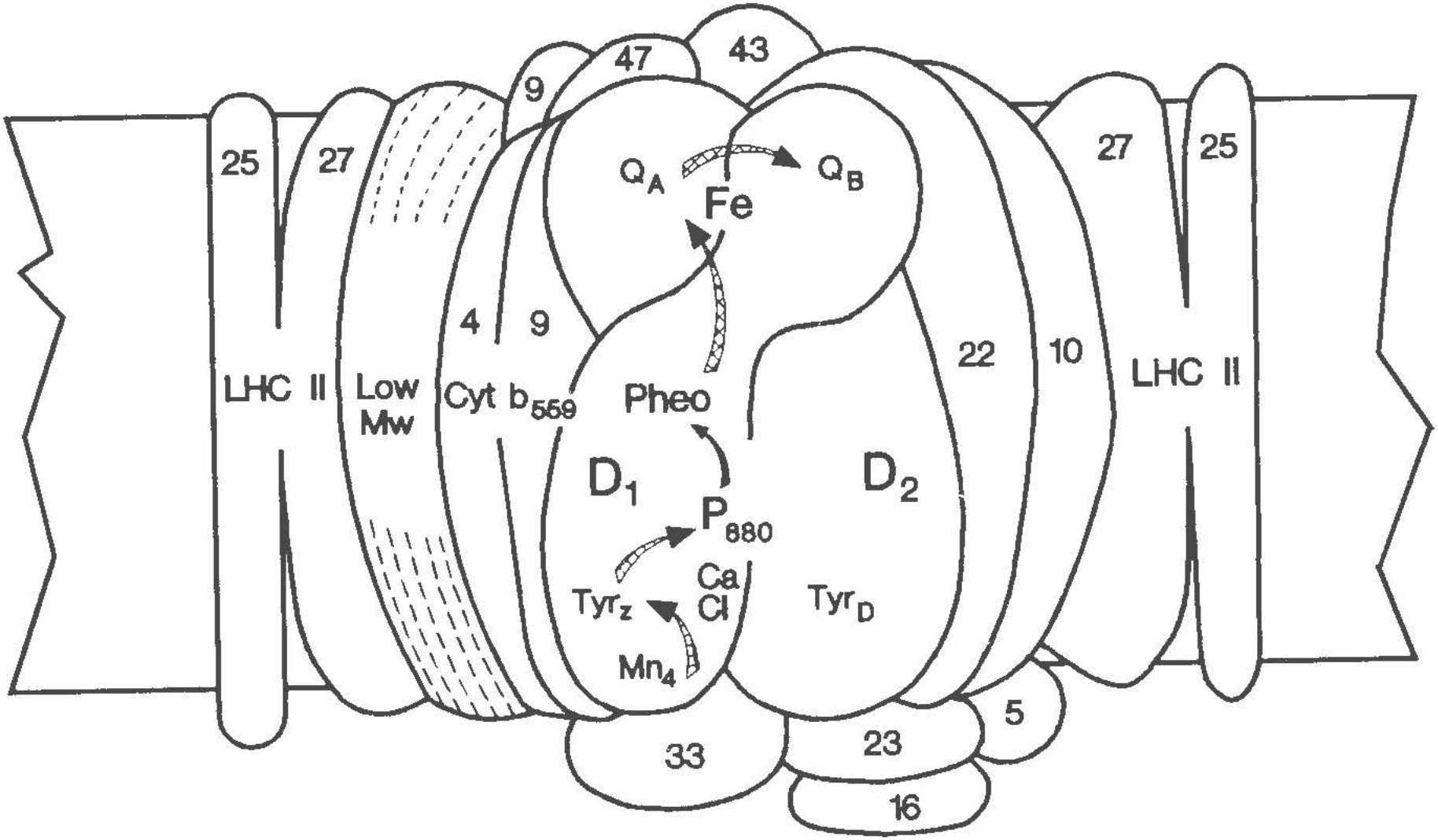
Absorption of Quanta of red and blue light lead to an excitation of 1.8 or 3 eV.

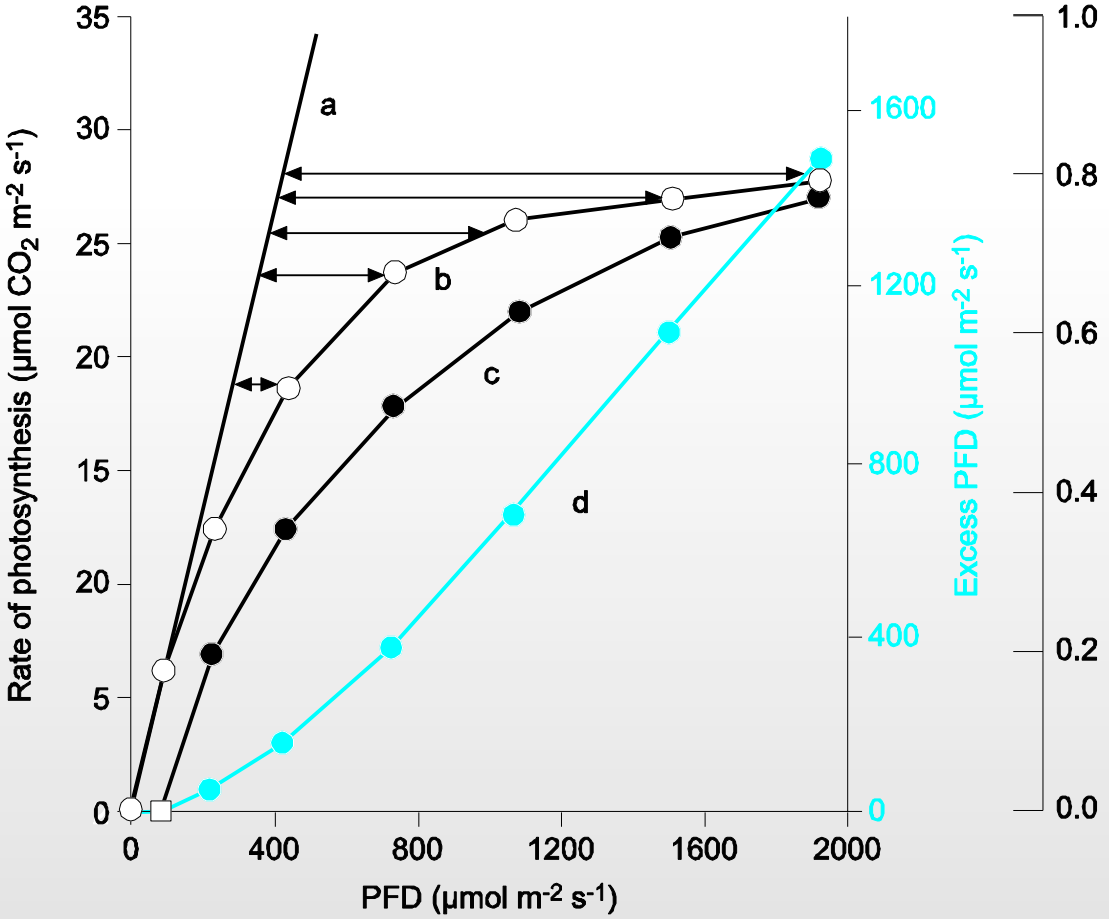
The relaxation of stage S2 is too fast to be used biochemically, only stage S1 can be used for biochemical reactions.

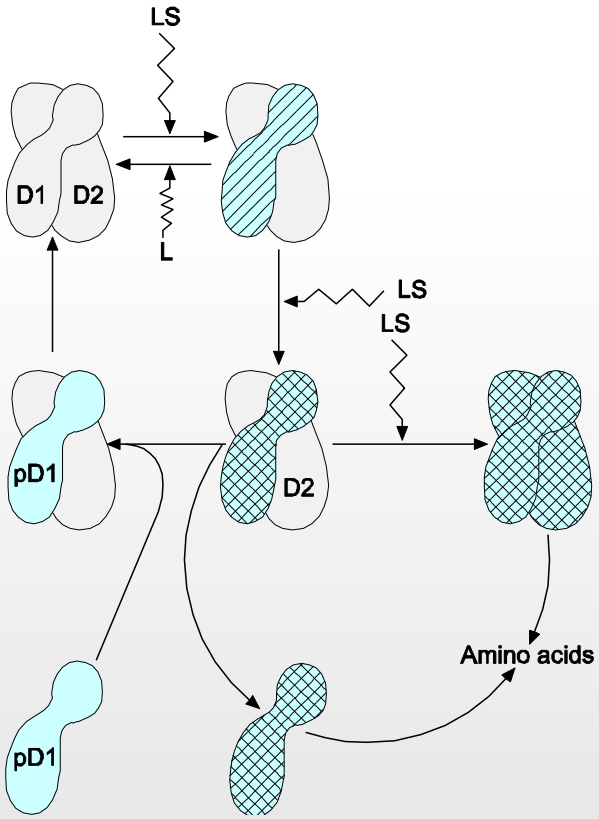


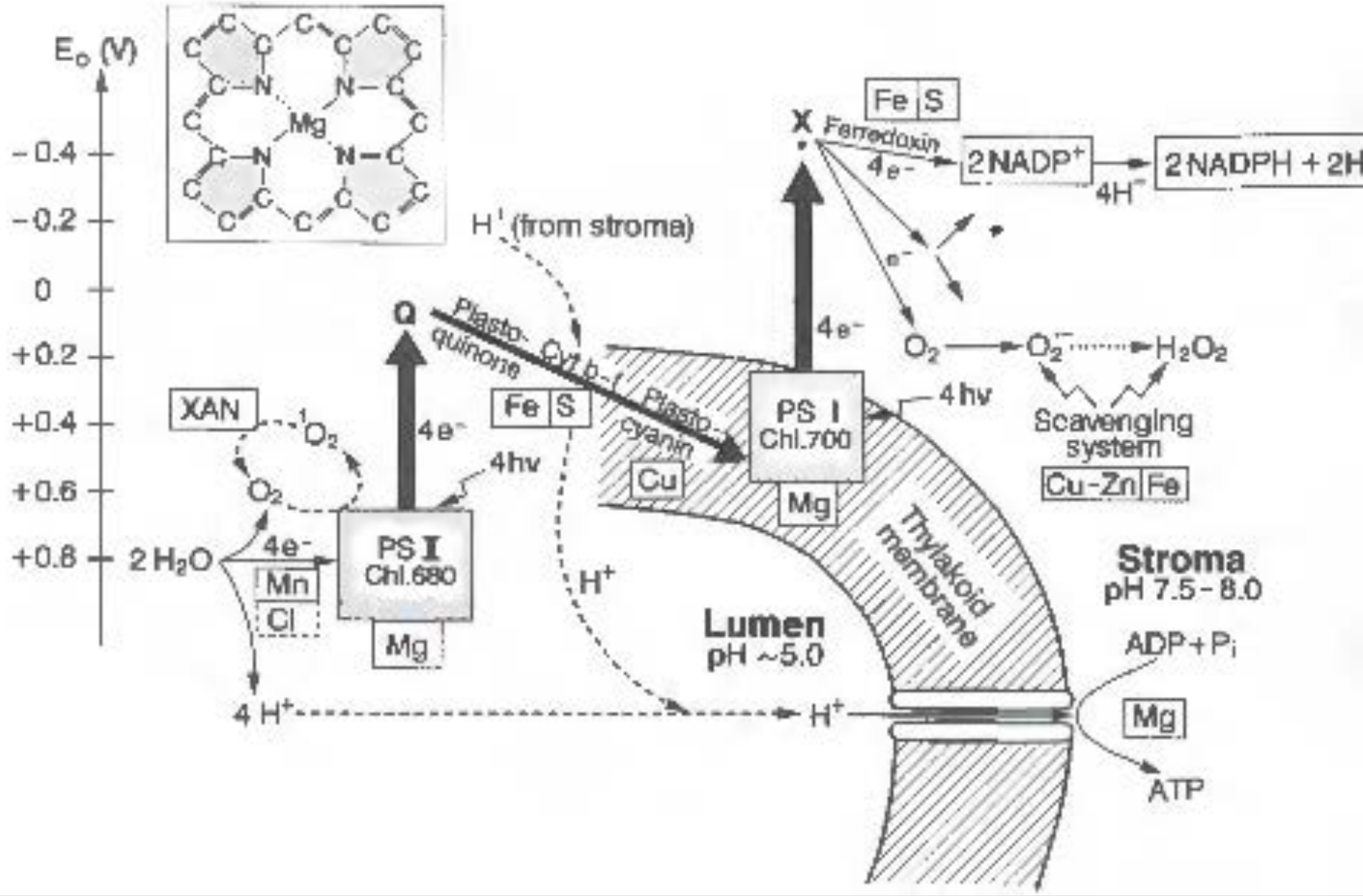

hν
Antennenpigmente
Chl red
Chl* red
Reaktionszentrum
Donator
e⁻
e⁻
Acceptor
Chl ox
Elektronentransport

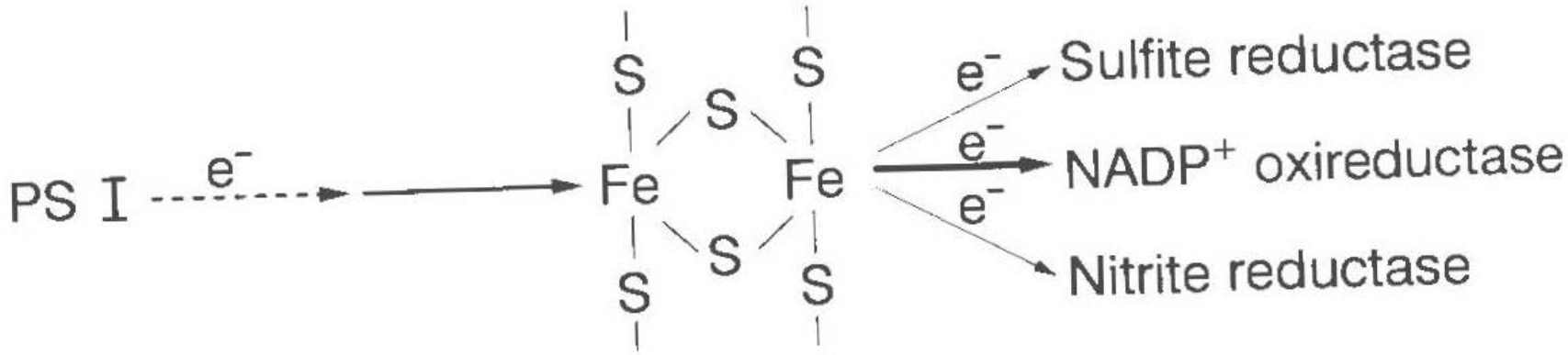

E0' (V)
-1,0
-0,32
0
+0,82
1,0
2 H2O
O2 + 4 H+
S
Tyr(Z)
P680*
Phaeophytin
QA
QB
P680+
4 Excitonen
Photosystem II
2 PQH2
2 PQ
FeSR
Cyt f
Cytochrom-b6/f-Komplex
4 PCred
4 PCox
2 NADP+ + 4 H+
2 NADPH + 2 H+
FNR
Fd
FeSA
FeSB
FeSx
A1
A0
A
P700*
P700+
4 Excitonen
Photosystem I
endergonisch
exergonisch


25
27
9
47
43
Q_A
Q_B
Fe
27
25
4
9
LHC II
Low Mw
Cyt b_{559}
Pheo
22
10
LHC II
D_1
D_2
P_{680}
Ca
Cl
Tyr_z
Tyr_D
Mn_4
5
33
23
16


Rate of photosynthesis (µmol CO_2 m^{-2} s^{-1})
PFD (µmol m^{-2} s^{-1})
Excess PFD (µmol m^{-2} s^{-1})
Closure of reaction centres
a
b
c
d
0
400
800
1200
1600
2000
5
15
20
25
30
35
0.0
0.2
0.4
0.6
0.8
1.0


LS
D1
D2
L
LS
LS
pD1
D2
Amino acids
pD1


E₀ (V)
−0.4
−0.2
0
+0.2
+0.4
+0.6
+0.8
Mg
Fe S
X
Ferredoxin
4e⁻
2 NADP⁺
4H⁺
2 NADPH + 2H
H⁺ (from stroma)
e⁻
Q
Plasto-quinone
Cyt b-f
Plasto-cyanin
Cu
4e⁻
O₂
O₂⁻
H₂O₂
4 hv
PS I
Chl.700
Mg
Scavenging system
Cu-Zn Fe
XAN
¹O₂
O₂
4e⁻
4hv
Fe S
2 H₂O
4e⁻
Mn
Cl
PS II
Chl.680
Mg
H⁺
Thylakoid membrane
Stroma
pH 7.5 - 8.0
Lumen
pH ~5.0
ADP + Pi
Mg
ATP
4 H⁺
H⁺

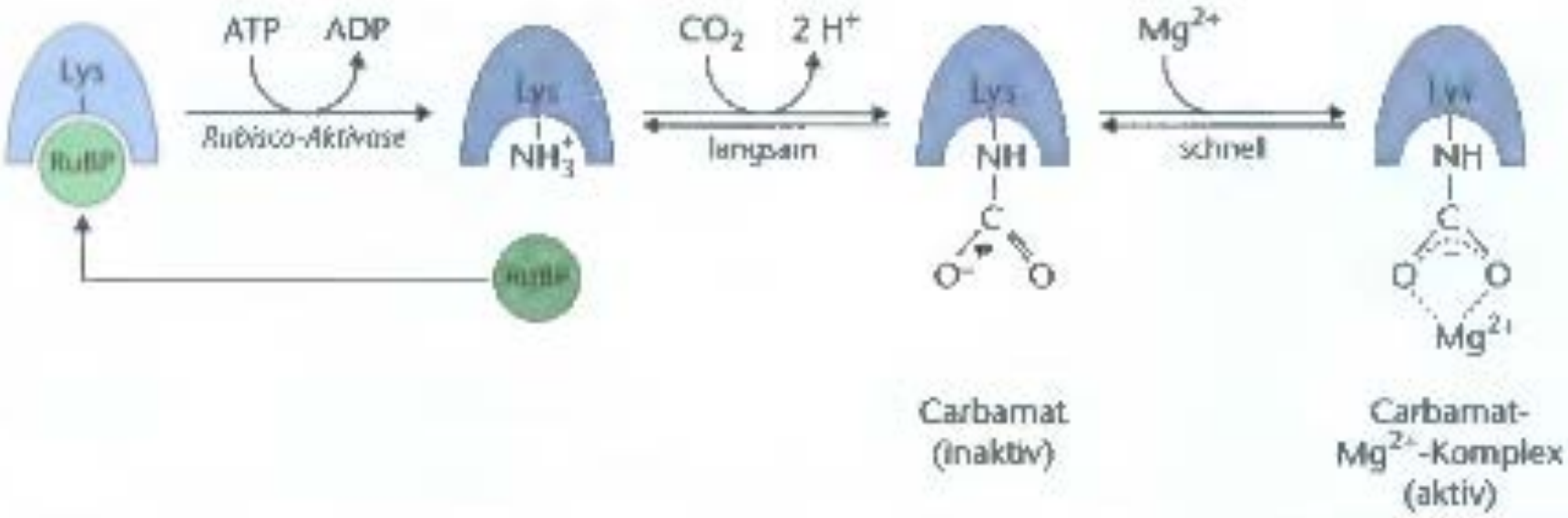

PS I
e⁻
S
S
S
Fe
Fe
S
S
S
e⁻
e⁻
e⁻
Sulfite reductase
NADP⁺ oxireductase
Nitrite reductase

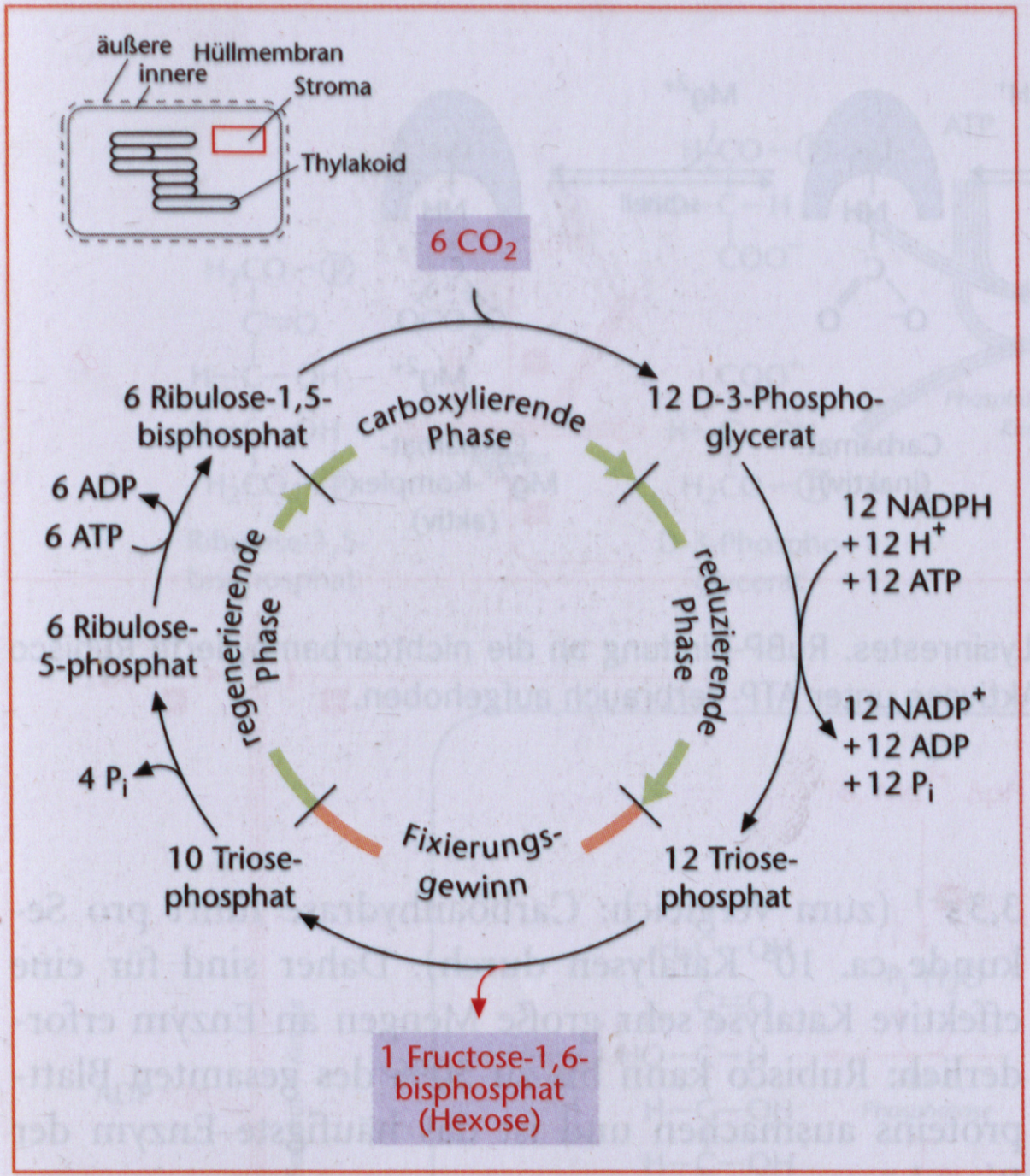
Carbon Fixation

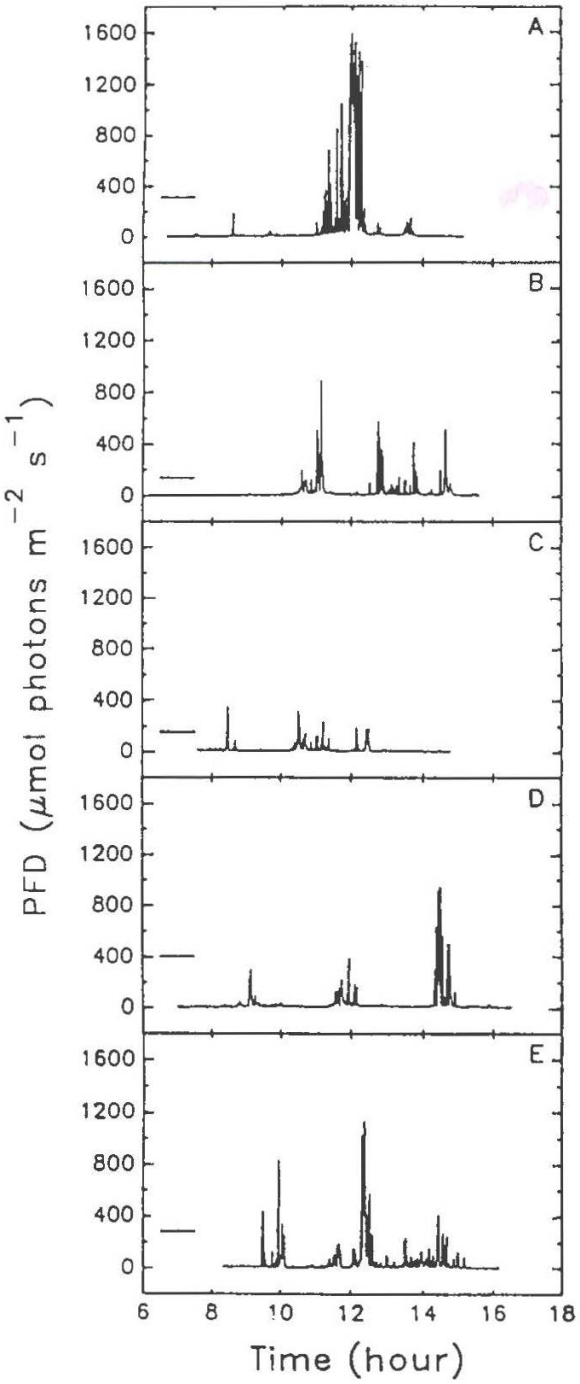
$$6\ CO_2 + 12\ H_2O \rightarrow C_6H_{12}O_6 + 6\ H_2O + 6O_2$$

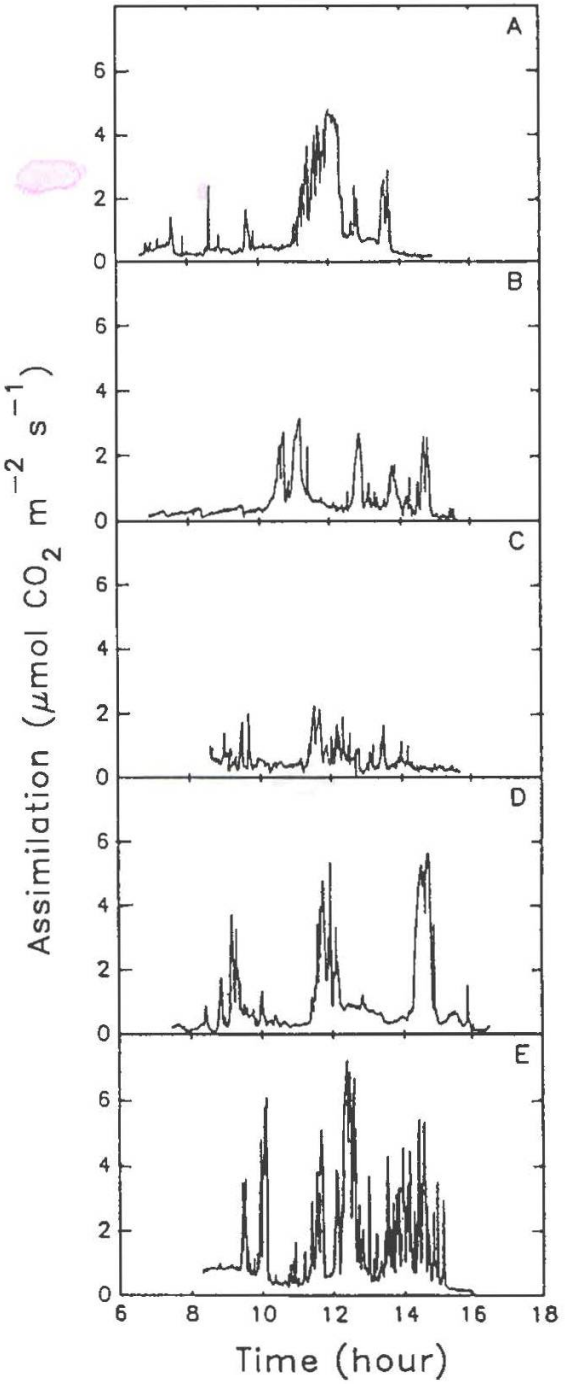
$$6\ CO_2 + 12NADPH + 12\ H^+ + 18\ ATP \rightarrow$$

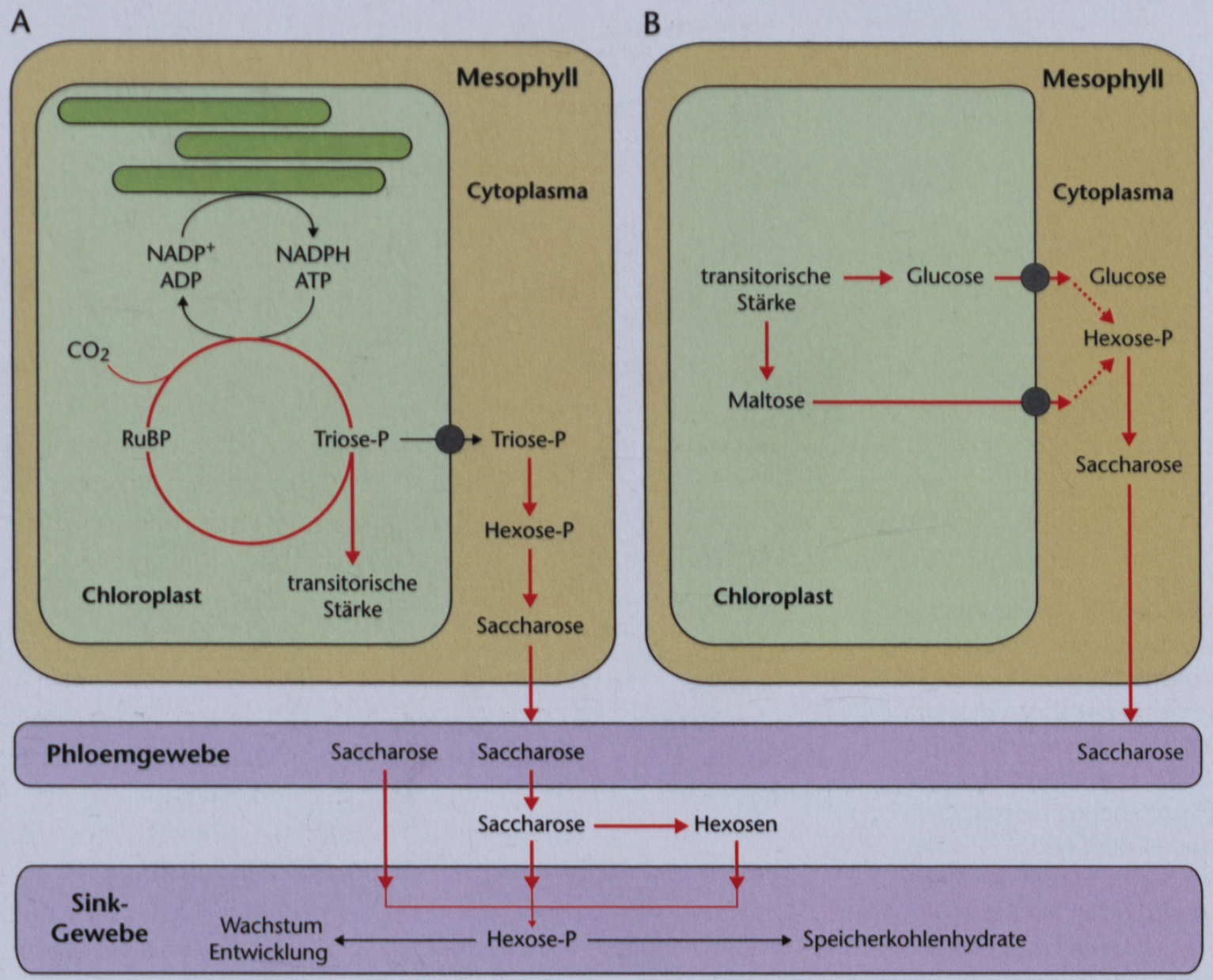
$$C_6H_{12}O_6 + 12\ NADP^+ + 18\ ADP + 18\ P_i + 6\ H_2O$$


Lys
RuBP
ATP
ADP
Rubisco-Aktivase
Lys
NH_3^+
CO_2
2 H^+
langsam
Lys
NH
C
O
O
Mg^{2+}
schnell
Lys
NH
C
O
O
Mg^{2+}
Carbamat
(inaktiv)
Carbamat-
Mg^{2+}-Komplex
(aktiv)

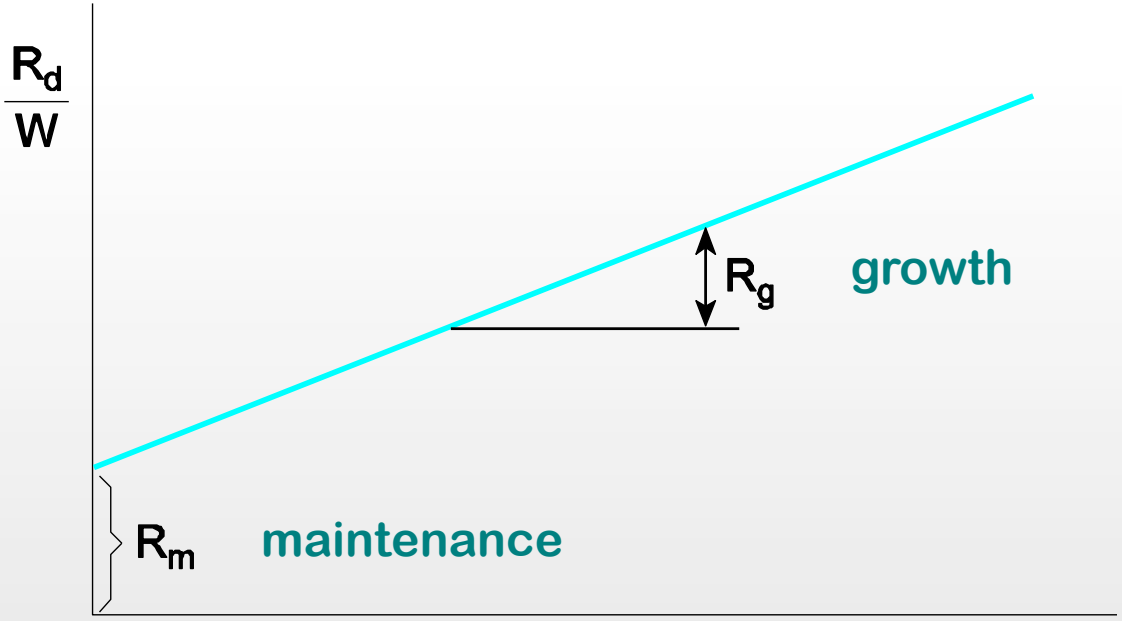

äußere Hüllmembran
innere
Stroma
Thylakoid
6 CO_2
carboxylierende Phase
12 D-3-Phospho-glycerat
12 NADPH +12 H^+ +12 ATP
12 $NADP^+$ +12 ADP +12 P_i
reduzierende Phase
12 Triose-phosphat
Fixierungs-gewinn
10 Triose-phosphat
4 P_i
regenerierende Phase
6 Ribulose-5-phosphat
6 ADP
6 ATP
6 Ribulose-1,5-bisphosphat
1 Fructose-1,6-bisphosphat (Hexose)


A
B
C
D
E
1600
1200
800
400
0
PFD (μmol photons m^{-2} s^{-1})
6
8
10
12
14
16
18
Time (hour)

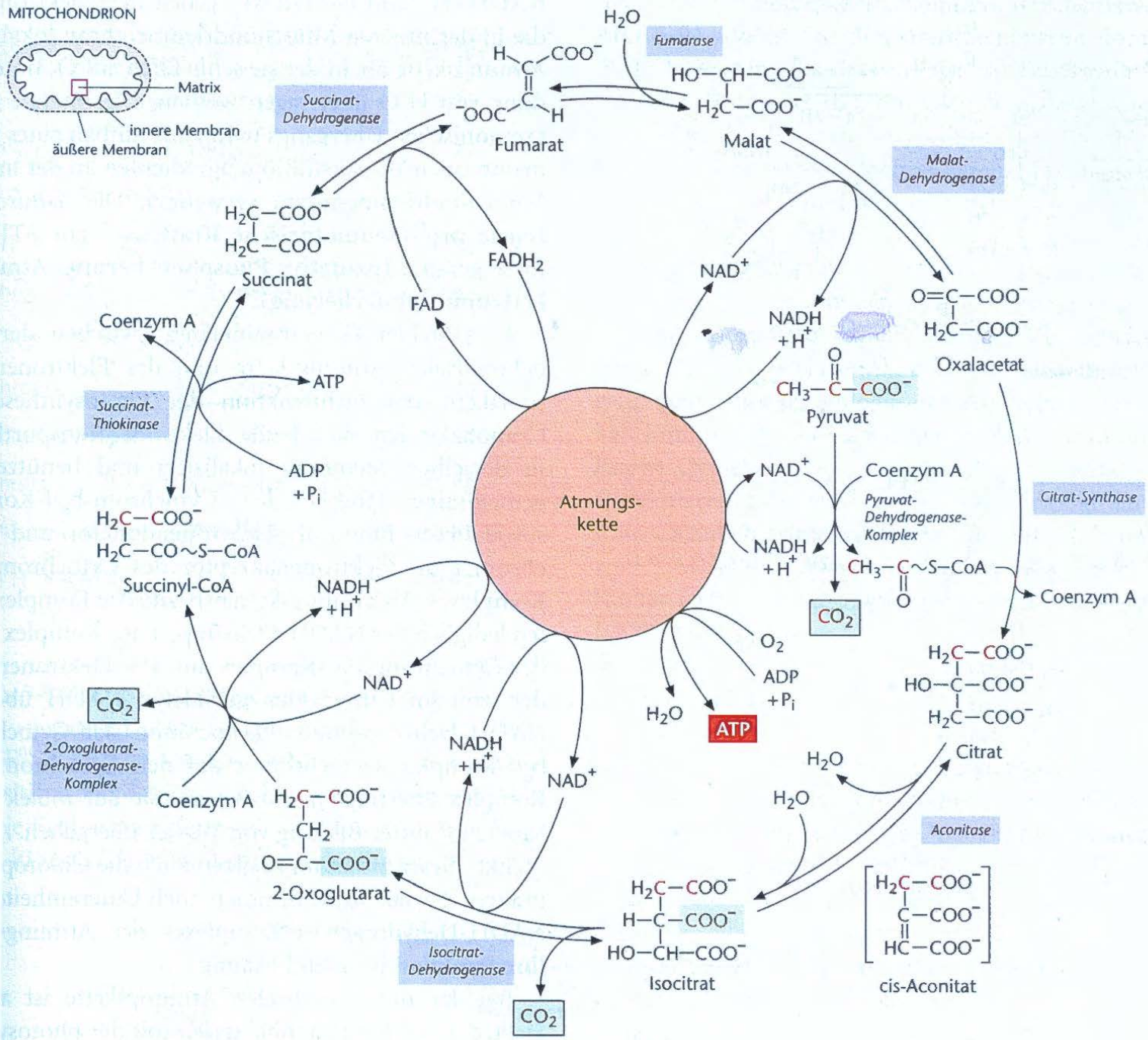

A
B
C
D
E
6
4
2
0
Assimilation (μmol CO$_2$ m^{-2} s^{-1})
6
8
10
12
14
16
18
Time (hour)

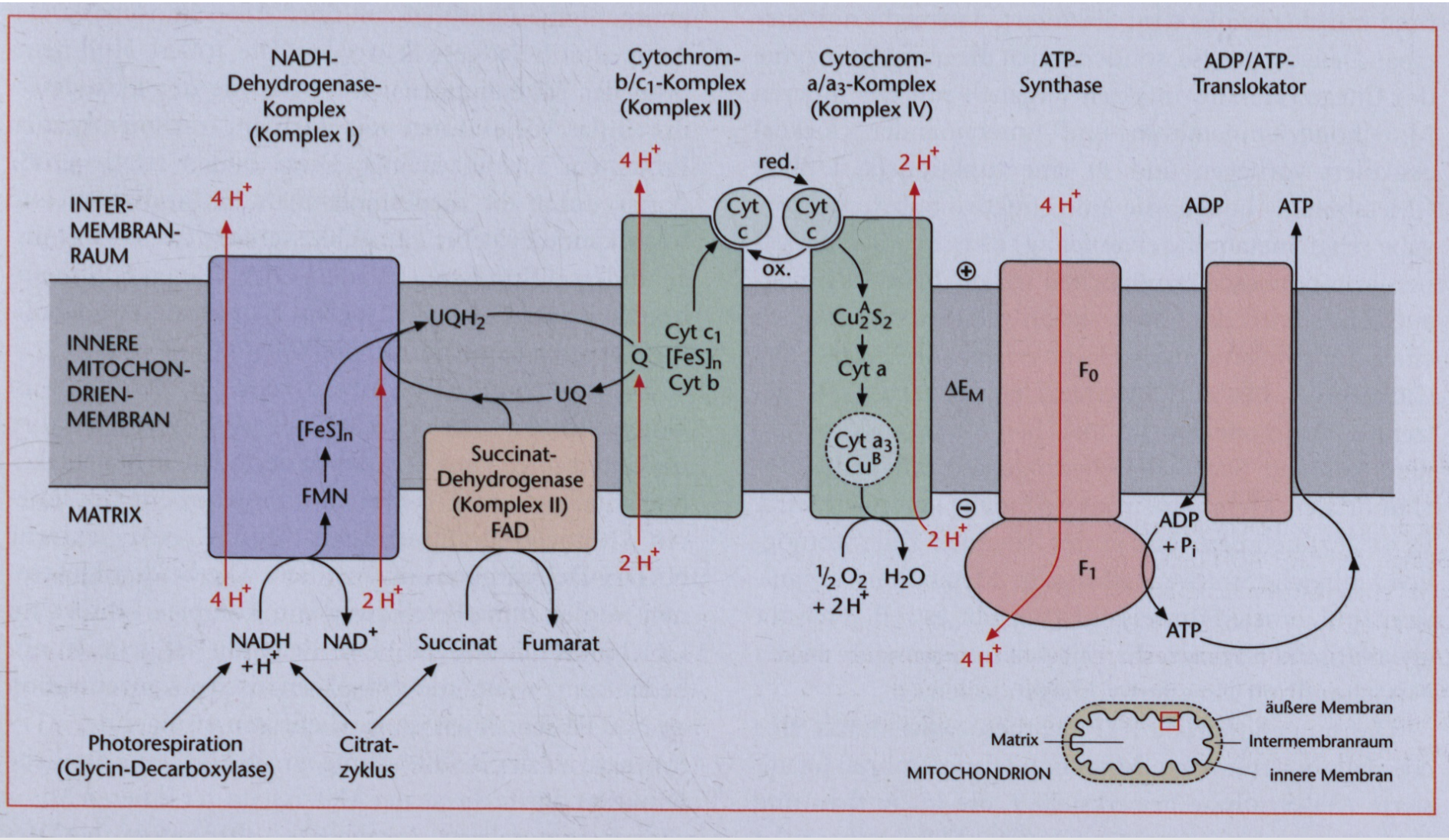

A
Mesophyll
Cytoplasma
NADP+
ADP
NADPH
ATP
CO2
RuBP
Triose-P
Triose-P
Hexose-P
Saccharose
Chloroplast
transitorische
Stärke
B
Mesophyll
Cytoplasma
transitorische
Stärke
Glucose
Glucose
Hexose-P
Maltose
Saccharose
Chloroplast
Phloemgewebe
Saccharose
Saccharose
Saccharose
Saccharose
Hexosen
Sink-
Gewebe
Wachstum
Entwicklung
Hexose-P
Speicherkohlenhydrate

- **Respiration**



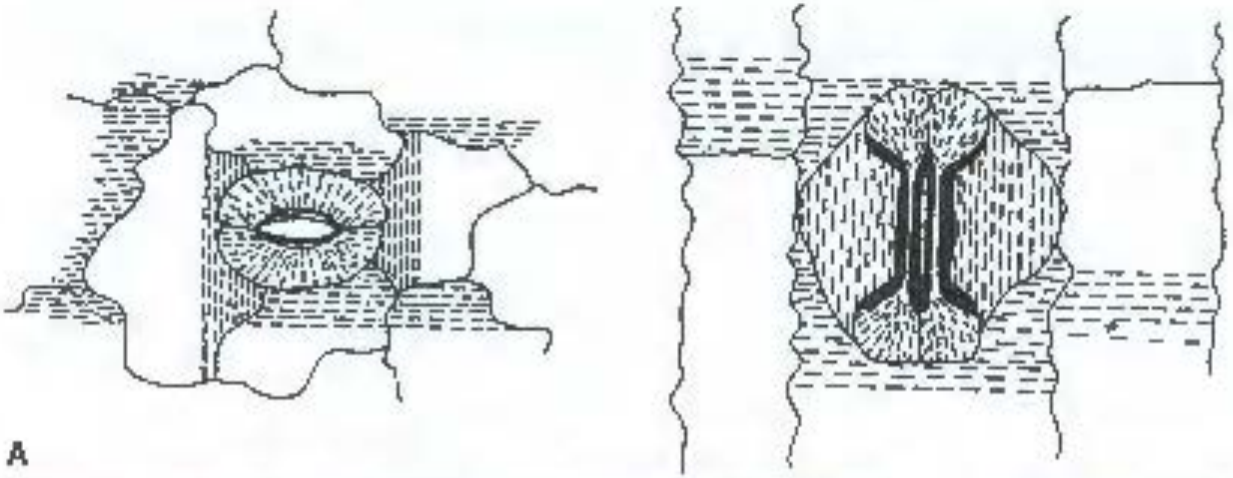
$$RGR = \frac{dW}{dt} \times \frac{1}{W}$$


MITOCHONDRION
Matrix
innere Membran
äußere Membran
Fumarase
H_2O
Fumarat
Malat
Succinat-Dehydrogenase
Malat-Dehydrogenase
Succinat
FAD
$FADH_2$
NAD^+
$NADH + H^+$
Oxalacetat
Pyruvat
Coenzym A
ATP
ADP $+ P_i$
Succinat-Thiokinase
Atmungs-kette
Pyruvat-Dehydrogenase-Komplex
Citrat-Synthase
Succinyl-CoA
CO_2
O_2
H_2O
ATP
Citrat
2-Oxoglutarat-Dehydrogenase-Komplex
2-Oxoglutarat
Aconitase
Isocitrat-Dehydrogenase
Isocitrat
cis-Aconitat

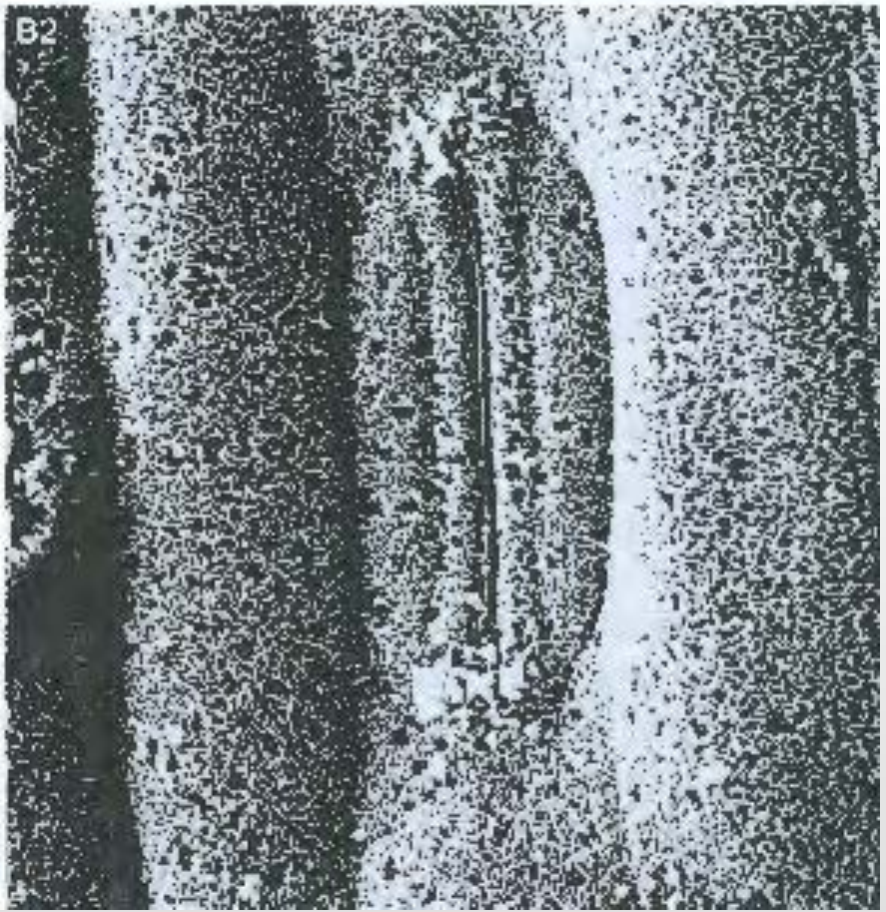

NADH-Dehydrogenase-Komplex (Komplex I)
Cytochrom-b/c1-Komplex (Komplex III)
Cytochrom-a/a3-Komplex (Komplex IV)
ATP-Synthase
ADP/ATP-Translokator
INTER-MEMBRAN-RAUM
INNERE MITOCHON-DRIEN-MEMBRAN
MATRIX
4 H+
2 H+
red.
ox.
Cyt c
Cyt c
UQH2
UQ
Q
Cyt c1
[FeS]n
Cyt b
[FeS]n
FMN
Succinat-Dehydrogenase (Komplex II) FAD
Cu2AS2
Cyt a
Cyt a3
CuB
ΔEM
F0
F1
ADP
ATP
ADP + Pi
½ O2 + 2H+
H2O
NADH +H+
NAD+
Succinat
Fumarat
Photorespiration (Glycin-Decarboxylase)
Citrat-zyklus
äußere Membran
Intermembranraum
innere Membran
Matrix
MITOCHONDRION

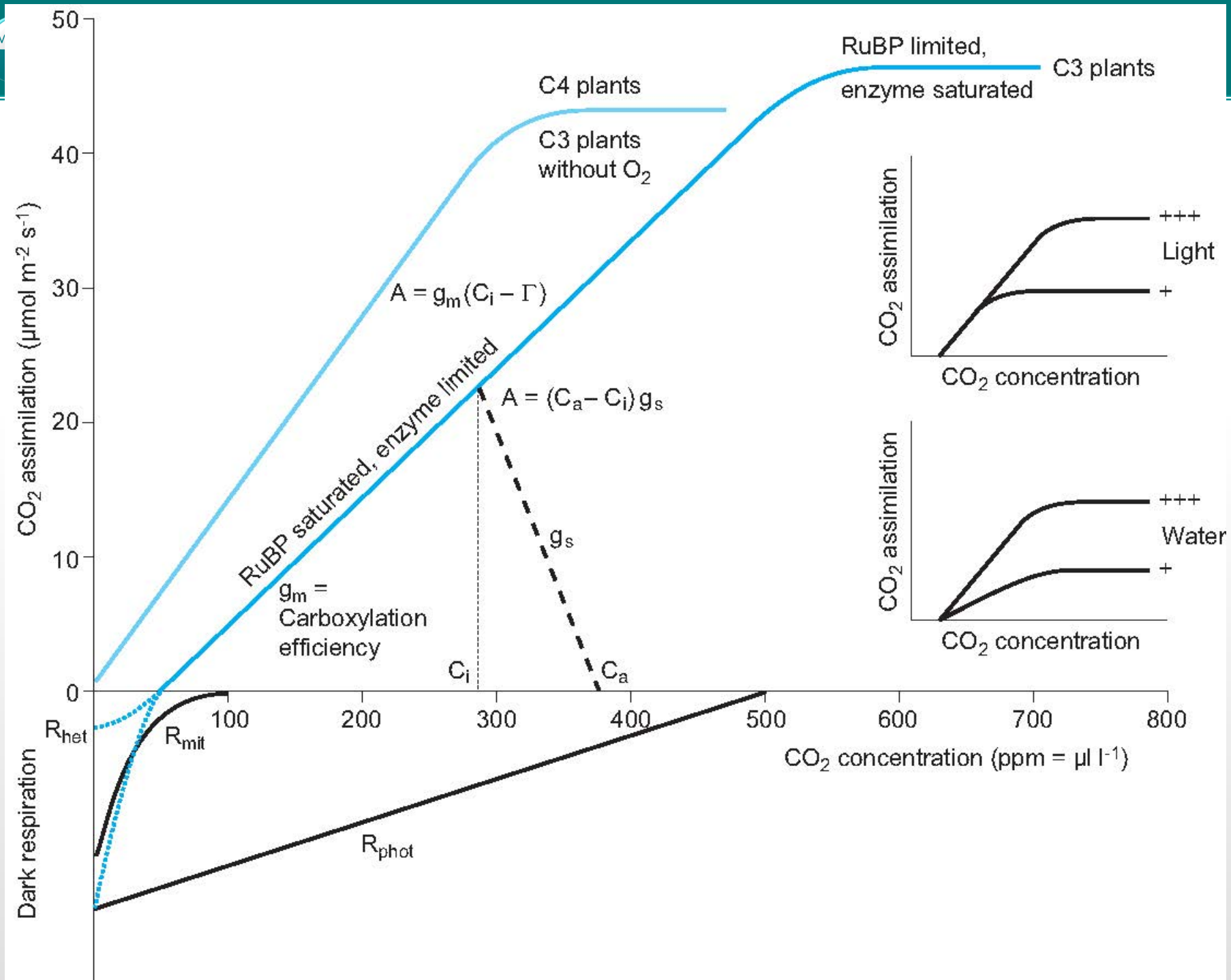
$$O_2 + 4H^+ + 4e^- = 2\,H_2O$$

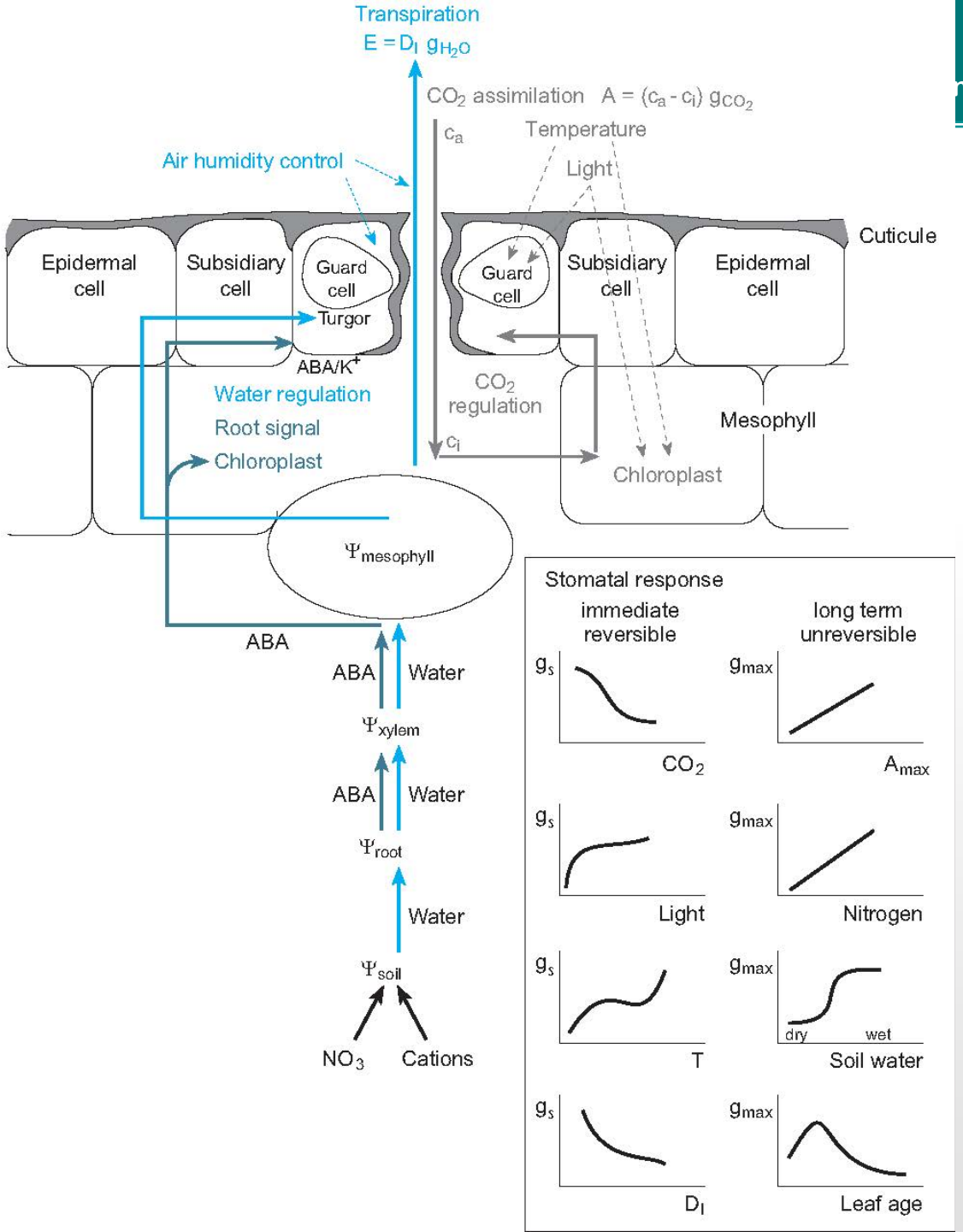
- **Gas exchange and stomata**


A

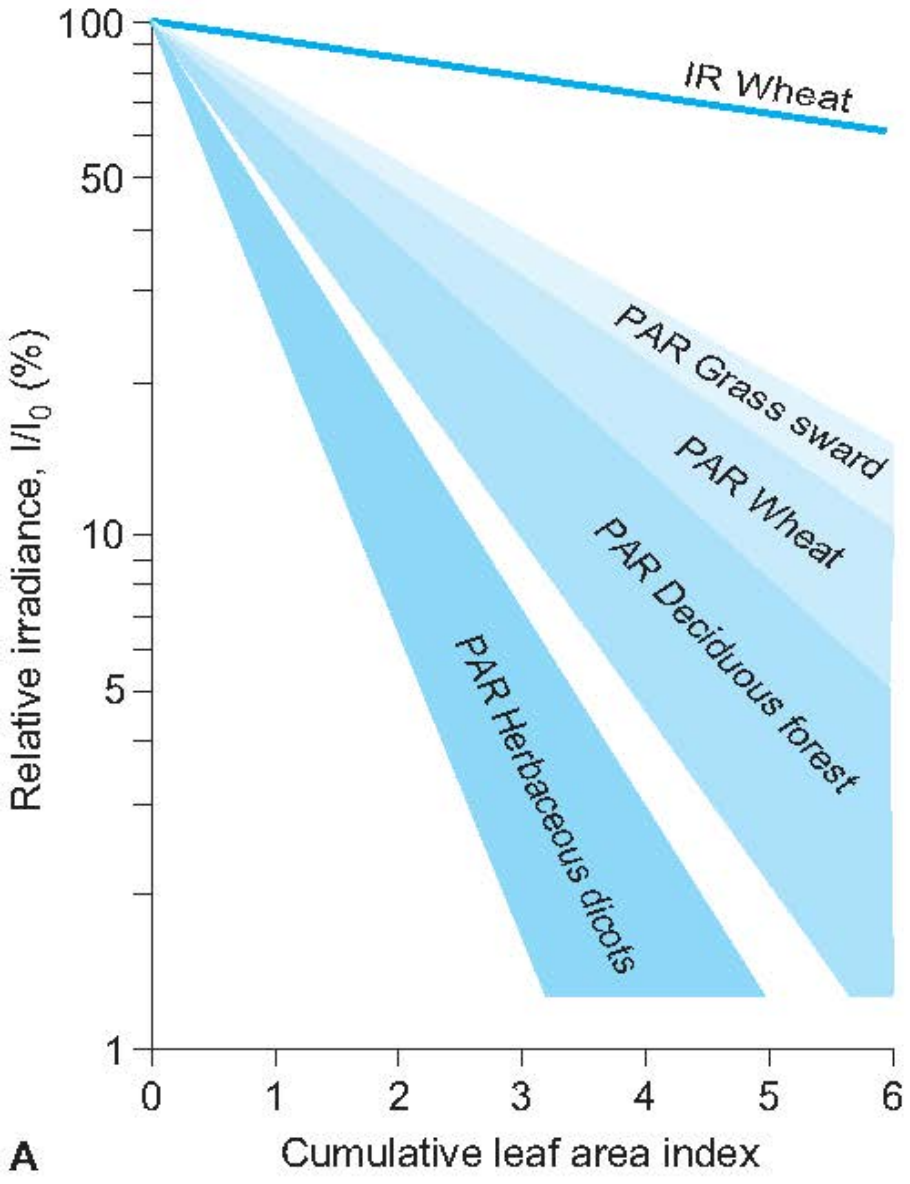

B1

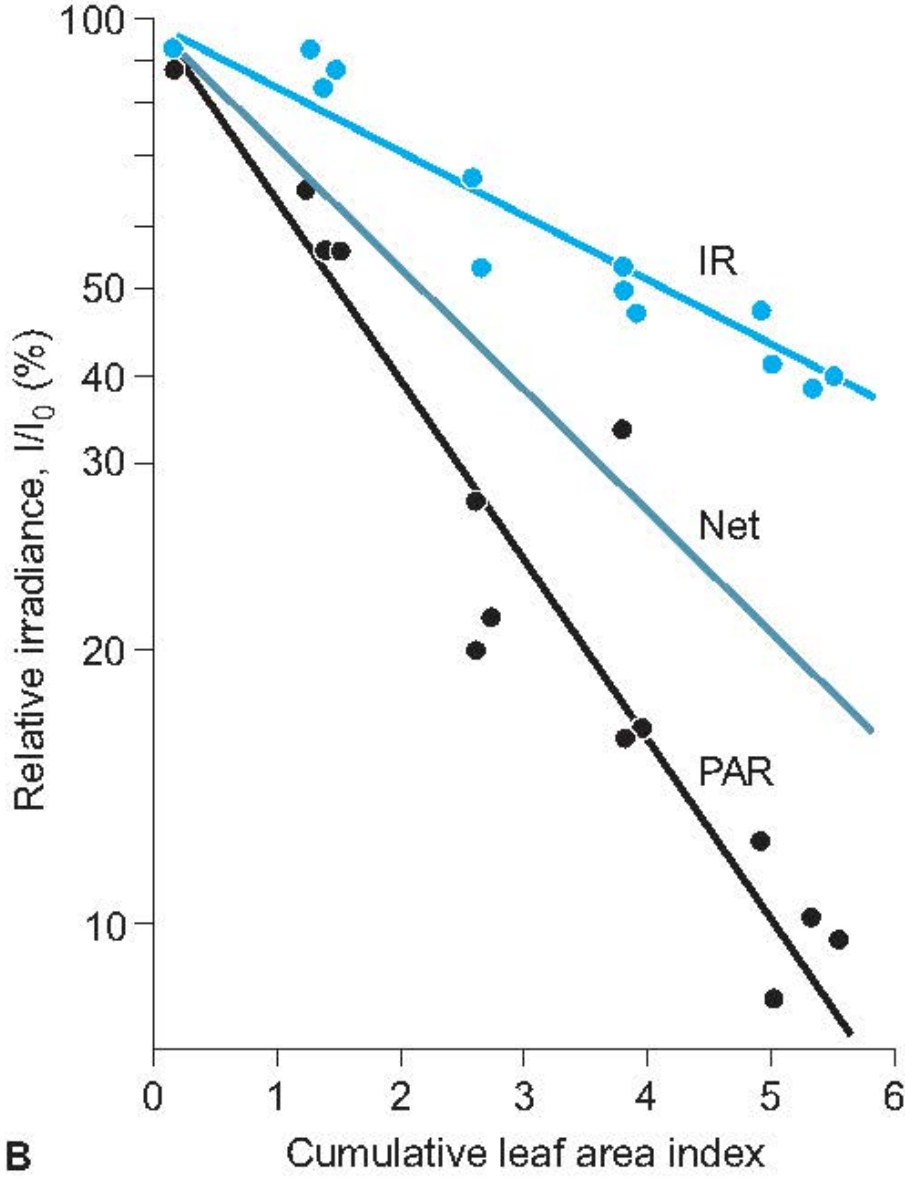

B2

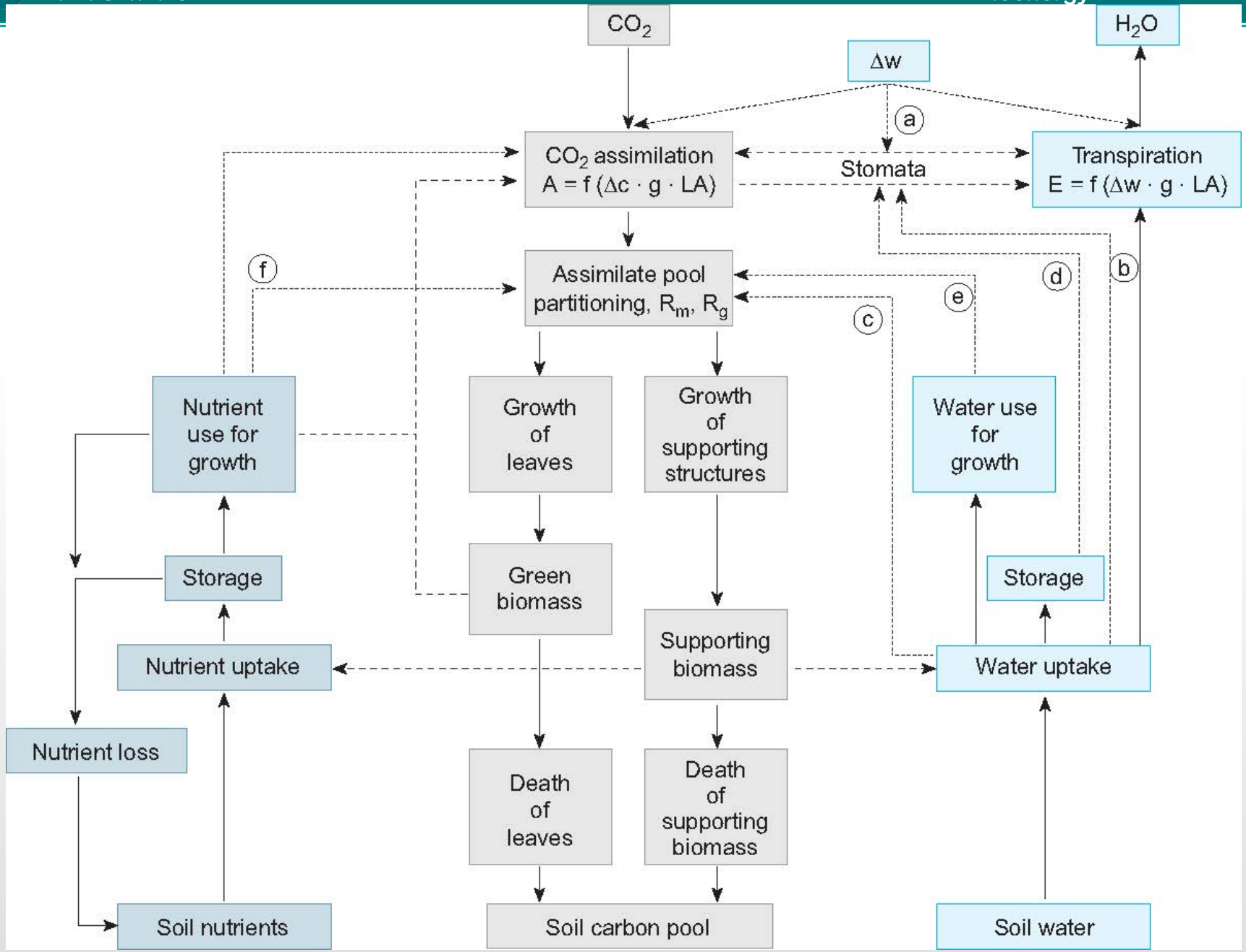

50
40
30
20
10
0
CO_2 assimilation (µmol m^{-2} s^{-1})
C4 plants
C3 plants
without O_2
RuBP limited,
enzyme saturated
C3 plants
$A = g_m(C_i - \Gamma)$
RuBP saturated, enzyme limited
$A = (C_a - C_i)\, g_s$
g_s
g_m =
Carboxylation
efficiency
C_i
C_a
R_{het}
R_{mit}
R_{phot}
Dark respiration
100
200
300
400
500
600
700
800
CO_2 concentration (ppm = µl l^{-1})
CO_2 assimilation
+++
Light
+
CO_2 concentration
CO_2 assimilation
+++
Water
+
CO_2 concentration

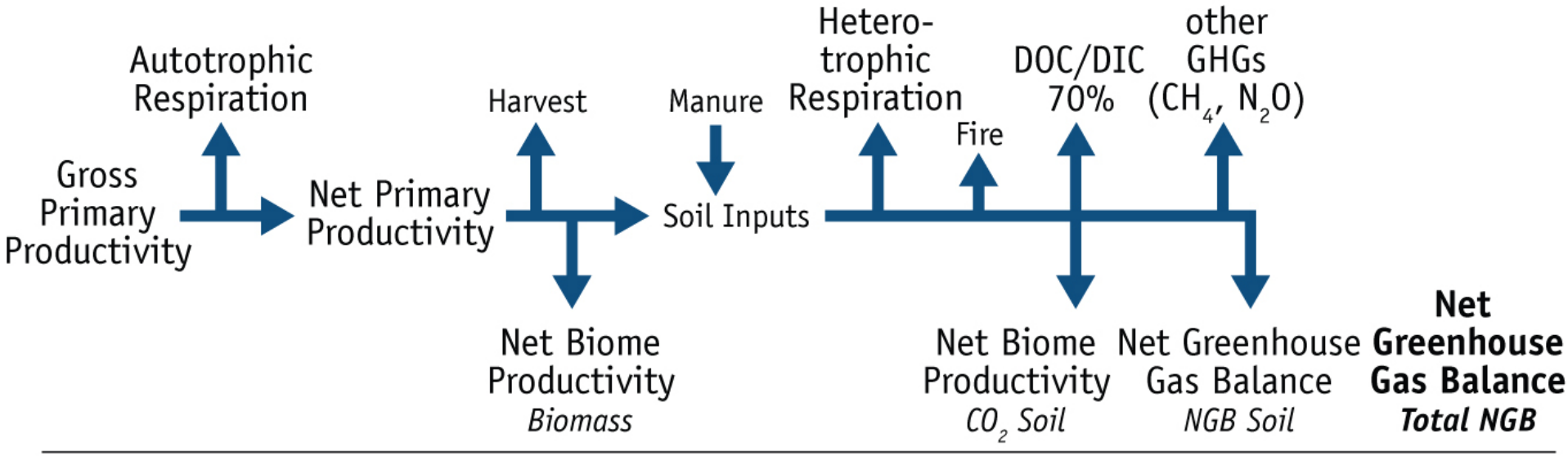

Transpiration
E = D_l g_H2O
CO2 assimilation A = (c_a - c_i) g_CO2
c_a
Temperature
Light
Air humidity control
Epidermal cell
Subsidiary cell
Guard cell
Turgor
ABA/K+
Cuticule
Water regulation
Root signal
Chloroplast
CO2 regulation
c_i
Mesophyll
Chloroplast
Ψmesophyll
ABA
ABA
Water
Ψxylem
ABA
Water
Ψroot
Water
Ψsoil
NO3
Cations
Stomatal response
immediate reversible
long term unreversible
gs
CO2
gmax
Amax
Light
Nitrogen
T
dry
wet
Soil water
Dl
Leaf age

- **Growth**

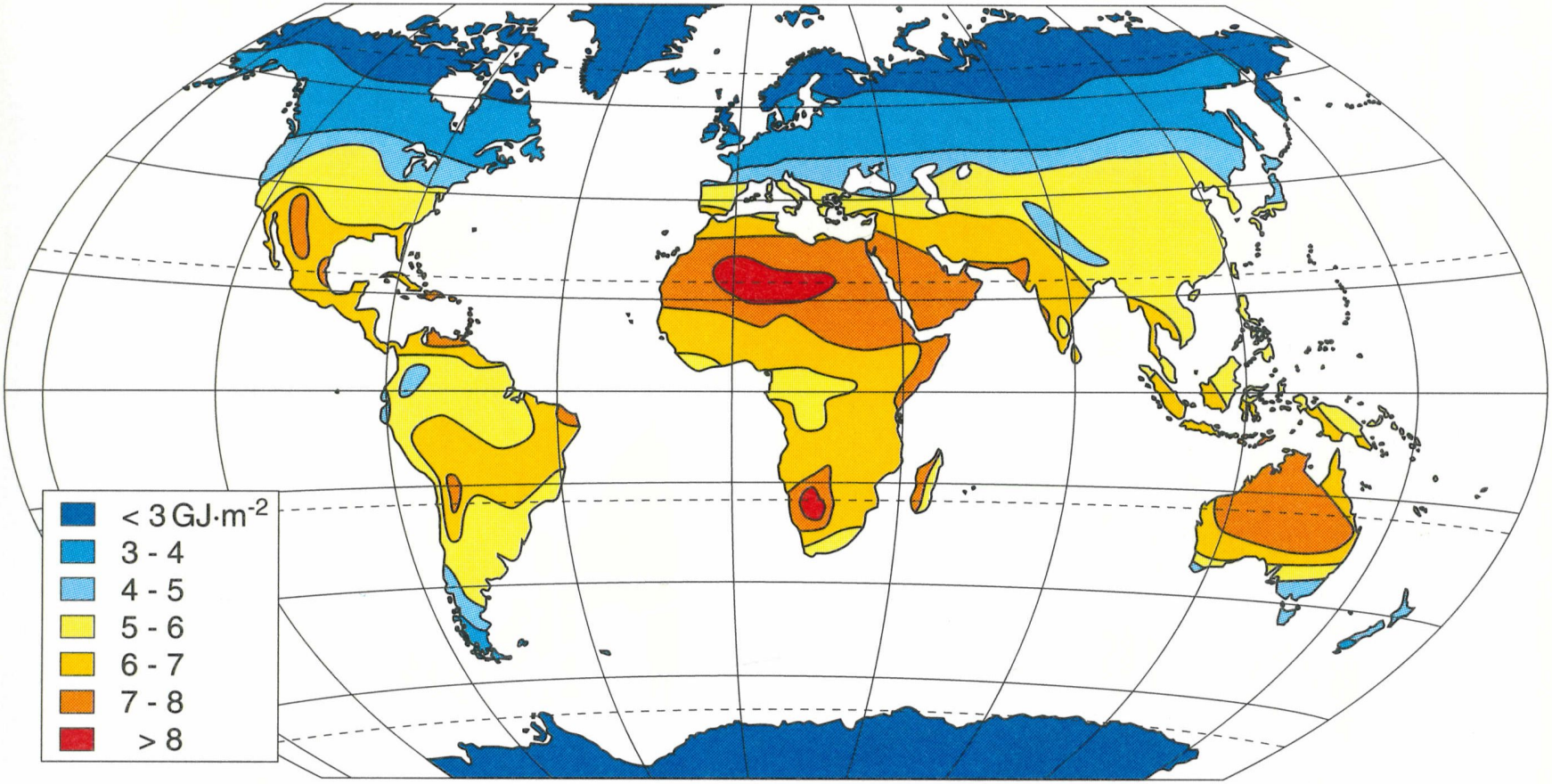

100
50
10
5
1
Relative irradiance, I/I_0 (%)
IR Wheat
PAR Grass sward
PAR Wheat
PAR Deciduous forest
PAR Herbaceous dicots
0
1
2
3
4
5
6
Cumulative leaf area index
A


100
50
40
30
20
10
Relative irradiance, I/I_0 (%)
IR
Net
PAR
0
1
2
3
4
5
6
Cumulative leaf area index
B

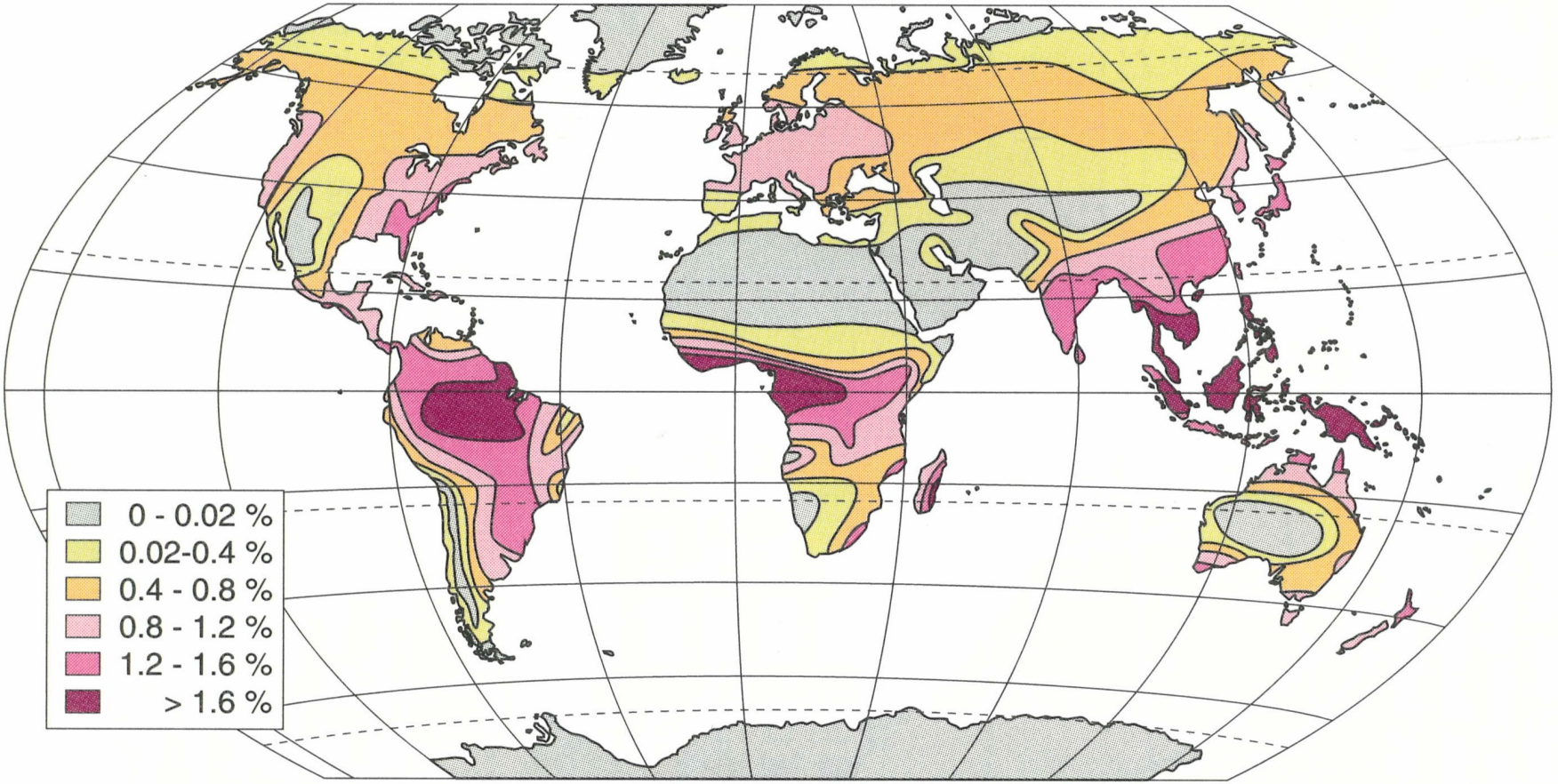

CO_2
H_2O
Δw
a
CO_2 assimilation
A = f (Δc · g · LA)
Stomata
Transpiration
E = f (Δw · g · LA)
f
Assimilate pool
partitioning, R_m, R_g
d
b
e
c
Nutrient
use for
growth
Growth
of
leaves
Growth
of
supporting
structures
Water use
for
growth
Storage
Green
biomass
Storage
Supporting
biomass
Nutrient uptake
Water uptake
Nutrient loss
Death
of
leaves
Death
of
supporting
biomass
Soil nutrients
Soil carbon pool
Soil water



Schulze et al., 2009

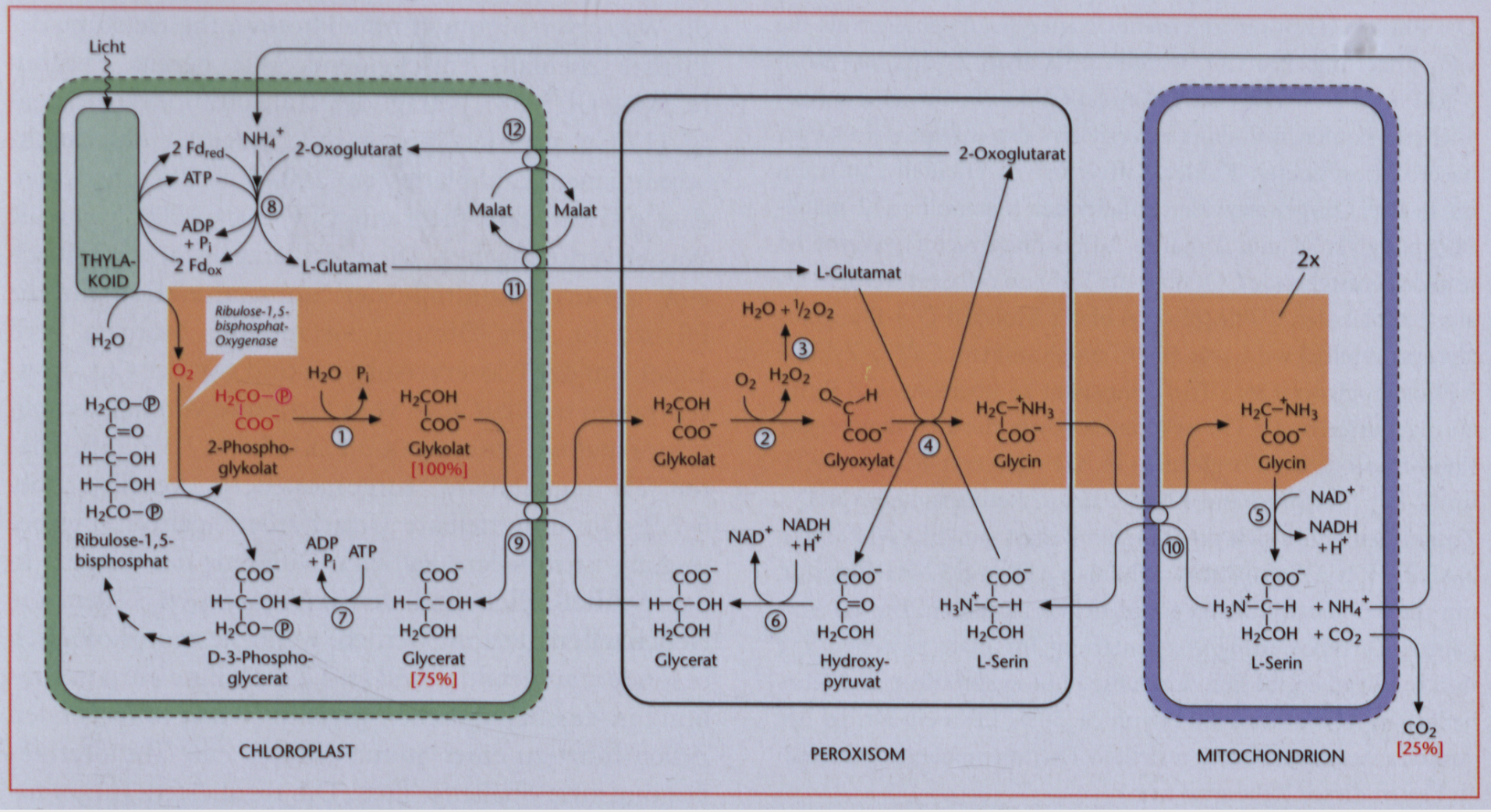


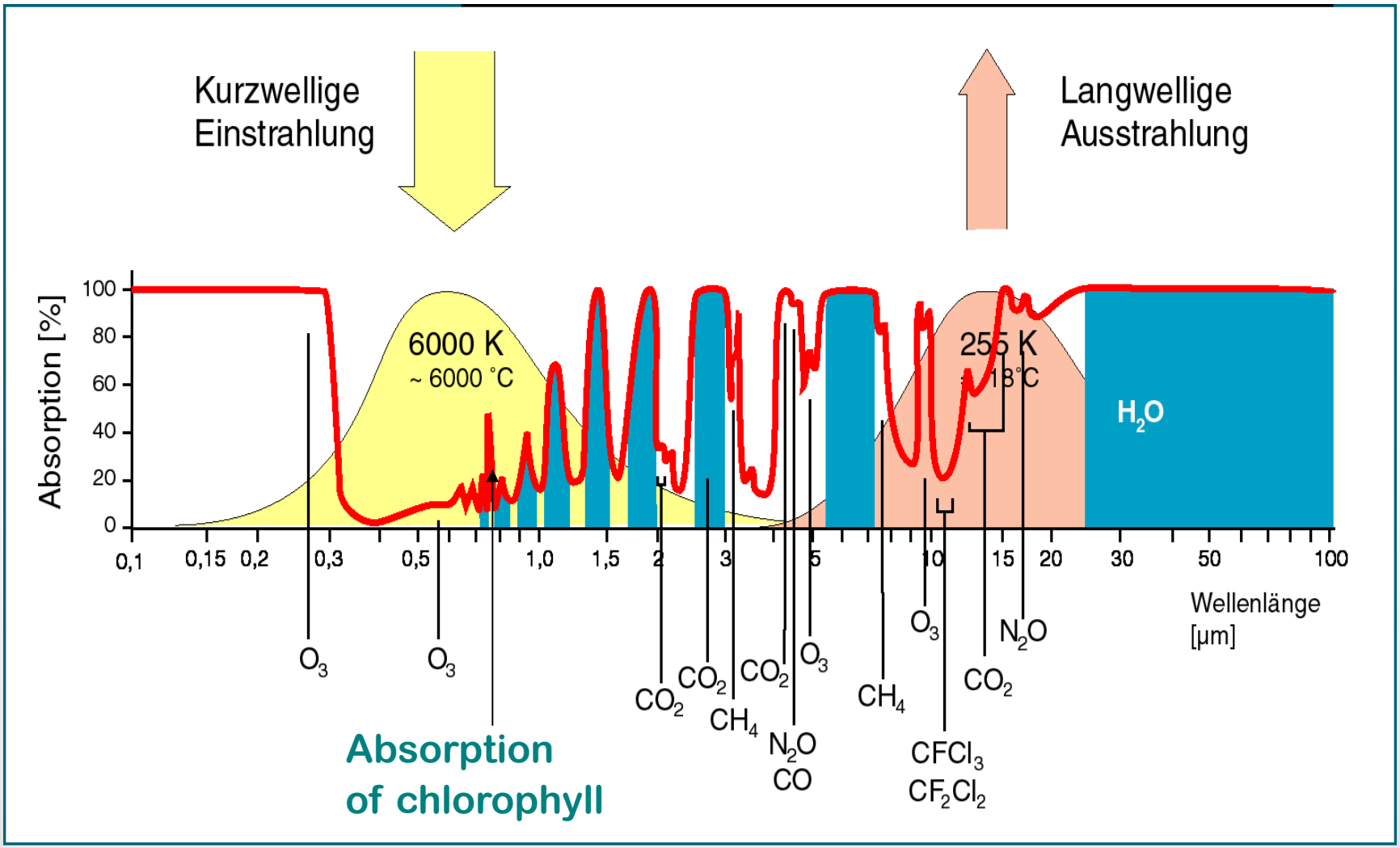
Color chart Ia (cf. page 33): Annual totals of global radiation (GJ m^{-2}). Local differences are mainly due to different latitudes and regionally varying cloud covers. (Adapted from maps in Uchijima and Seino 1987; Kotlyakov et al. 1998)



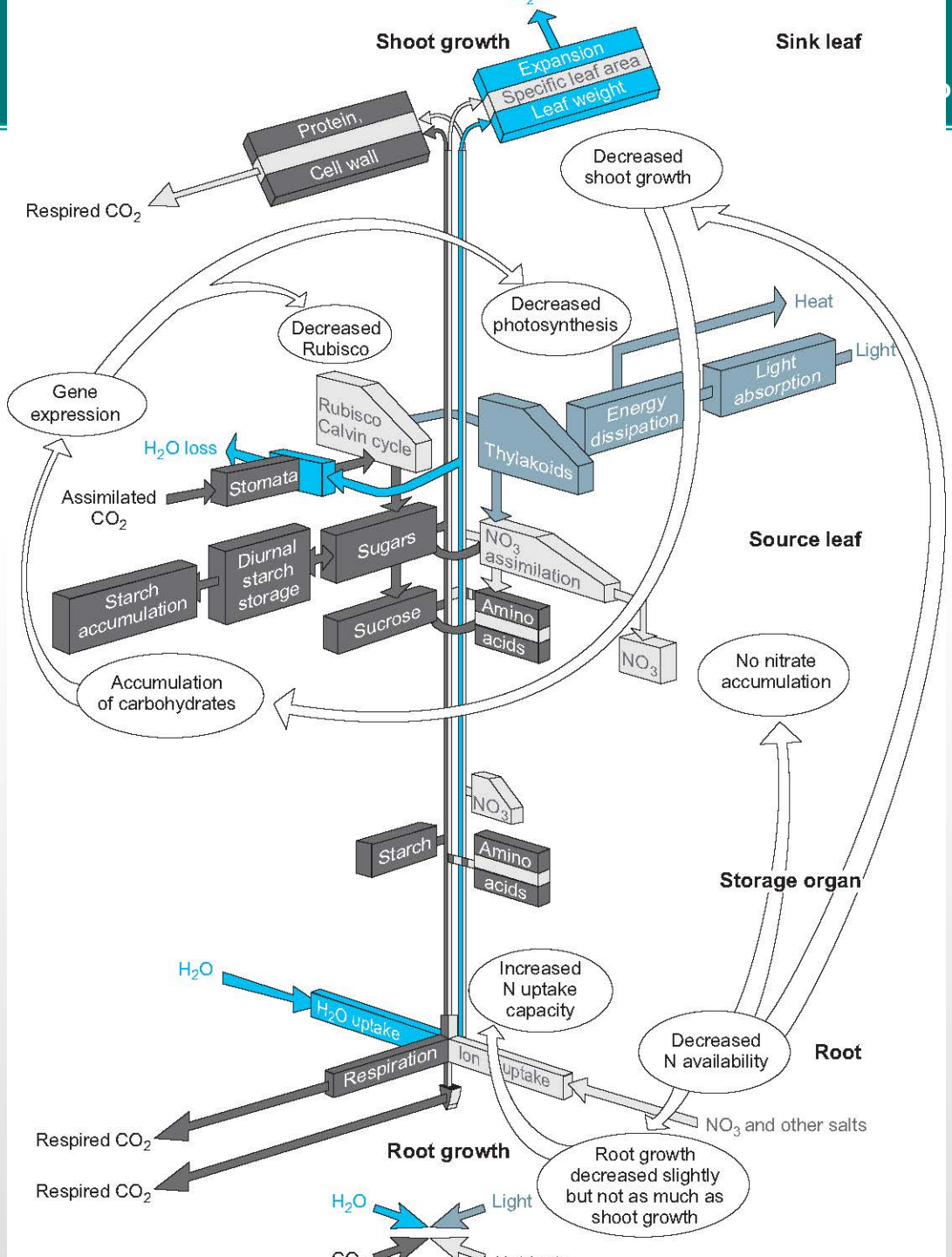
Color chart Ib (cf. page 176): Global distribution of radiation use efficiency of the vegetation. Energy efficiency, i.e. energy content of net primary production, is expressed as percentage of the global annual photosynthetically active radiation. (After Uchijima and Seino 1987)

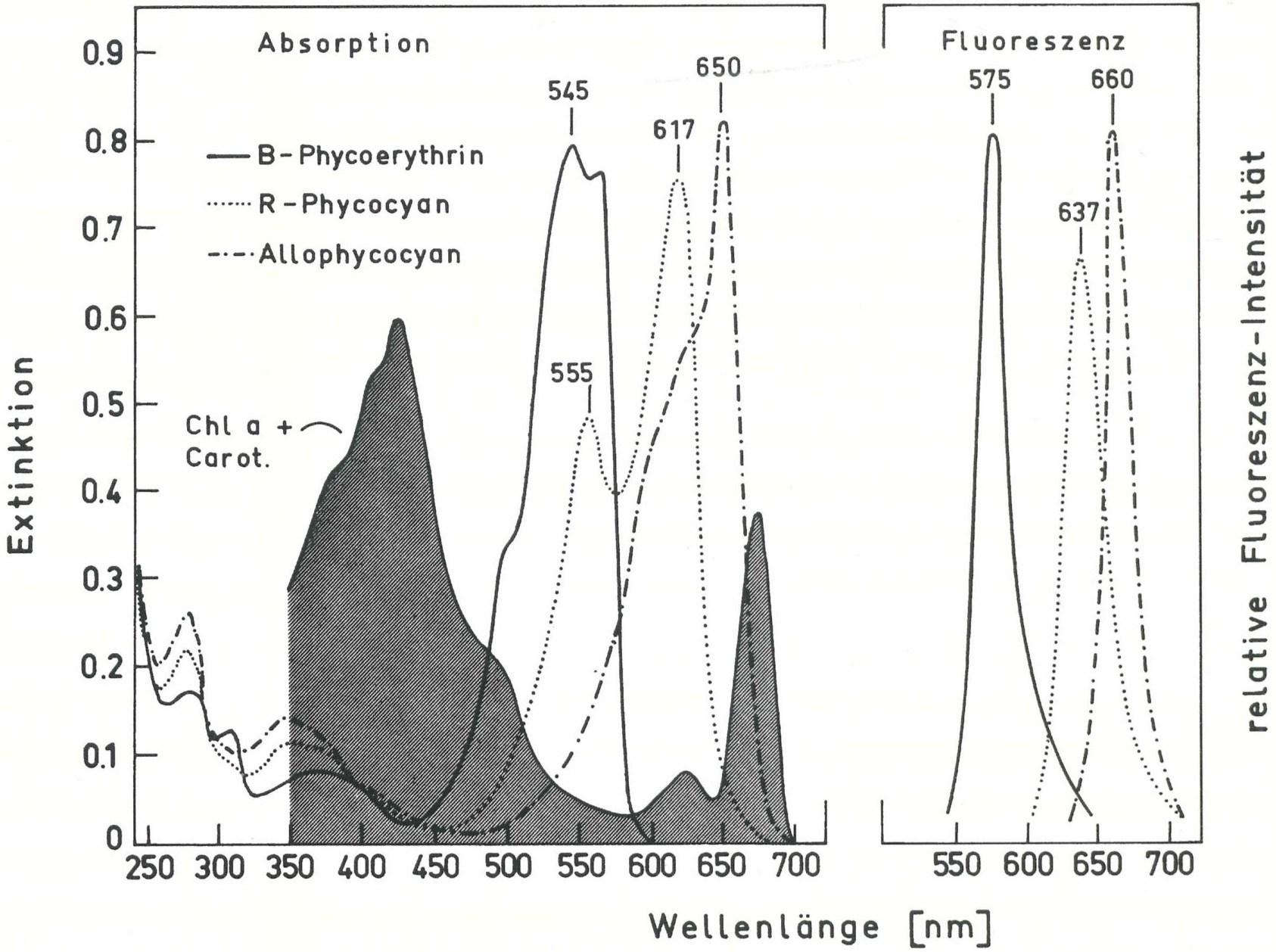
Thanks

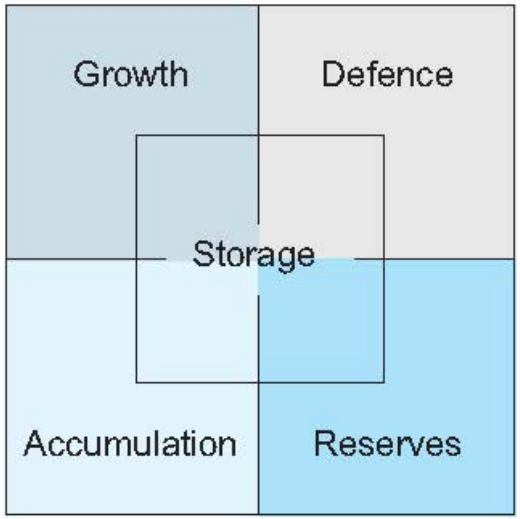

Licht
THYLA-KOID
H_2O
O_2
NH_4^+
2 Fd_{red}
ATP
ADP + P_i
2 Fd_{ox}
2-Oxoglutarat
L-Glutamat
Malat
Malat
Ribulose-1,5-bisphosphat-Oxygenase
H_2O P_i
2-Phospho-glykolat
Glykolat [100%]
Ribulose-1,5-bisphosphat
ADP + P_i
ATP
D-3-Phospho-glycerat
Glycerat [75%]
CHLOROPLAST
2-Oxoglutarat
L-Glutamat
$H_2O + ½ O_2$
O_2 H_2O_2
Glykolat
Glyoxylat
Glycin
NAD+ NADH + H^+
Glycerat
Hydroxy-pyruvat
L-Serin
PEROXISOM
2x
Glycin
NAD+ NADH + H^+
L-Serin
NH_4^+
CO_2
CO_2 [25%]
MITOCHONDRION
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫



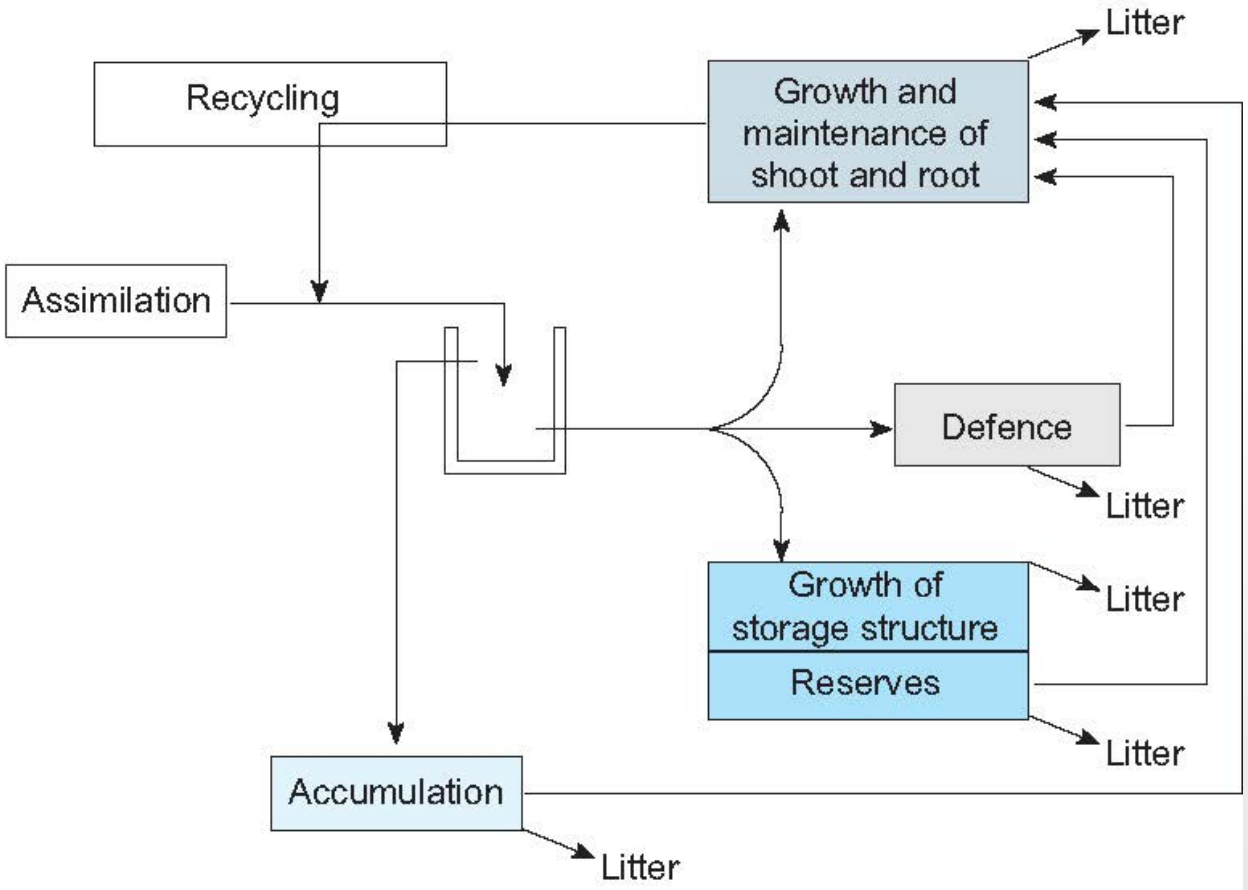
Nach WBGU Jahresgutachten 1997, S. 61


Shoot growth
Sink leaf
Expansion
Specific leaf area
Leaf weight
Protein
Cell wall
Respired CO_2
Decreased shoot growth
Decreased photosynthesis
Heat
Light
Light absorption
Energy dissipation
Decreased Rubisco
Gene expression
Rubisco Calvin cycle
Thylakoids
H_2O loss
Stomata
Assimilated CO_2
Sugars
Diurnal starch storage
Starch accumulation
NO_3 assimilation
Amino acids
Sucrose
Source leaf
NO_3
No nitrate accumulation
Accumulation of carbohydrates
NO_3
Starch
Amino acids
Storage organ
H_2O
H_2O uptake
Increased N uptake capacity
Respiration
Ion uptake
Decreased N availability
Root
NO_3 and other salts
Respired CO_2
Root growth
Respired CO_2
Root growth decreased slightly but not as much as shoot growth
H_2O
Light

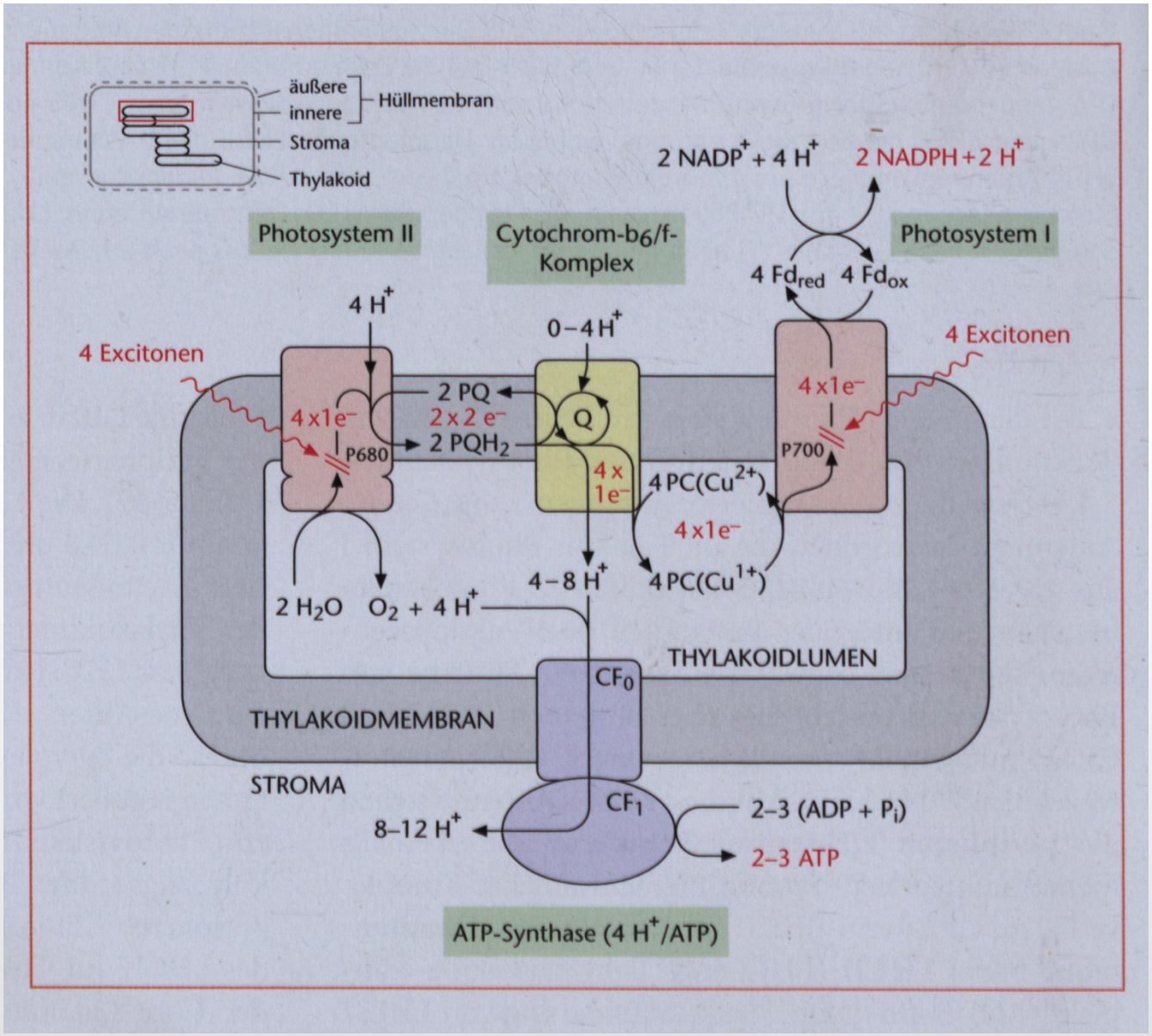

Absorption
Fluoreszenz
B-Phycoerythrin
R-Phycocyan
Allophycocyan
Chl a +
Carot.
545
555
617
650
575
637
660
Extinktion
relative Fluoreszenz-Intensität
Wellenlänge [nm]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
250 300 350 400 450 500 550 600 650 700
550 600 650 700


Growth
Defence
Storage
Accumulation
Reserves

A


Litter
Recycling
Growth and maintenance of shoot and root
Assimilation
Defence
Litter
Growth of storage structure
Litter
Reserves
Litter
Accumulation
Litter

B



Ingredients:

- A membrane for charge separation
- A number of redox systems for electrontransfer and storage as NADP-H and ATP
- 8 photones:
  4 at 680 nm,
  4 at 700 nm
- Efficiency 36%

PQ Plastochinone
PC Plastocyanine
Fd Ferredoxine