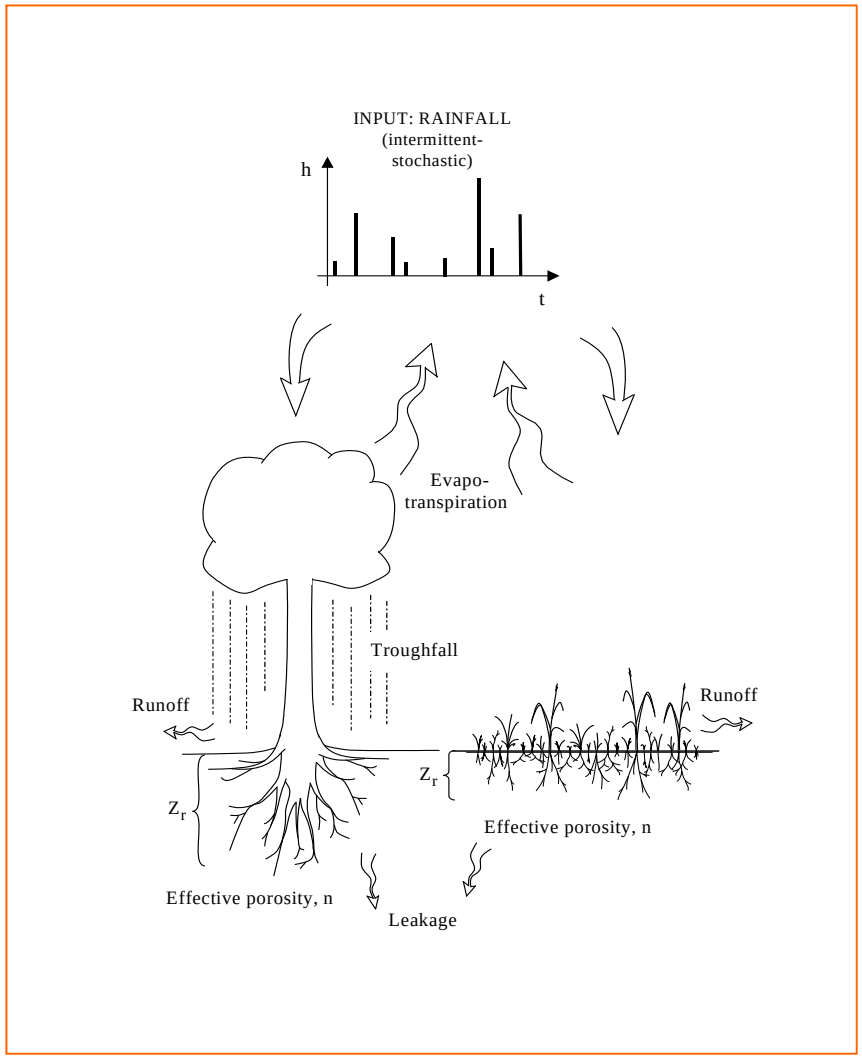
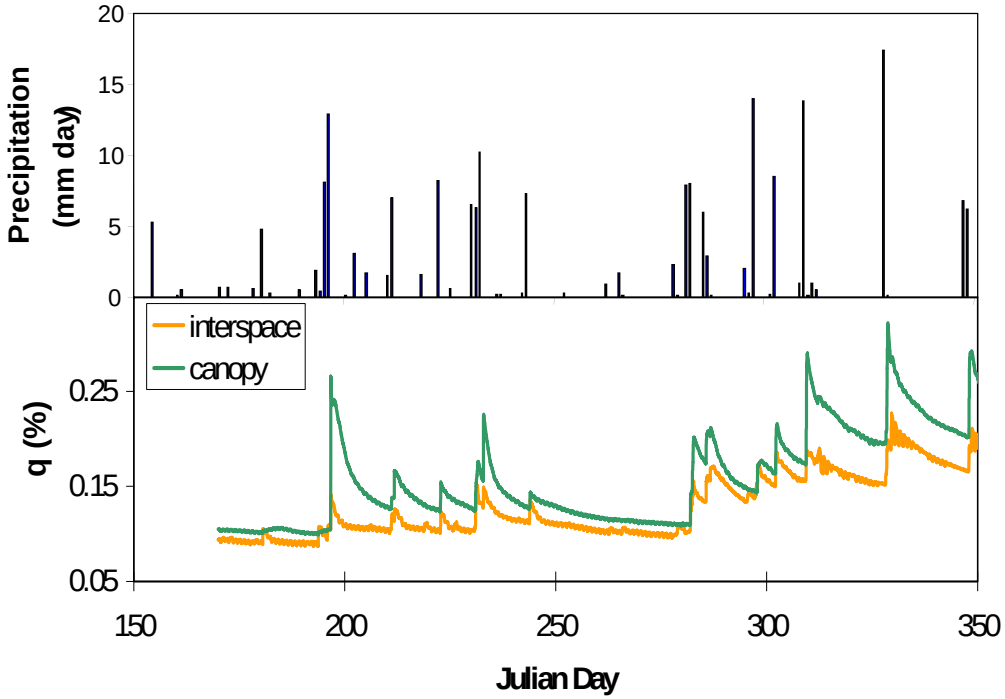
On the Active Role of Plants on Land-Atmosphere Processes

Amilcare Porporato

Duke University

From stochastic rainfall to soil moisture dynamics and plant water stress





Sevilleta, NM

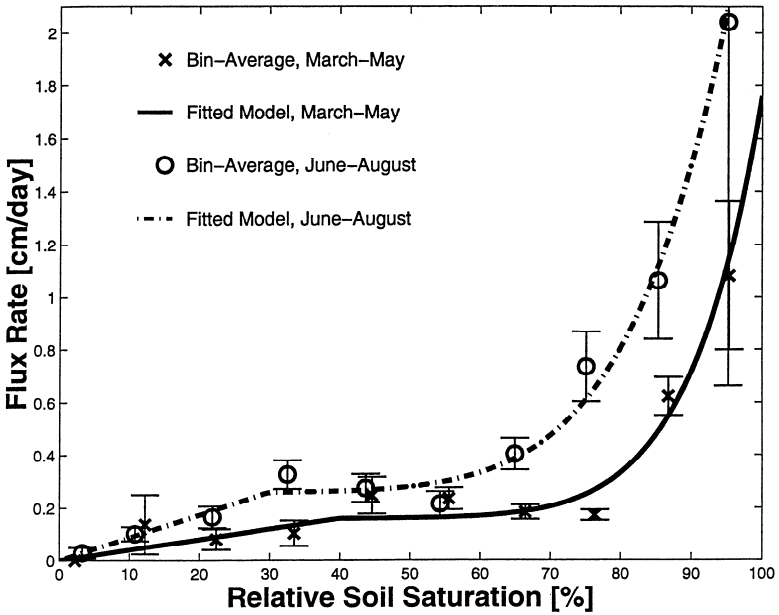
Courtesy of Eric Small

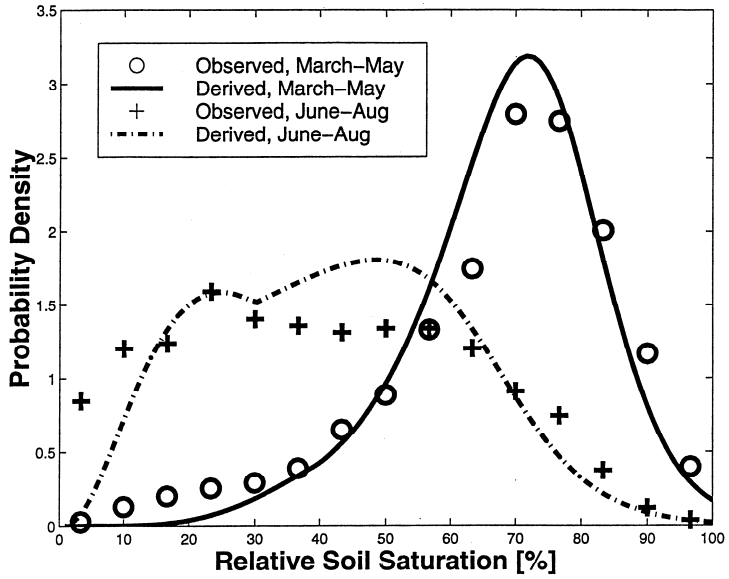
Soil Moisture PDF: climate soil and vegetation

$$p(s) = \frac{c}{\rho(s)} Exp\left(-\gamma s + \lambda \int_s \frac{du}{\rho(u)} \right)$$

Rodriguez-Iturbe et al., Proc. Royal Soc. A, 455, 3789, 1999
Laio et al. AWR 2001;
Porporato et al. Am. Nat., 2004

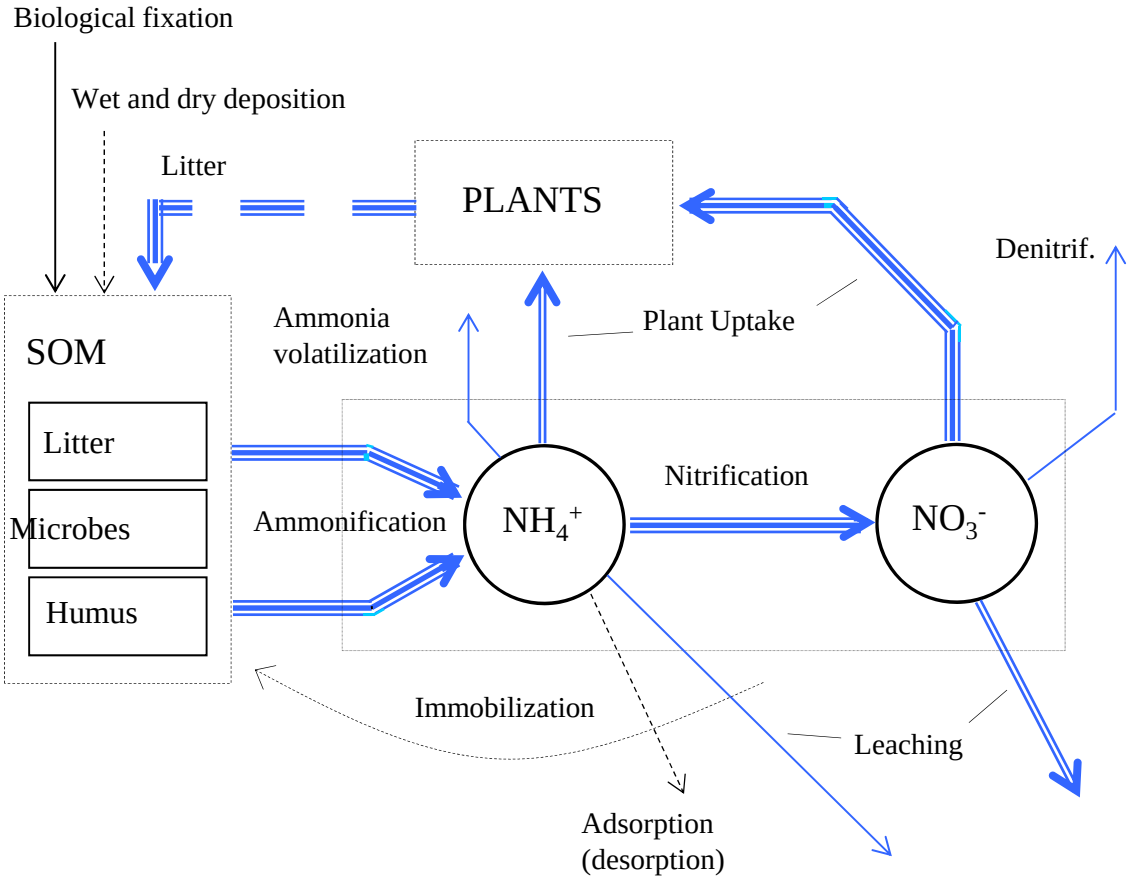
Experimental verification

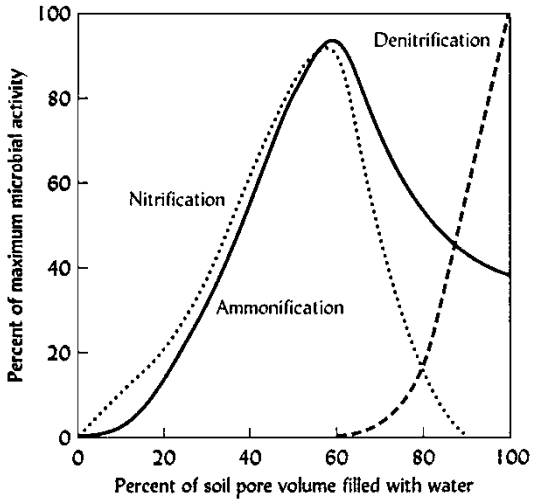




Salvucci G. (2001) Water Resour. Res. 37(5), 1357-1365.

Soil moisture control on C-N cycling

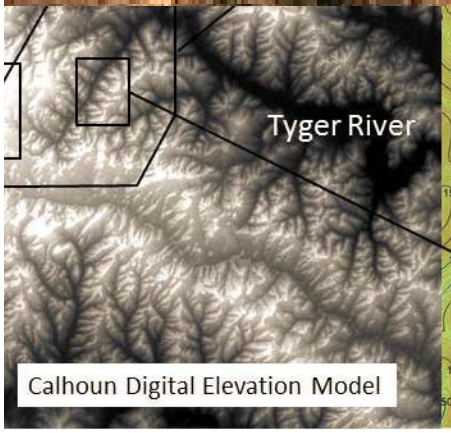


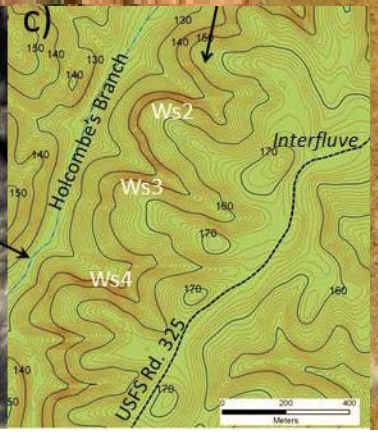


Porporato et al. AWR 2003; Manzoni et al., Science 2008


REYNOLDS
EEL
BOULDER
IML
SHALE HILLS
CHRISTINA
SOUTHERN SIERRA
CATALINA / JEMEZ
CALHOUN
Duke UNIVERSITY
Critical Zone Observatories
Supported by the
National Science Foundation
NSF
LUQUILLO

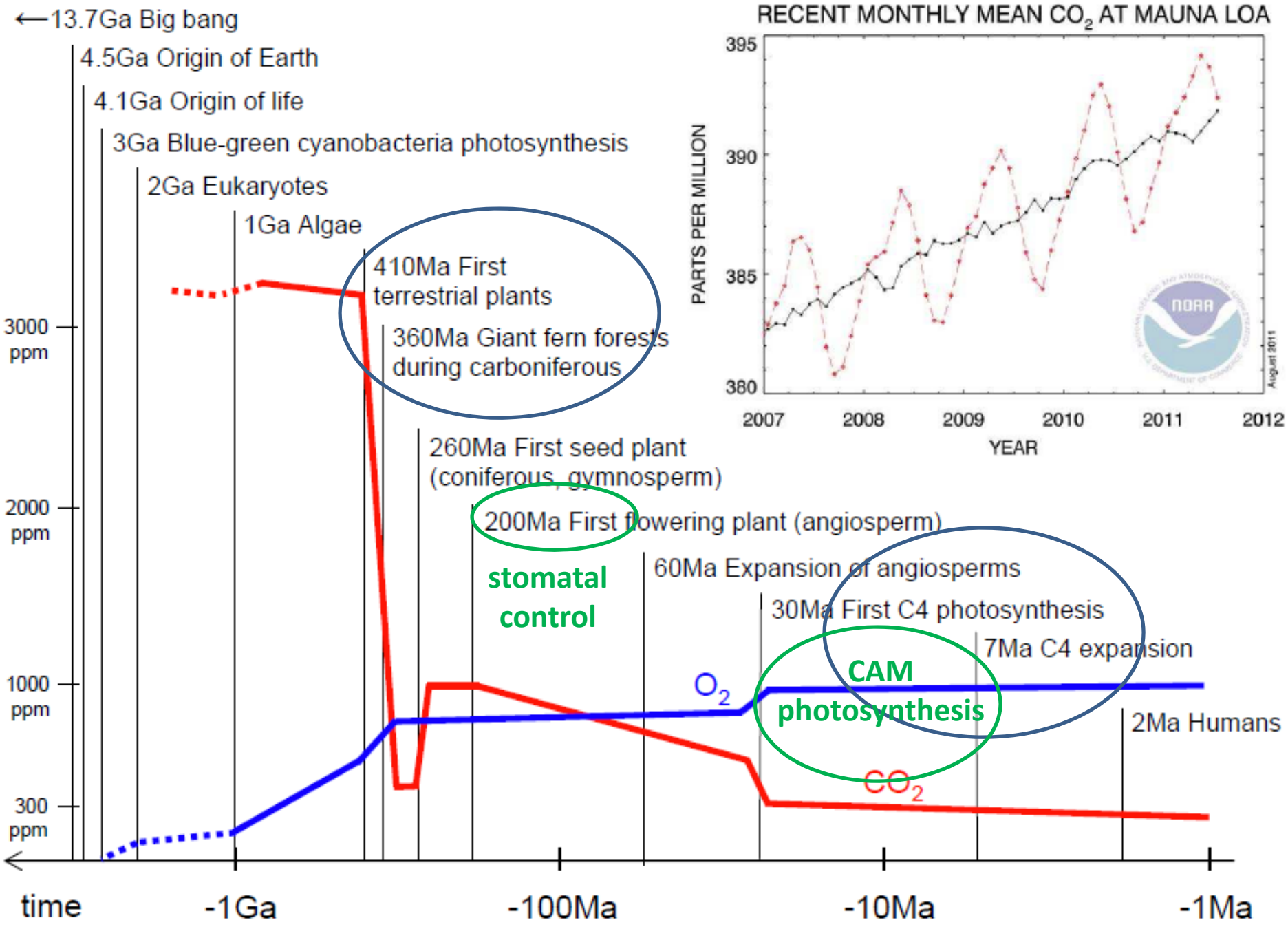

Calhoun, 1950 circa


Tyger River
Calhoun Digital Elevation Model


C)
Holcombe's Branch
Ws2
Interfluve
Ws3
Ws4
USFS Rd. 325

NSF-FESD – frontiers in earth system dynamics

Geo-genomics – geology, eco-hydrology and evolution of biodiversity in the Amazon


←13.7Ga Big bang
4.5Ga Origin of Earth
4.1Ga Origin of life
3Ga Blue-green cyanobacteria photosynthesis
2Ga Eukaryotes
1Ga Algae
410Ma First terrestrial plants
360Ma Giant fern forests during carboniferous
260Ma First seed plant (coniferous, gymnosperm)
200Ma First flowering plant (angiosperm)
60Ma Expansion of angiosperms
30Ma First C4 photosynthesis
7Ma C4 expansion
2Ma Humans
stomatal control
CAM photosynthesis
O_2
CO_2
3000 ppm
2000 ppm
1000 ppm
300 ppm
time
-1Ga
-100Ma
-10Ma
-1Ma
RECENT MONTHLY MEAN CO_2 AT MAUNA LOA
PARTS PER MILLION
395
390
385
380
2007
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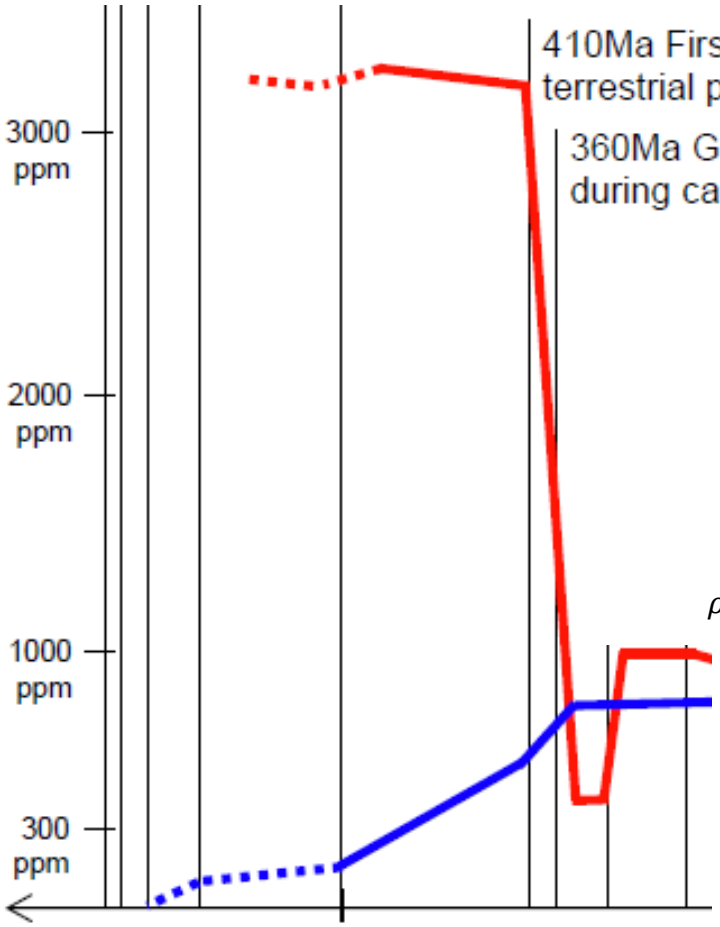
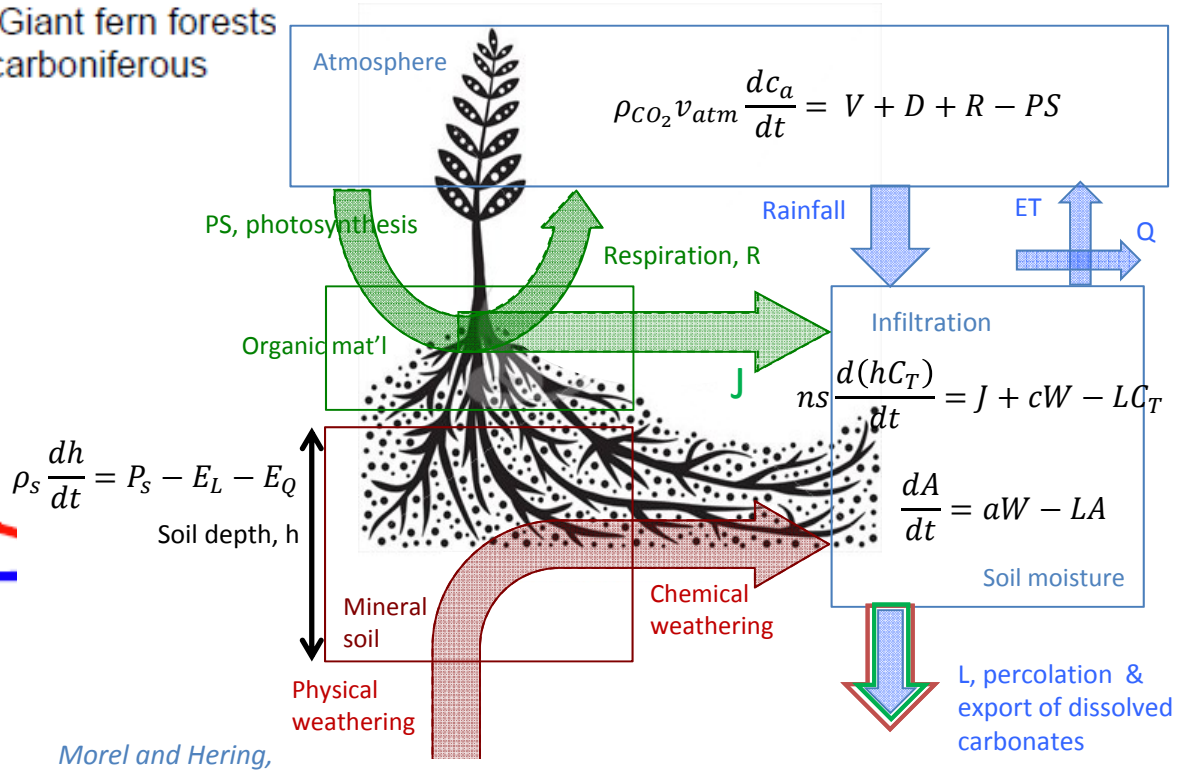
YEAR
NOAA
August 2011

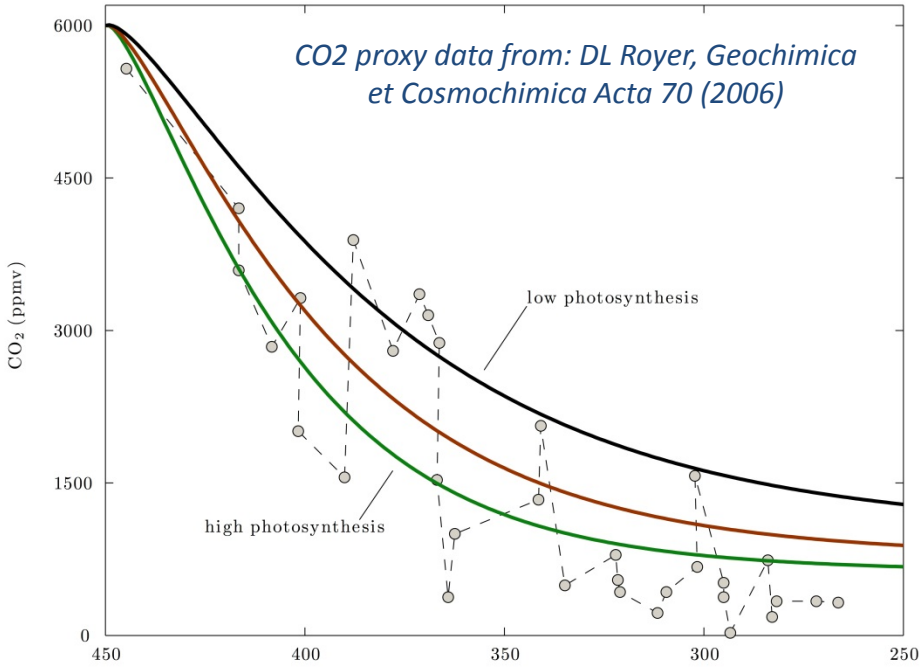
Plants, Leaching & Soil formation

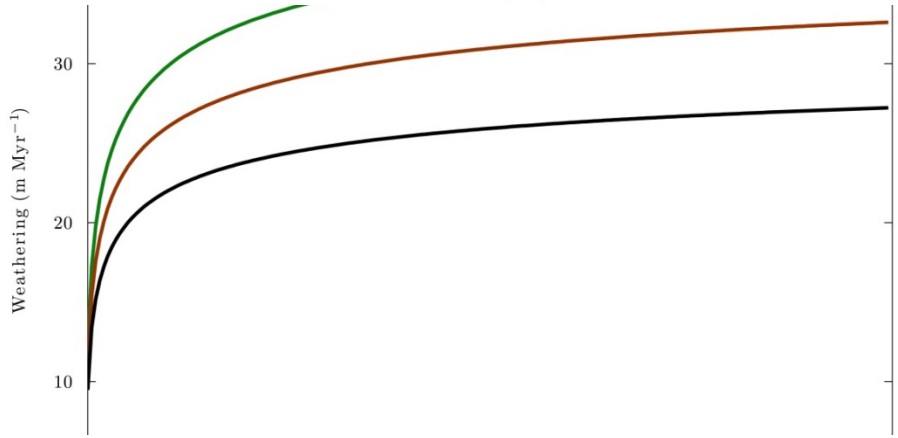
Devoninan (400-360 Ma) and Carboniferous (360-300 Ma)





Simplified model





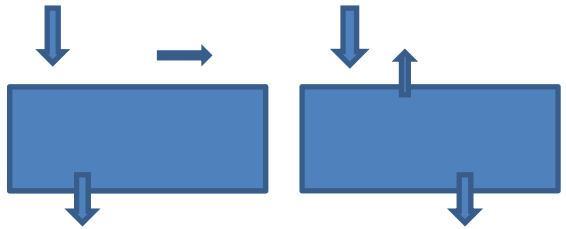
Quasi-steady state assumptions in the soil solution

$$\eta \frac{dc_a}{dt} = V + D(c_a, c_g) + R_a[b(h)] - PS[b(h)]$$

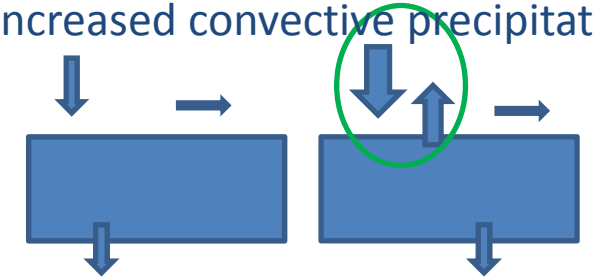
$$\rho_s \frac{dh}{dt} = P_s - c_{sus} RO - MW_{min} \frac{L}{a} \cdot A\left[C_T\left(b(h)\right)\right]$$

we know that L decreases with h …

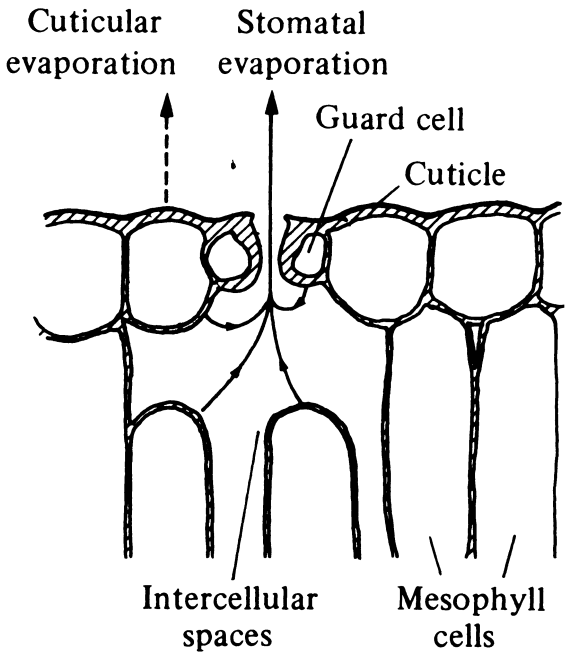
→ increased infiltration?



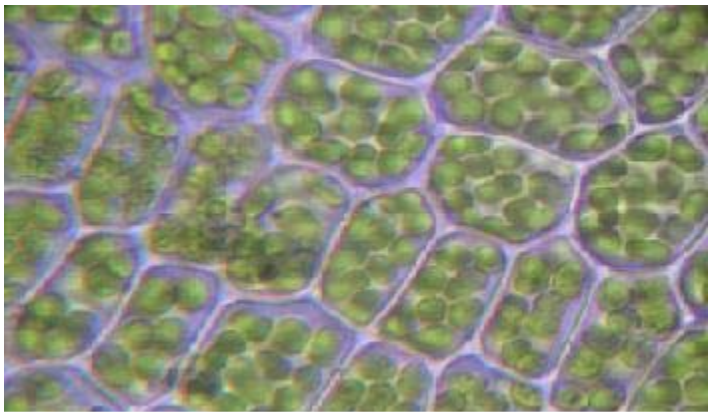
→ Increased convective precipitation?



Ecohydrology and photosynthetic pathways

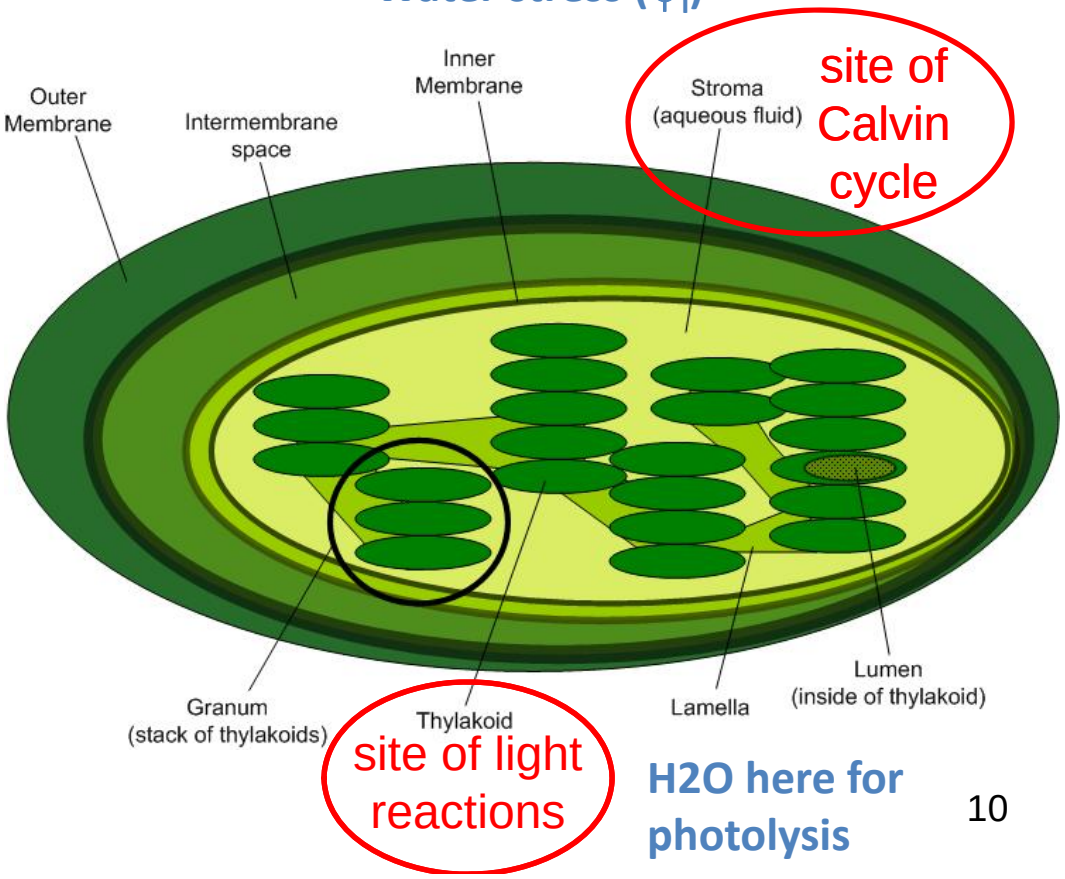


Chloroplasts in the mesophyll



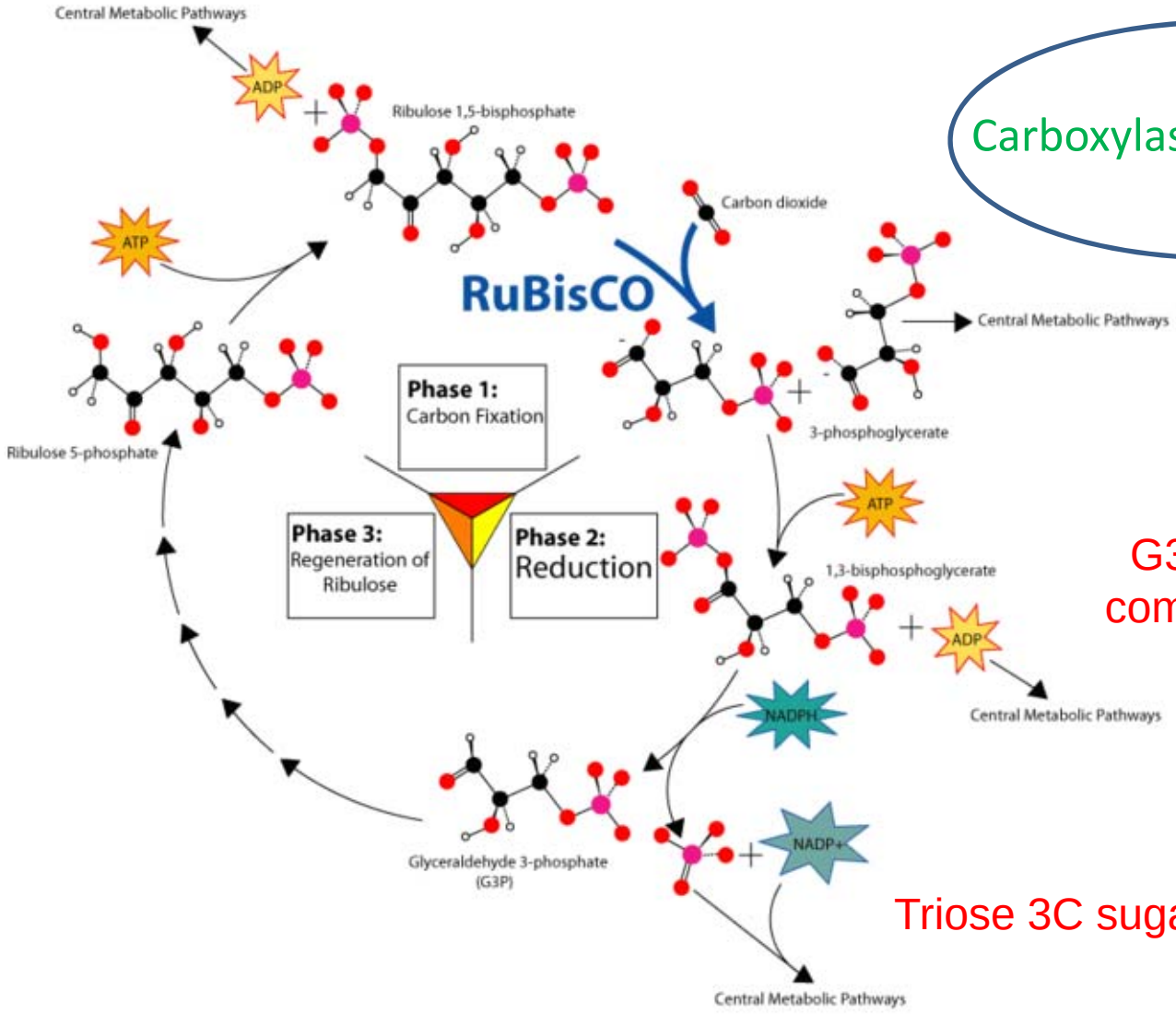
Water stress function on Farquhar's model of photosynthesis only in 2004:
Daly et al. JHM (2004)
Tuzet et al. PCE (2004)

Water stress (ψ_l)



H2O here for photolysis

C3 photosynthesis – Calvin cycle: a chemical engine to produce sugar

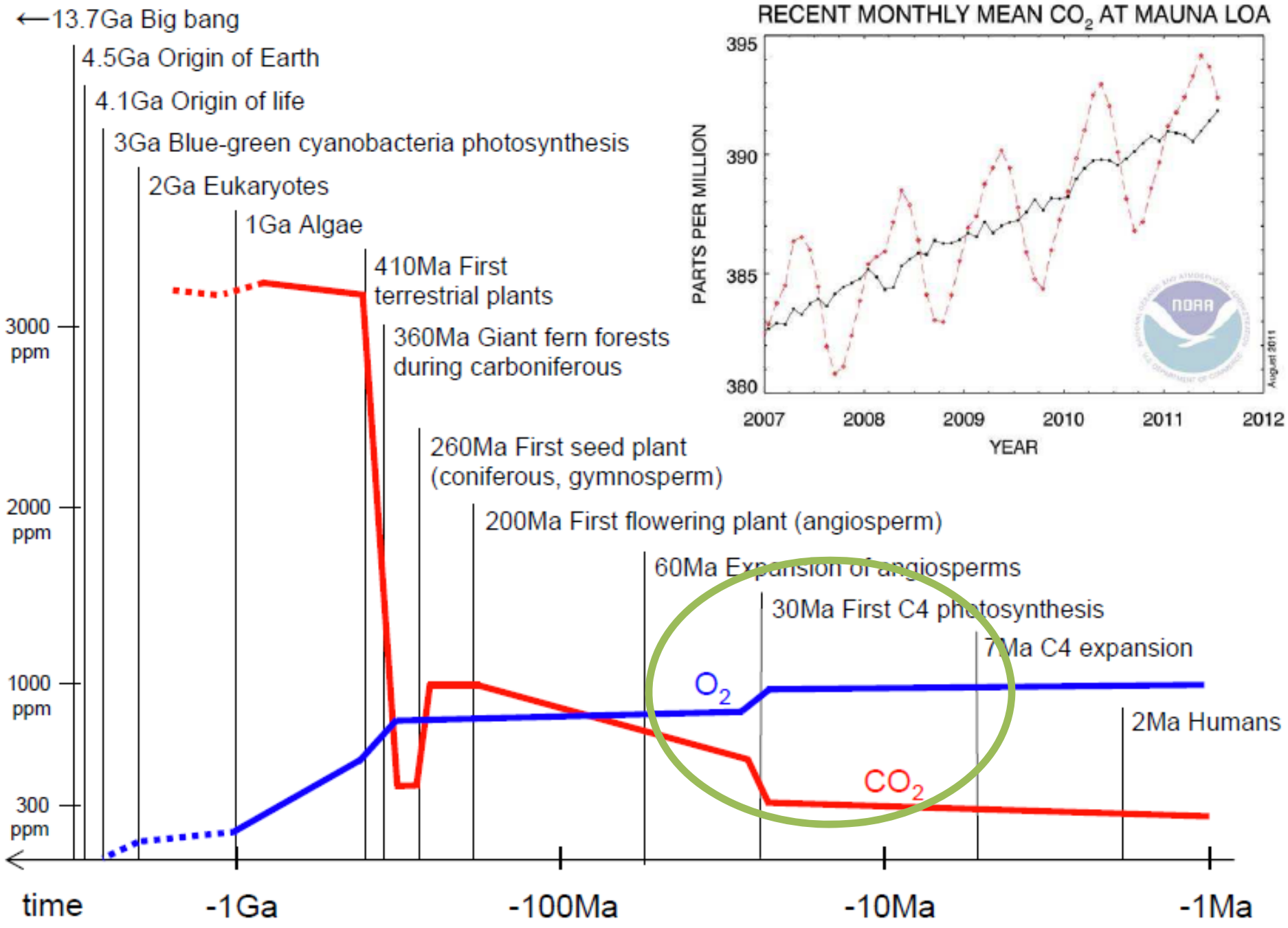


Carboxylase/Oxygenase

…

G3P 3C compound

Triose 3C sugar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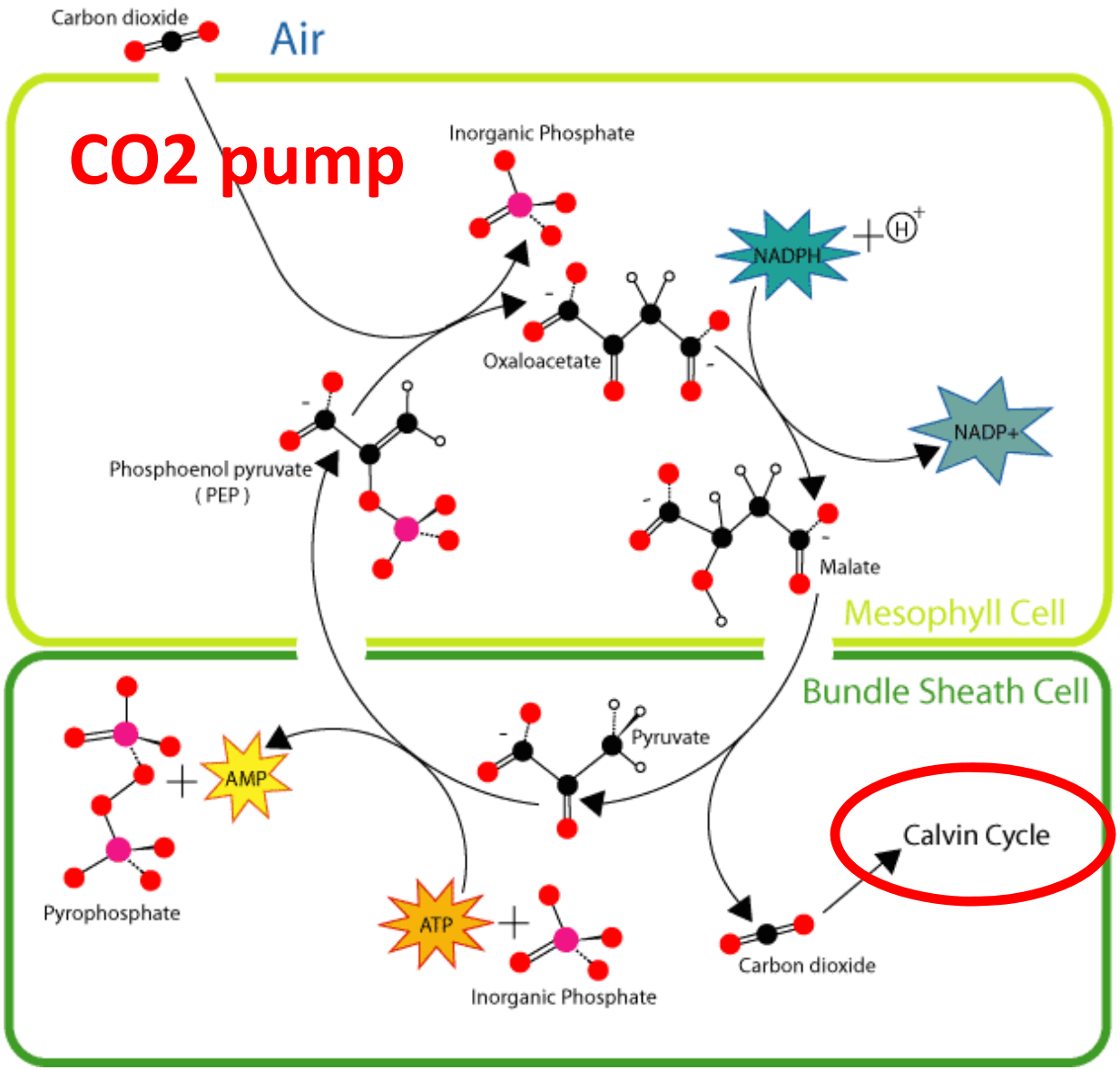
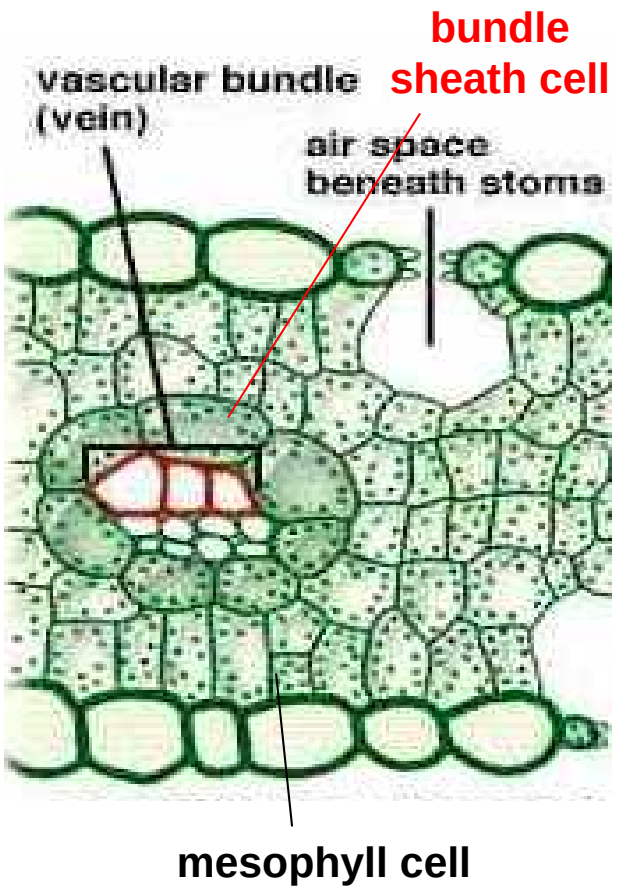
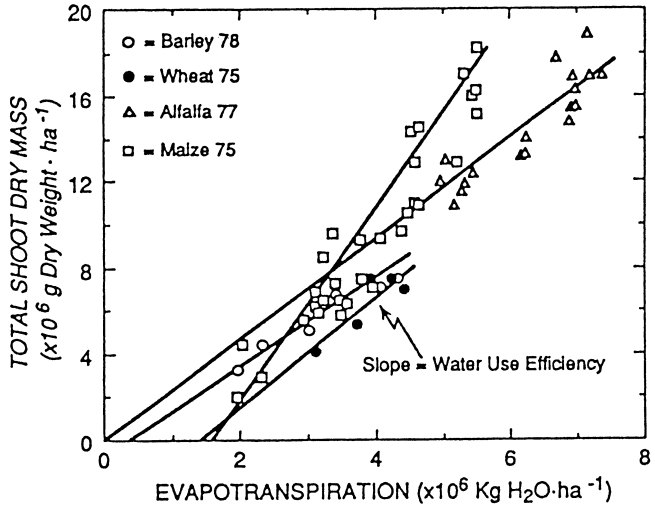
C4 photosynthesis: Krantz anatomy



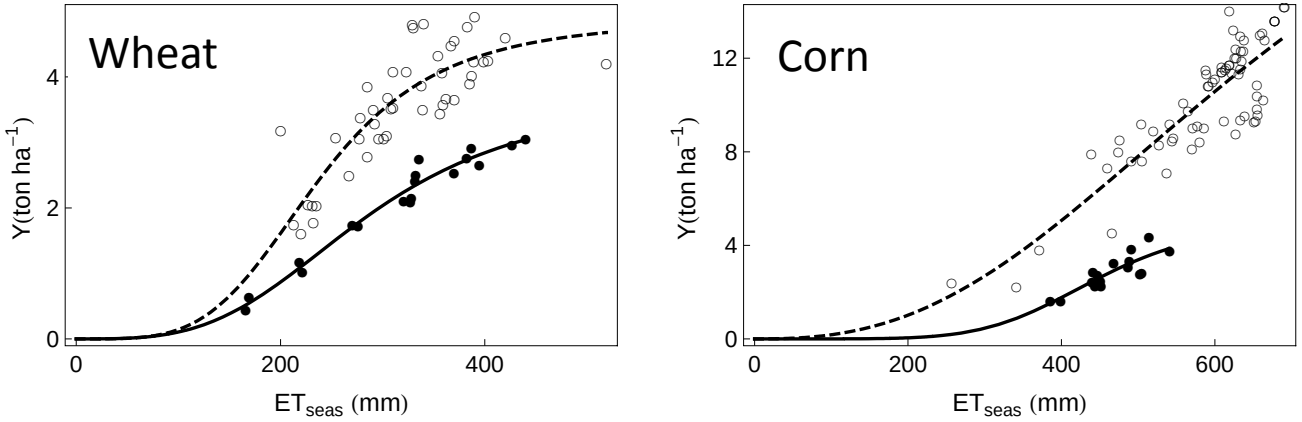


greater WUE



Kramers and Boyer 1995

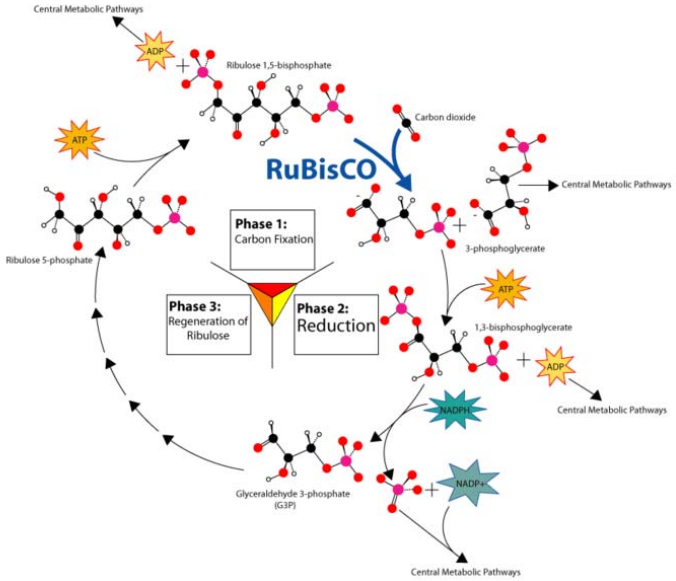
very productive crops with water and energy availability

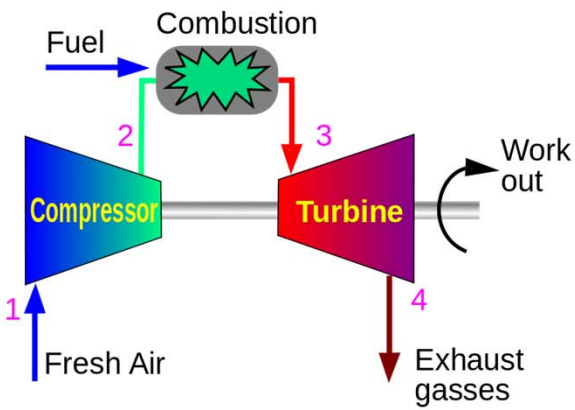


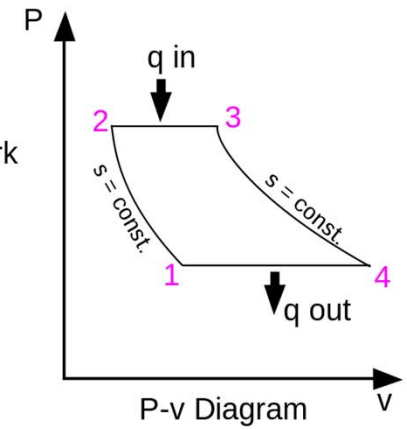
Vico and Porporato, AWR (2012)

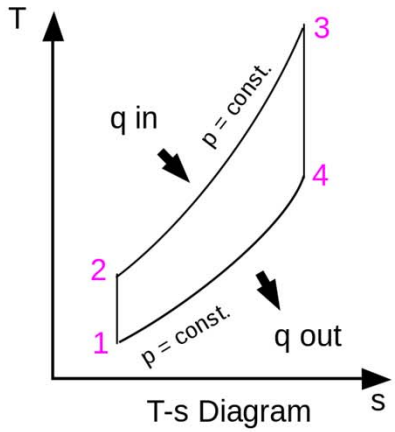
A curious analogy…

CO2 pump

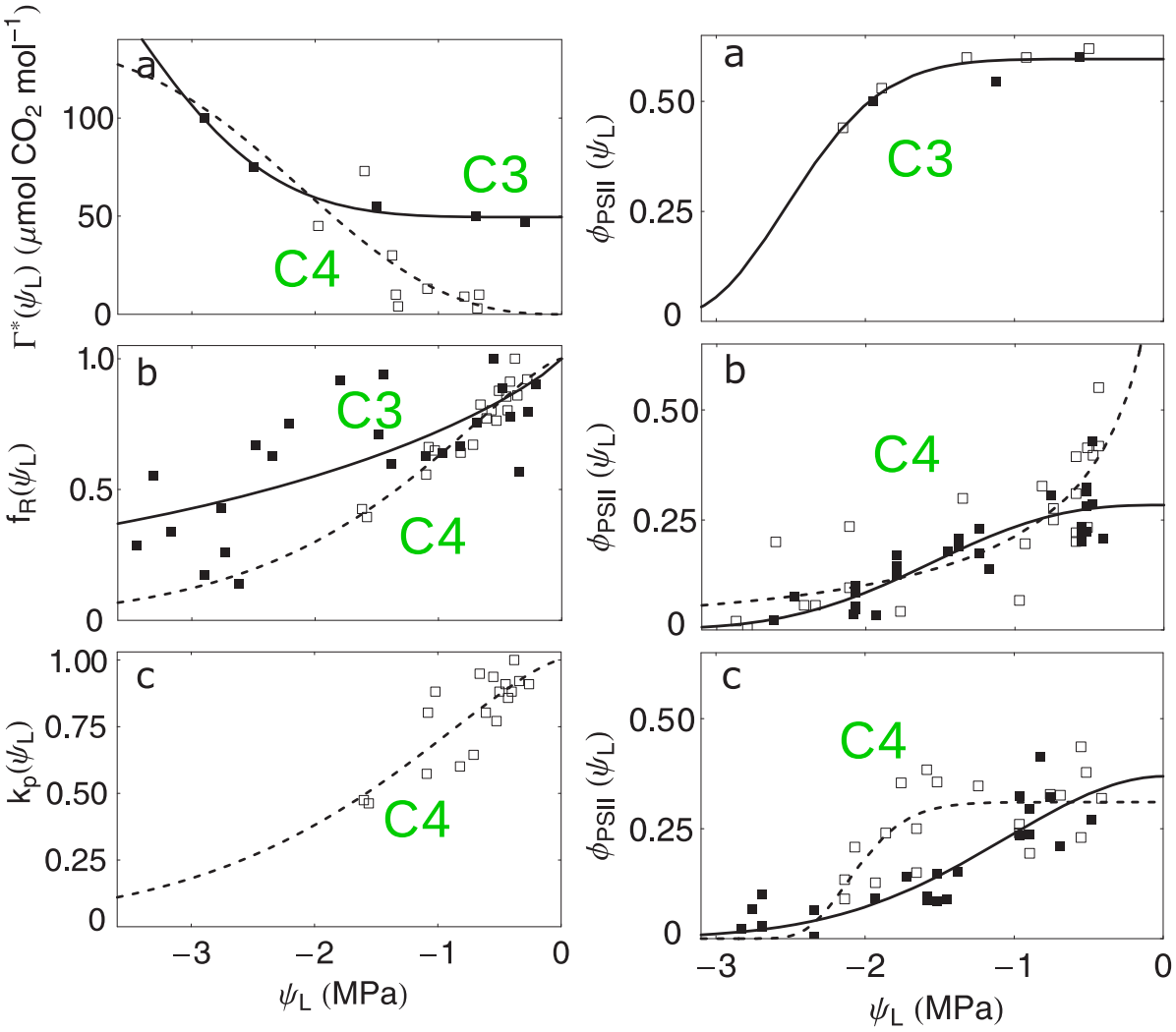






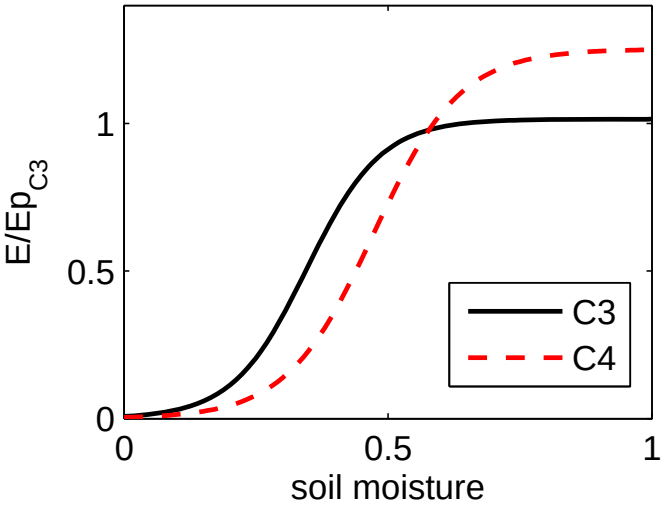


But C4 is more sensitive to water stress



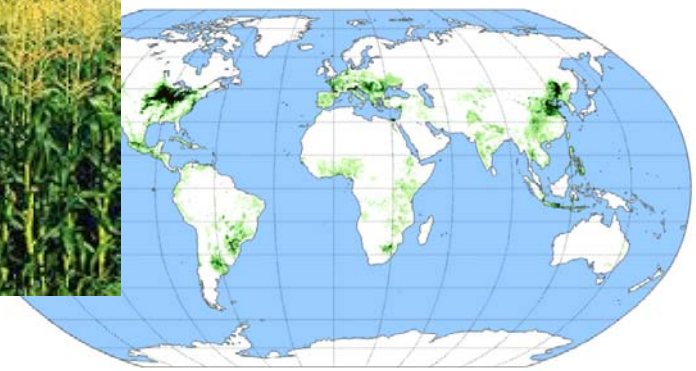
Weibull-type vulnerability curve

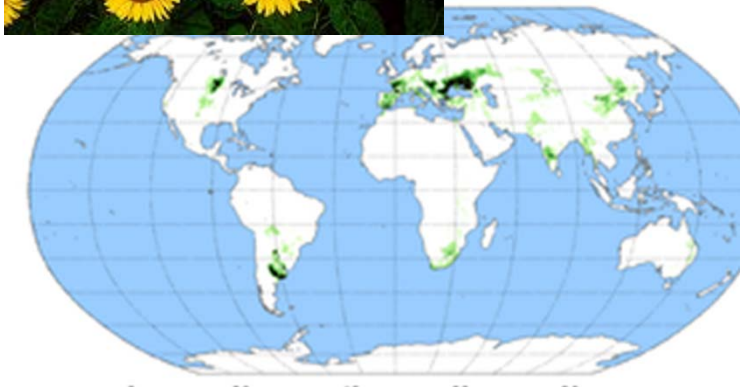
$$f(\psi_l) = a\,Exp\left[-\left(\frac{-\psi_l}{d}\right)^c\right]$$



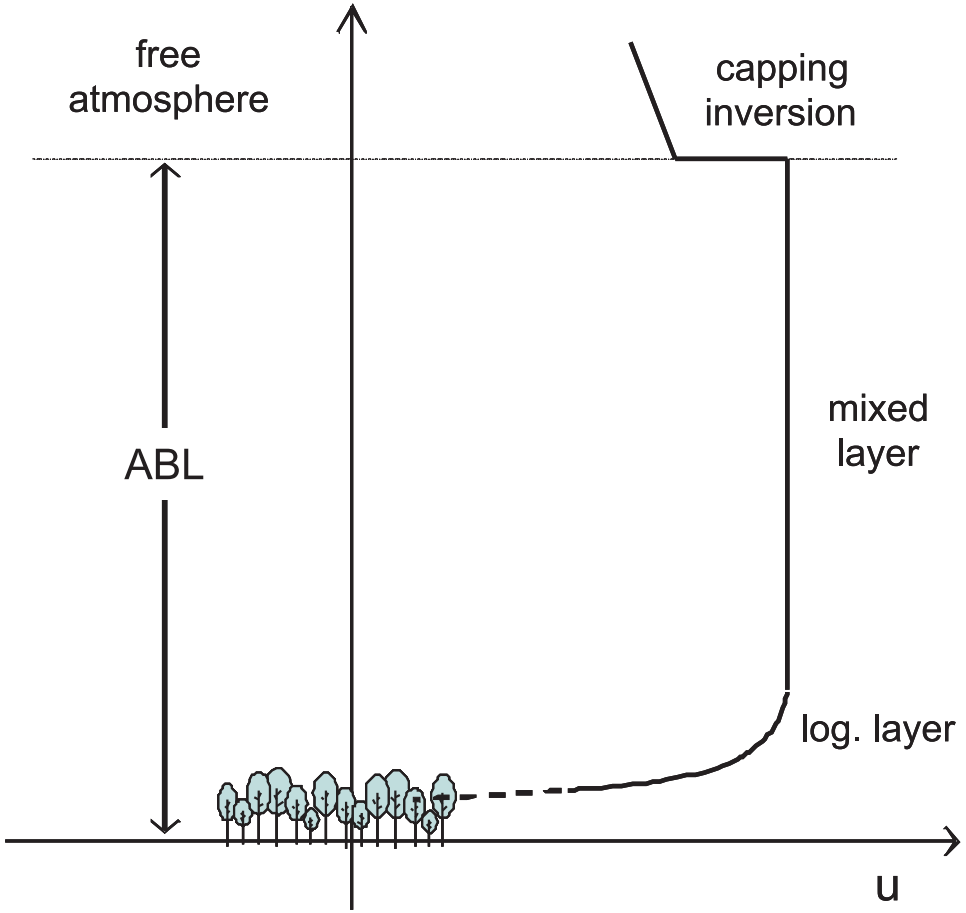
Vico and Porporato, C3 and C4 photosynthesis under-water stressed conditions, Plant and soil (2008)

Largescale land-atmosphere feedback?





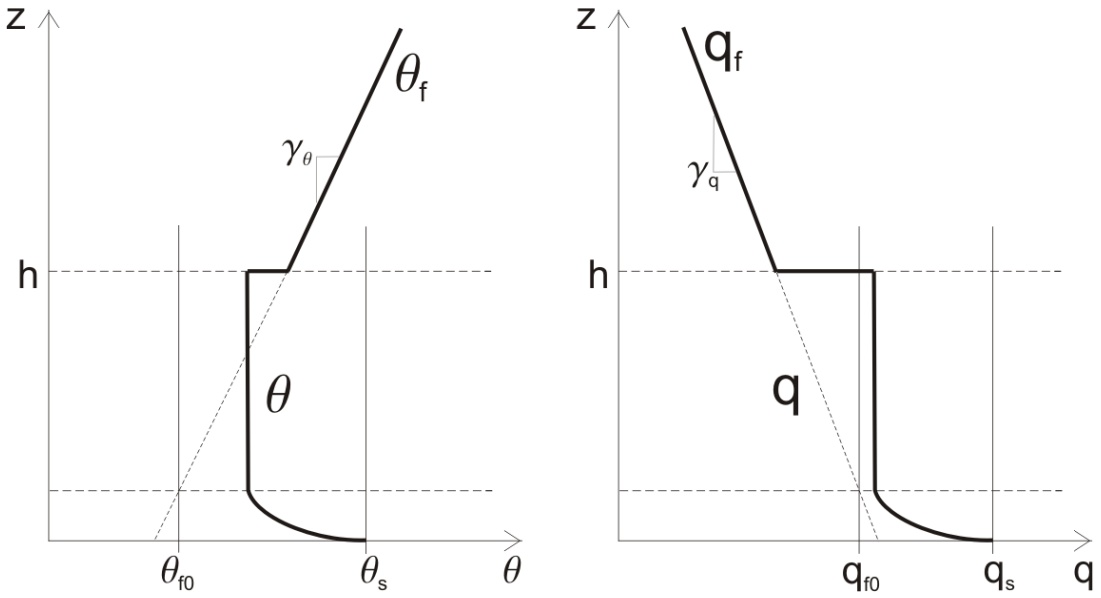
ABL development and convective precipitation



as the ABL grows, the conditions for convective precipitation:

1) LCL crossing
2) CAPE>400

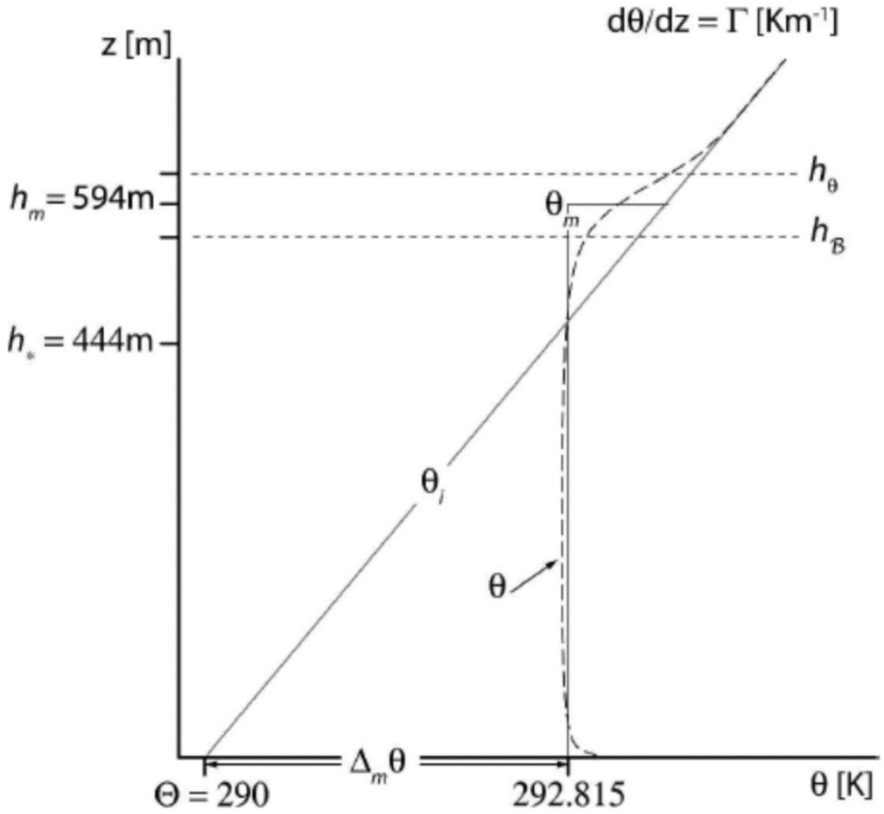
Slab or mixed-layer models of the ABL



- Idealized ABL
  - Hydrostatic atmosphere
  - Homogeneous horizontal conditions
  - Well-mixed vertically (instantaneous)
  - Zero-order “jump” at capping inversion
  - No latent heat release
- Simplified profiles/geometry
  - Constant in mixed layer
  - Linear in free atmosphere

It is a good approximation ☺:
e.g., Large Eddy Simulation of ABL

after Stevens – J. Atm. Sci. (2007)



– Surface energy balance:

$$H = \rho c_p g_a (\theta_0 - \theta_a)$$

$$\rho_w E = \rho \frac{g_s g_a}{g_s + g_a} (q_i - q_a)$$

$$Q_n = H + \rho_w \lambda_w E$$

– Conservation equations in the mixed layer:

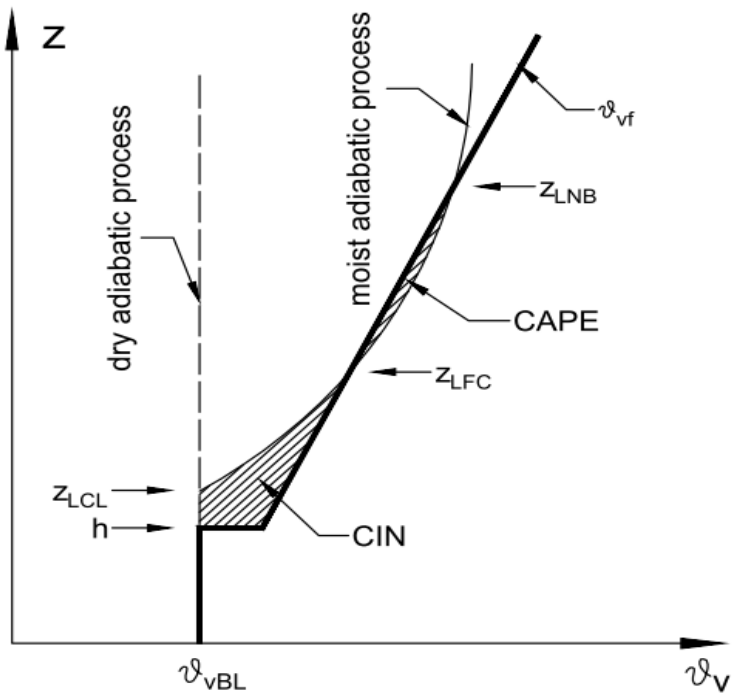
$$\rho c_p h \frac{d\theta}{dt} = H + \rho c_p (\vartheta_f - \vartheta) \frac{dh}{dt}$$

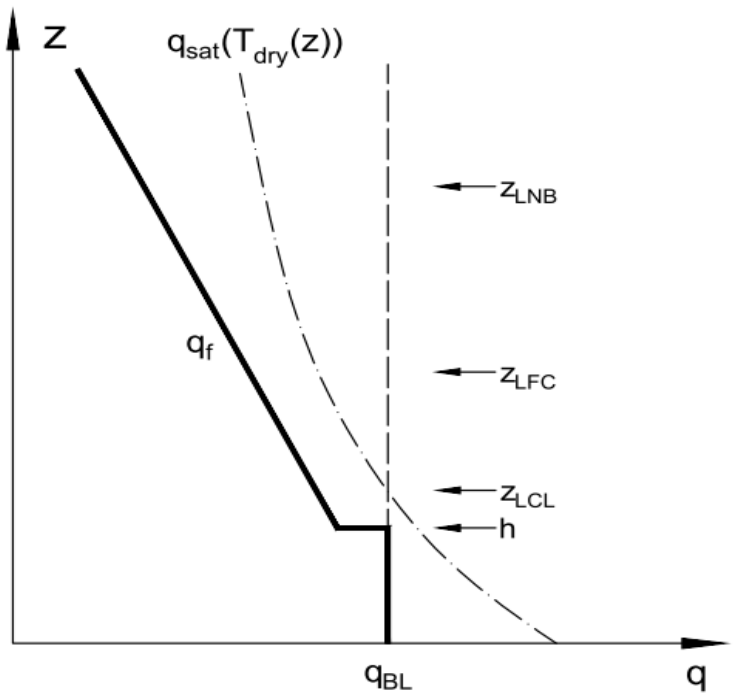
$$\rho h \frac{dq}{dt} = \rho_w E + \rho (q_f - q) \frac{dh}{dt}$$

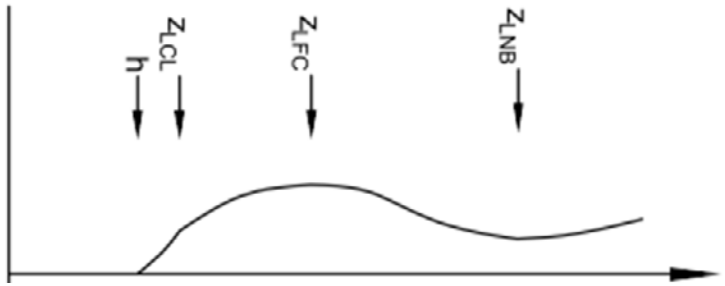
$$\frac{dh}{dt} = \frac{(1+2\beta)H}{\rho c_p \gamma_\vartheta h}$$

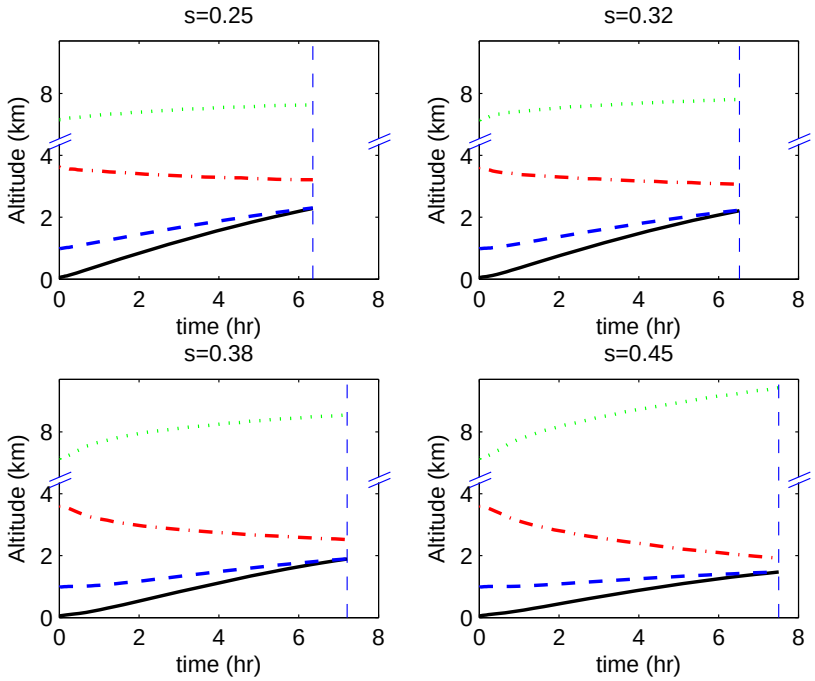
e.g., Garrett 1994

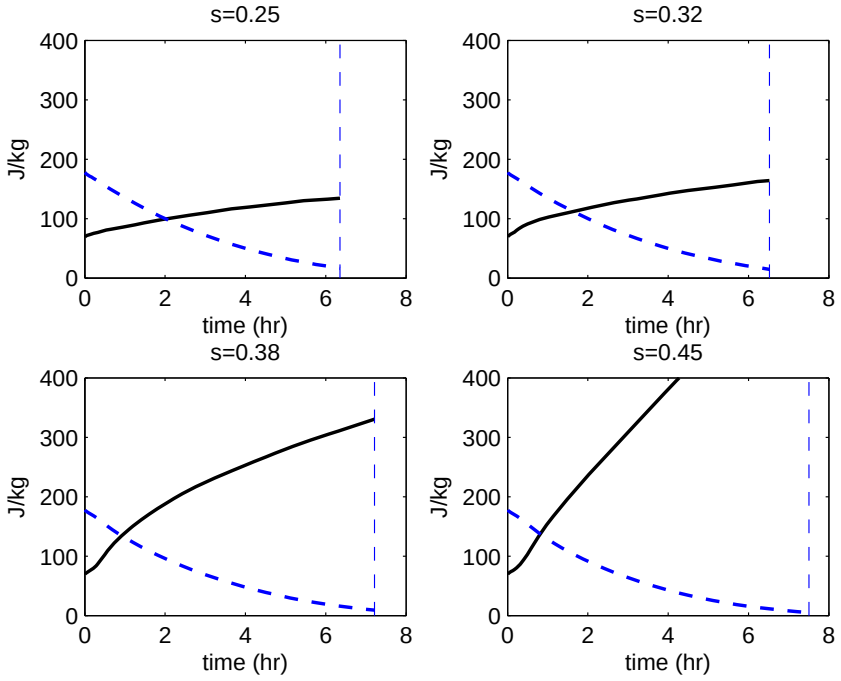
Porporato BLM 2009

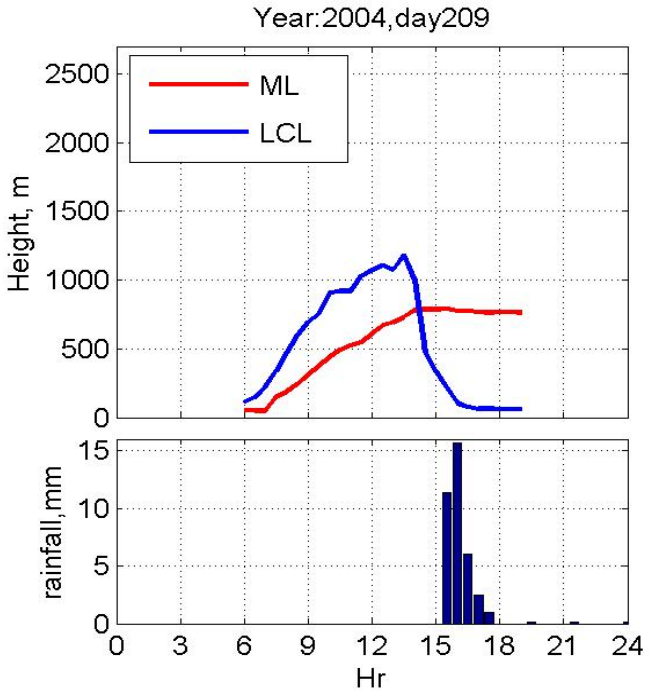

z
dry adiabatic process
moist adiabatic process
ϑ_{vf}
z_{LNB}
CAPE
z_{LFC}
z_{LCL}
h
CIN
ϑ_{vBL}
ϑ_v


z
$q_{sat}(T_{dry}(z))$
z_{LNB}
q_f
z_{LFC}
z_{LCL}
h
q_{BL}
q


z_{LCL}
h
z_{LFC}
z_{LNB}



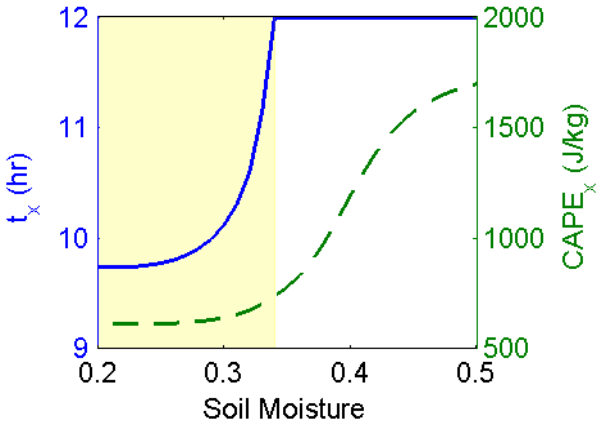




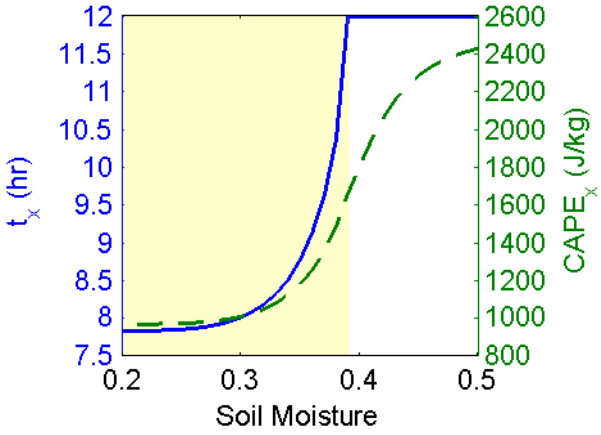
Yin et al. (in preparation)

Huang et al. WRR (2007)

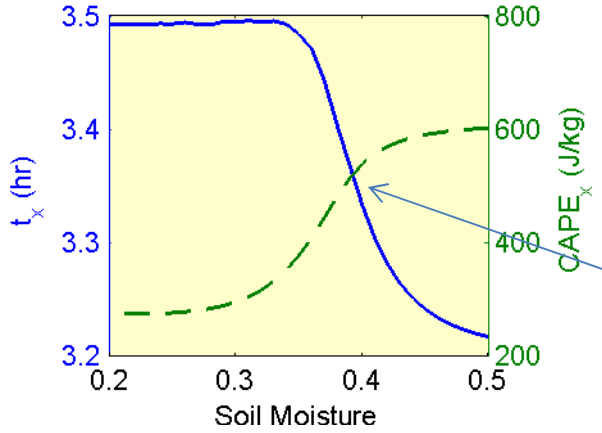
(A)
Dry soil
advantage
regime



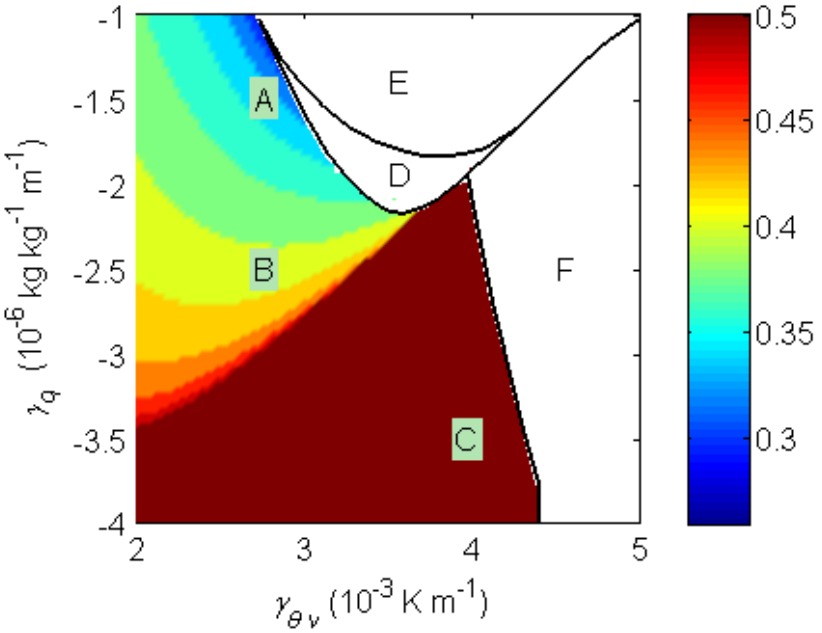
(B)
Transitional
regime



(C)
Wet soil
advantage
regime



(E) No crossing
(D & F) LCL crosses at certain soil conditions but CAPE<400J/Kg



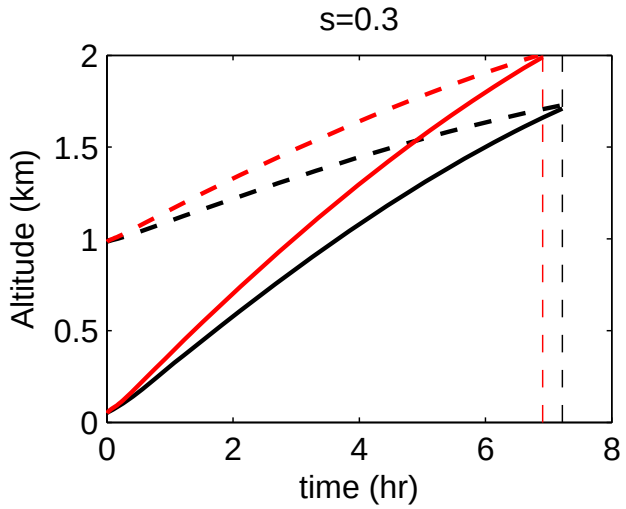
wet

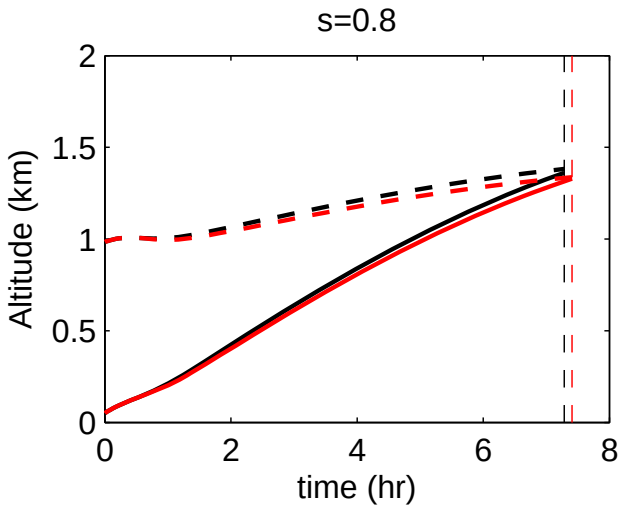
unstable

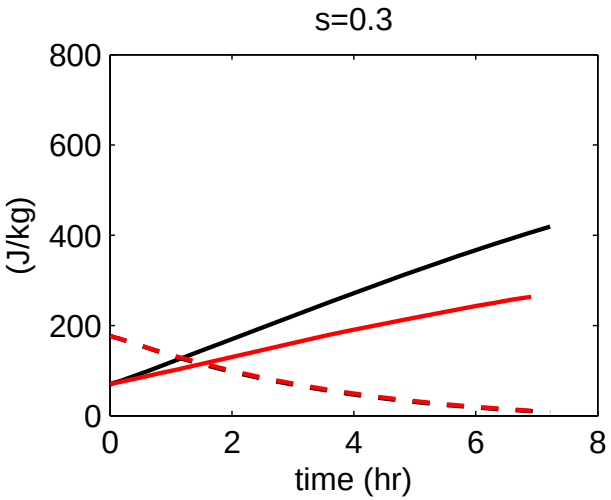
s_{max} soil moisture that likely triggers strongest convection for the given atmospheric conditions

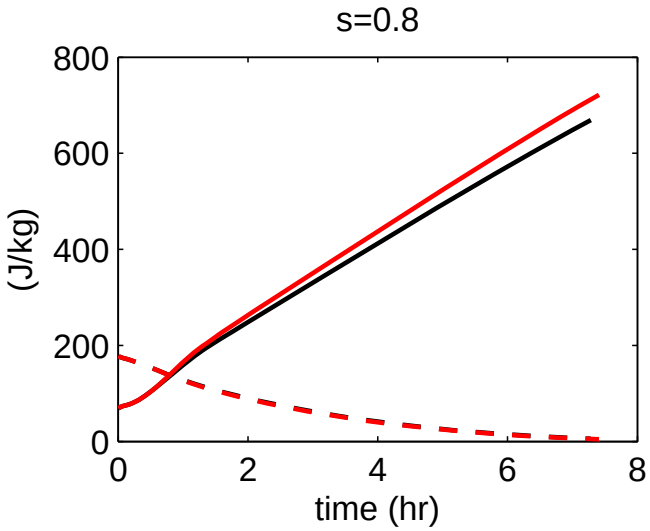
Yin et al. (in preparation)

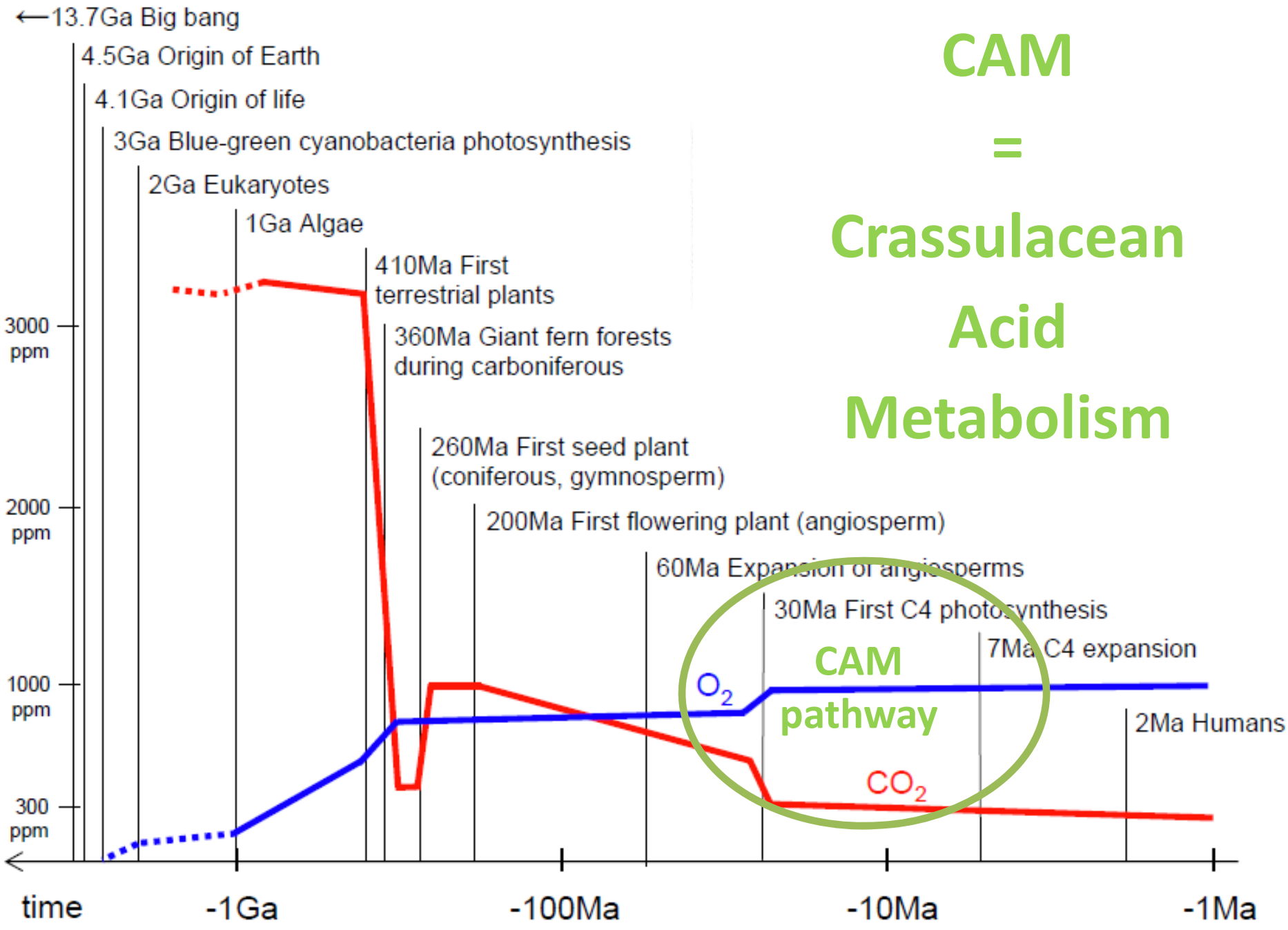
C3 vs C4


s=0.3
Altitude (km)
time (hr)
0
0.5
1
1.5
2
0
2
4
6
8


s=0.8
Altitude (km)
time (hr)
0
0.5
1
1.5
2
0
2
4
6
8


s=0.3
(J/kg)
time (hr)
0
200
400
600
800
0
2
4
6
8

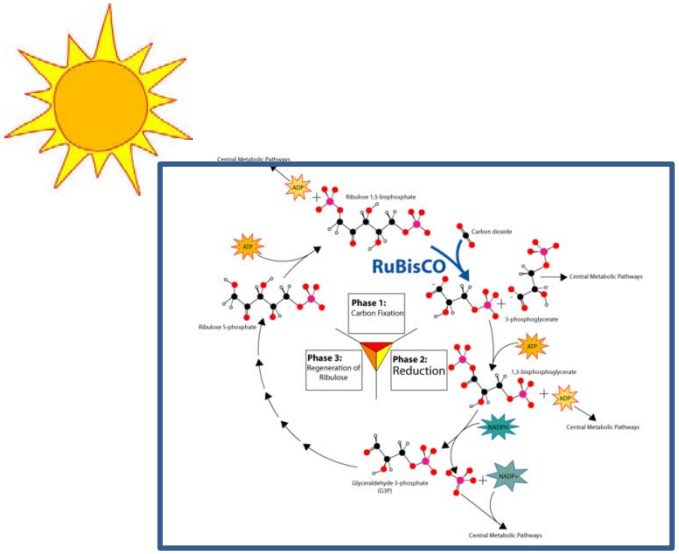

s=0.8
(J/kg)
time (hr)
0
200
400
600
800
0
2
4
6
8

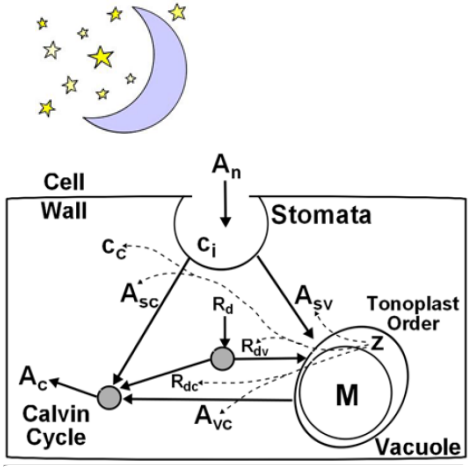


CAM = Crassulacean Acid Metabolism

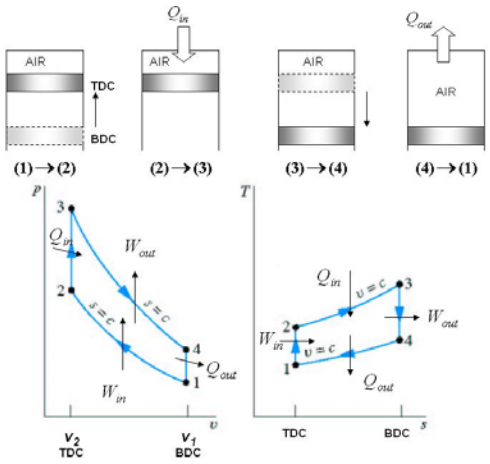
Thick-leaved orchid:
Phalaenopsis amabilis

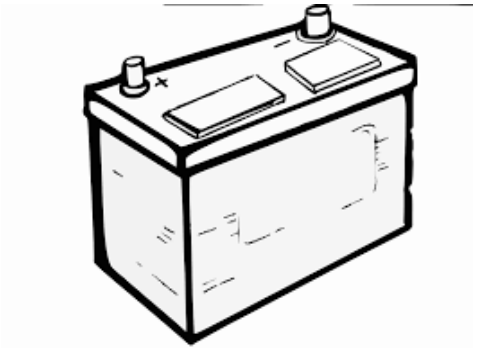
Storage of malic acid in cell vacuoles + control system (circadian rhythm)

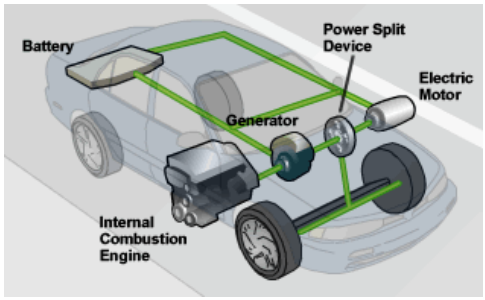




Bartlett, Vico and Porporato, Plant and Soil (2014)
Hartzell et al. JTB in revision



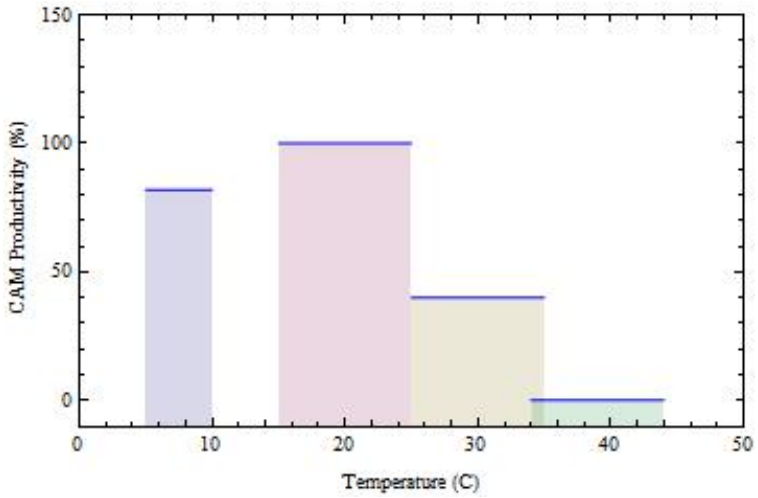


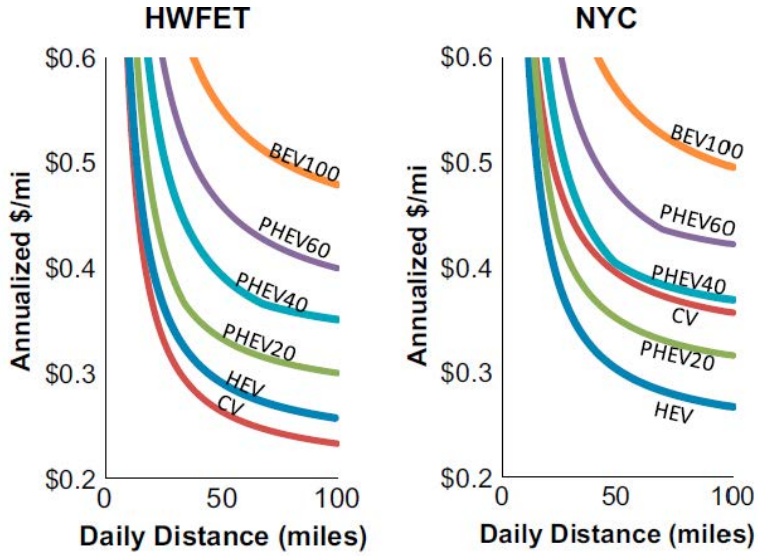


Pursuing the analogy a bit further…

Porporato et al. in preparation 2014

- Similar evolutionary sequence
- C4: low CO2 ↔ turbocharger: low oxygen (more power/works well at high elevations)
- CAM ↔ hybrid: storage limits and costs: variability is essential



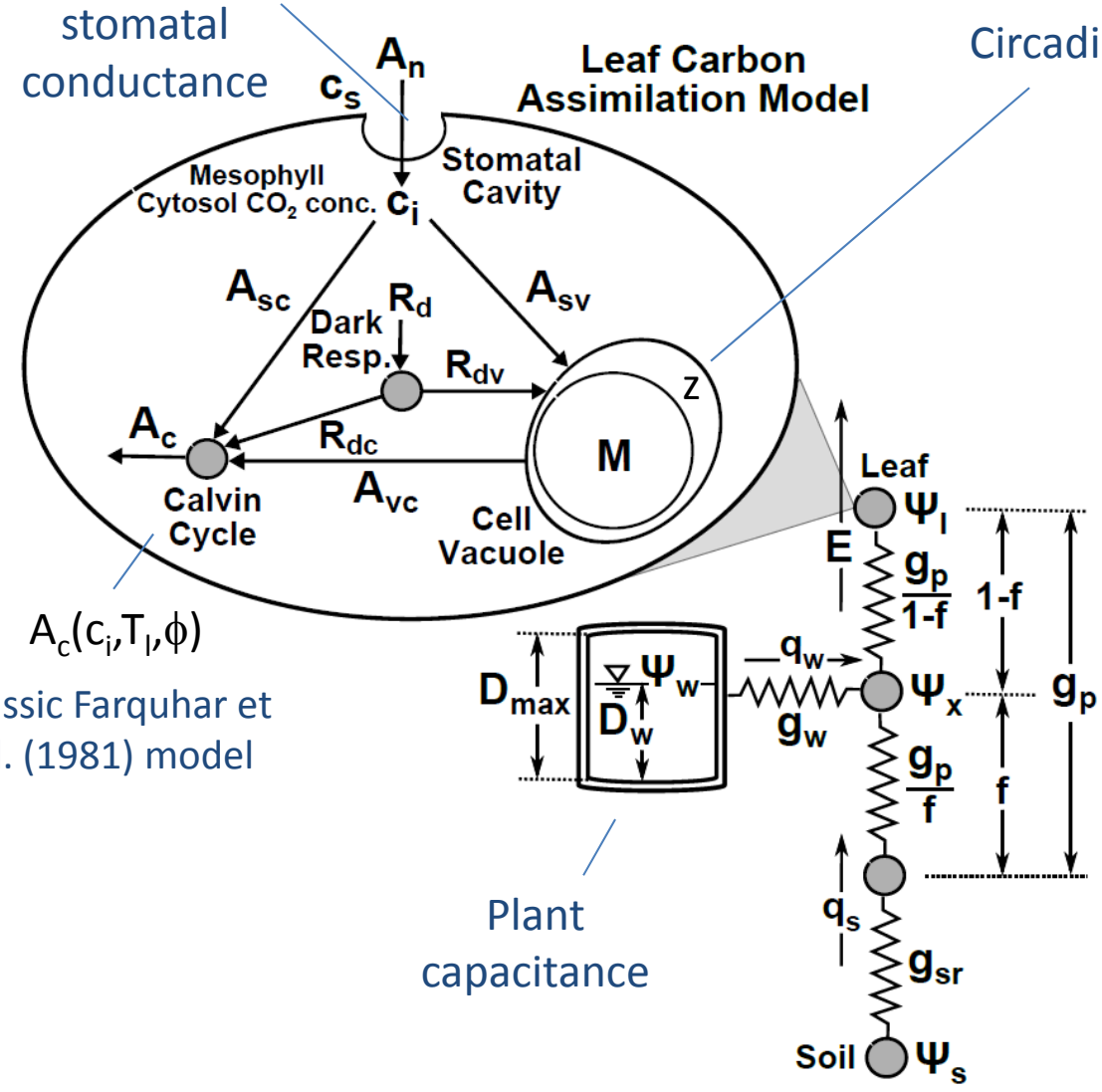


NOBEL, P.S. Biologia ambiental.
In: Agroecologia, cultivo e uso da palma forrageira.
FAO, 1995. SEBRAE-PB. p.36-48. 216p. 2001.

K. Orkun and J. Michalek, Influence of driving patterns on life cycle cost and emissions of hybrid and plug-in electric vehicle powertrains.
Energy Policy 60 (2013): 445-461.

Model for CAM photosynthesis

Demand-driven stomatal conductance



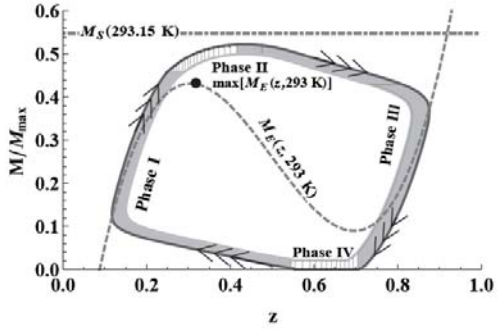
$A_c(c_i,T_l,\phi)$

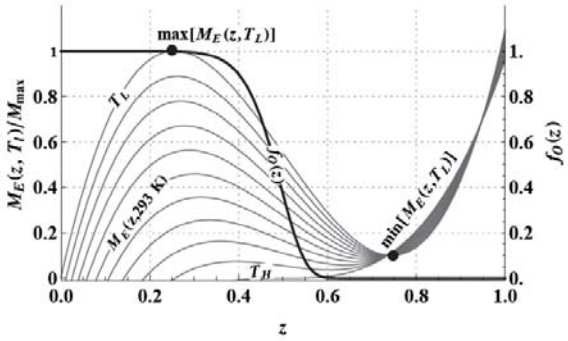
classic Farquhar et al. (1981) model

Plant capacitance

Circadian rhythm

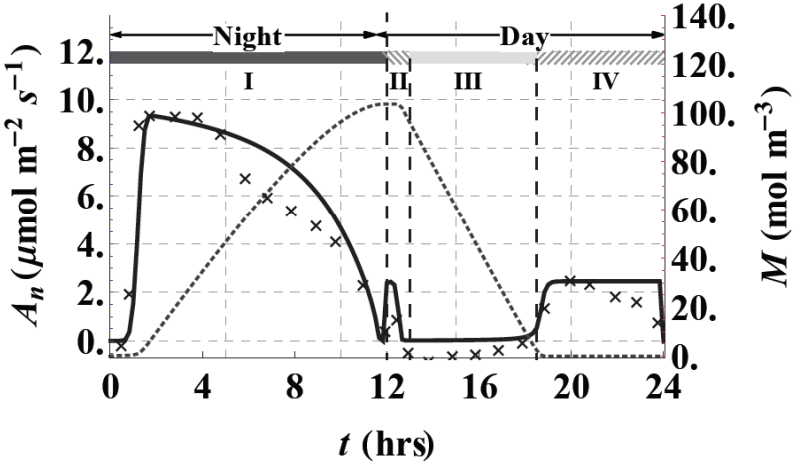
$$\begin{cases} \dfrac{dM}{dt} = A_{sv} + R_{dv} - A_{vc} \\ \tau \dfrac{dz}{dt} = M_E(z,T_l) - M \end{cases}$$



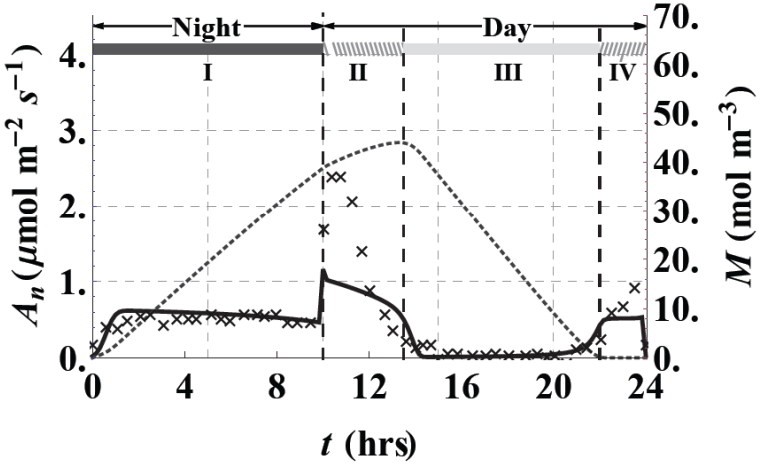


Bartlett, Vico and Porporato, Plant and Soil (2014)
Hatzell et al. JTB in revision

results



Agave tequiliana



Clusia minor

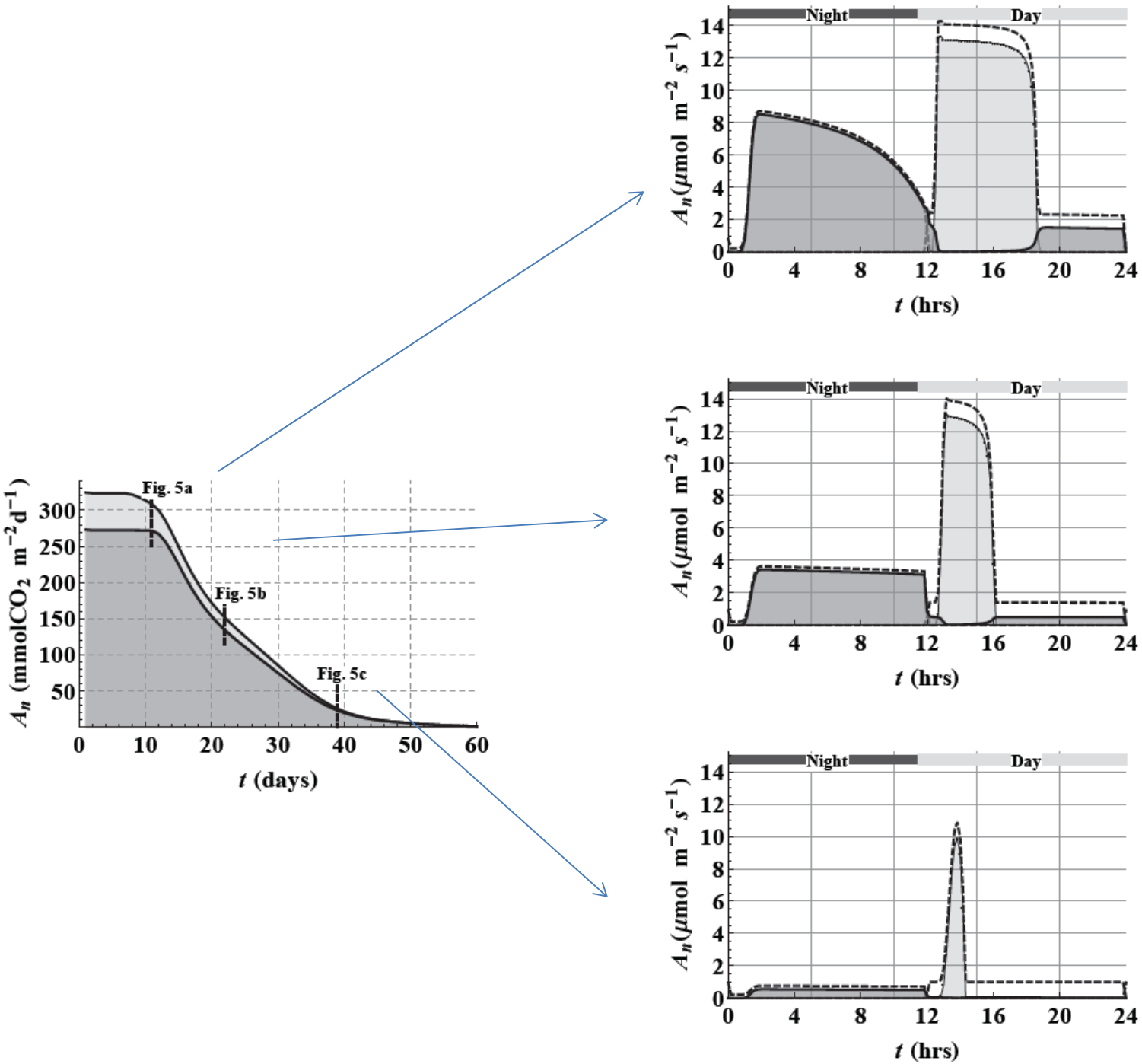
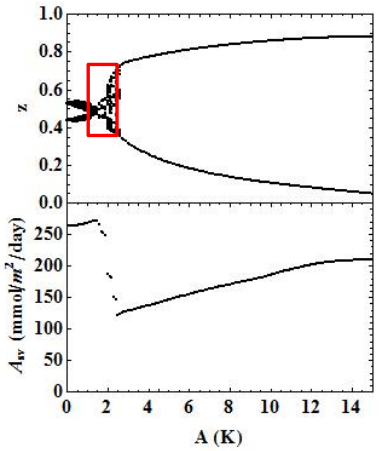
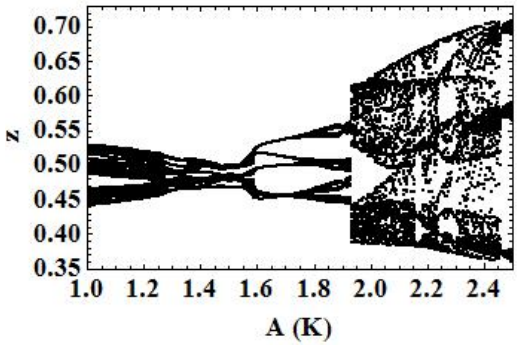
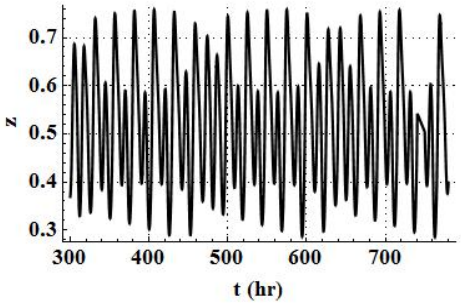
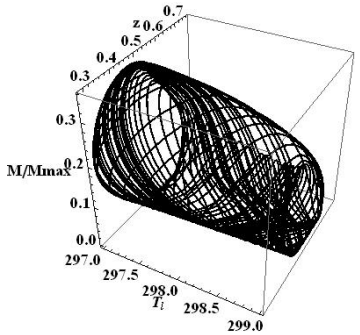


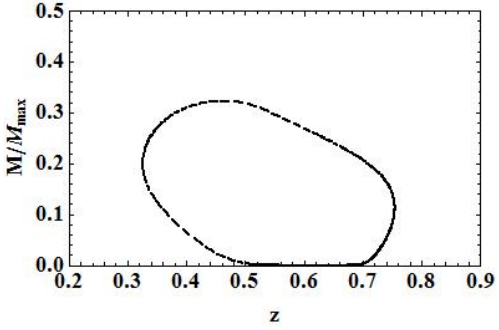
Fig. 5a
Fig. 5b
Fig. 5c
A_n (mmolCO$_2$ m^{-2}d^{-1})
300
250
200
150
100
50
0
10
20
30
40
50
60
t (days)
Night
Day
A_n(μmol m^{-2} s^{-1})
14
12
10
8
6
4
2
0
0
4
8
12
16
20
24
t (hrs)
Night
Day
A_n(μmol m^{-2} s^{-1})
14
12
10
8
6
4
2
0
0
4
8
12
16
20
24
t (hrs)
Night
Day
A_n(μmol m^{-2} s^{-1})
14
12
10
8
6
4
2
0
0
4
8
12
16
20
24
t (hrs)

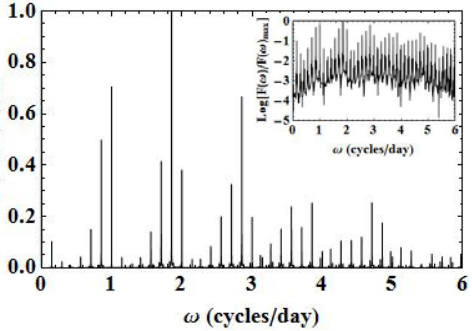

z
A_{sv} (mmol/m^2/day)
A (K)

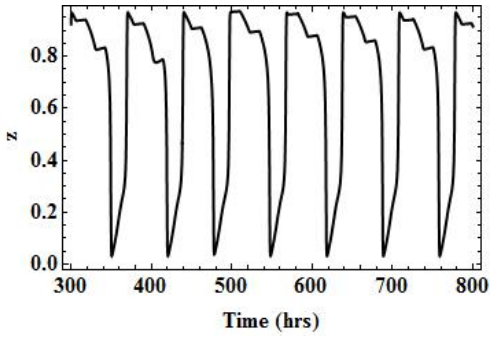

z
A (K)

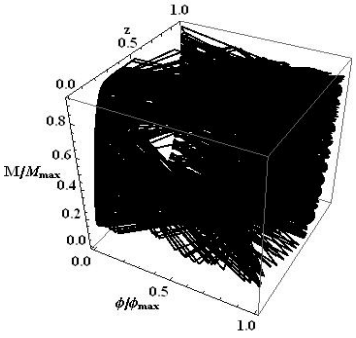

z
t (hr)

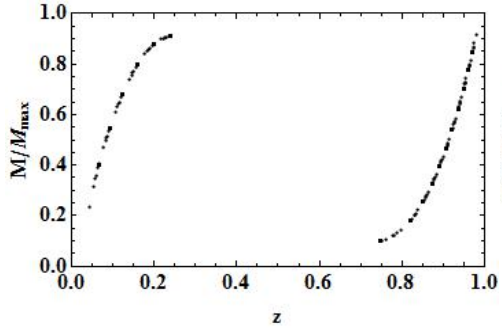

z
M/Mmax
T_i

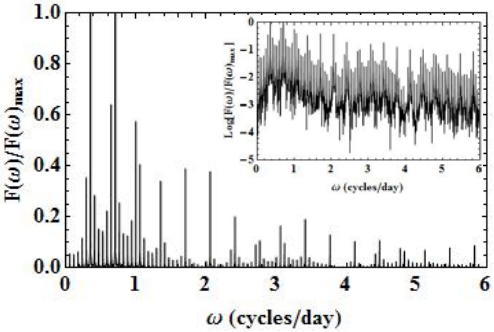

M/M_{max}
z


F(ω)/F(ω)max
Log[F(ω)/F(ω)max]
ω (cycles/day)
ω (cycles/day)

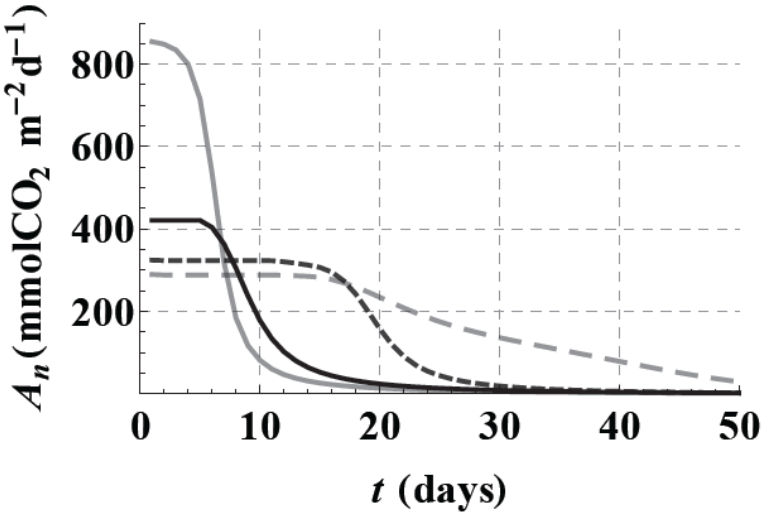

z
Time (hrs)

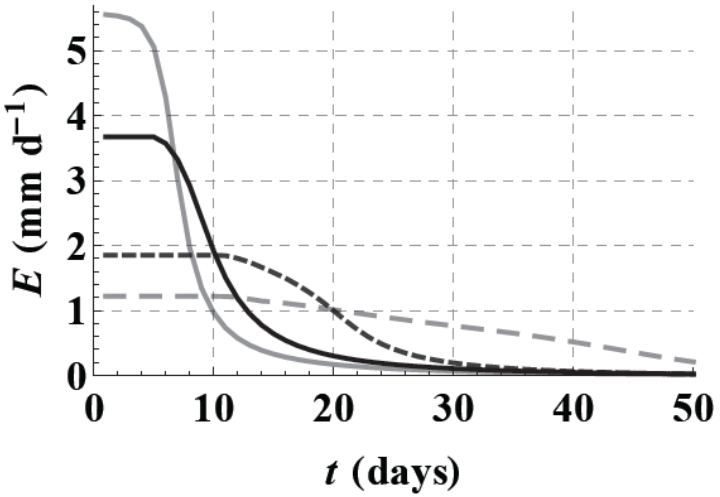

z
M/M_{max}
ϕ/ϕ_{max}


M/M_{max}
z

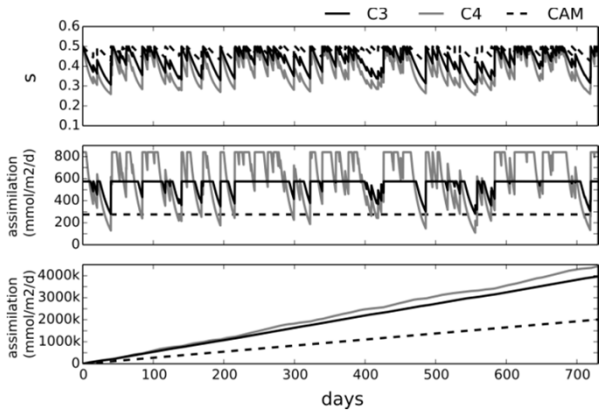

F(ω)/F(ω)max
Log[F(ω)/F(ω)max]
ω (cycles/day)
ω (cycles/day)

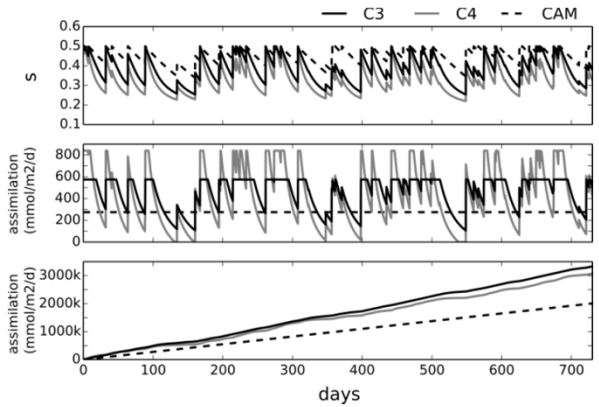
Comparison of C3, C4 and CAM plants

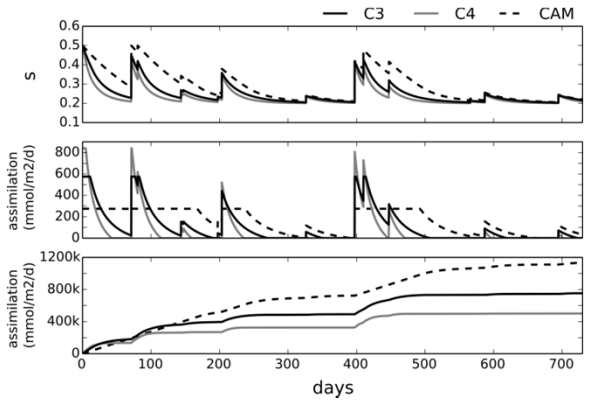




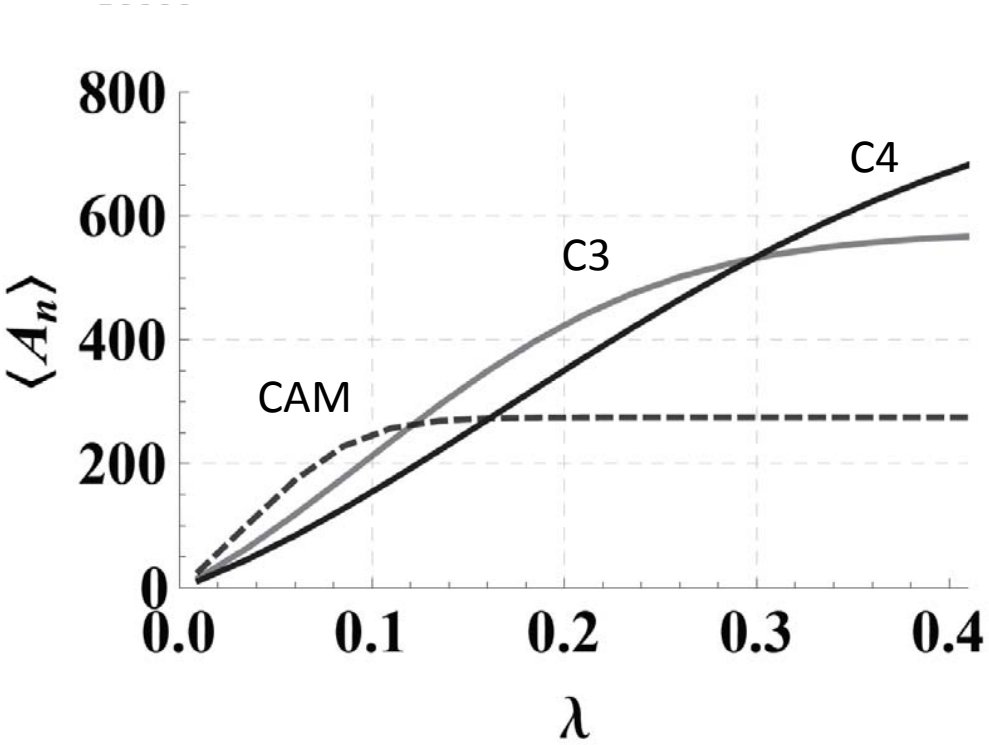
Decreasing rainfall frequency

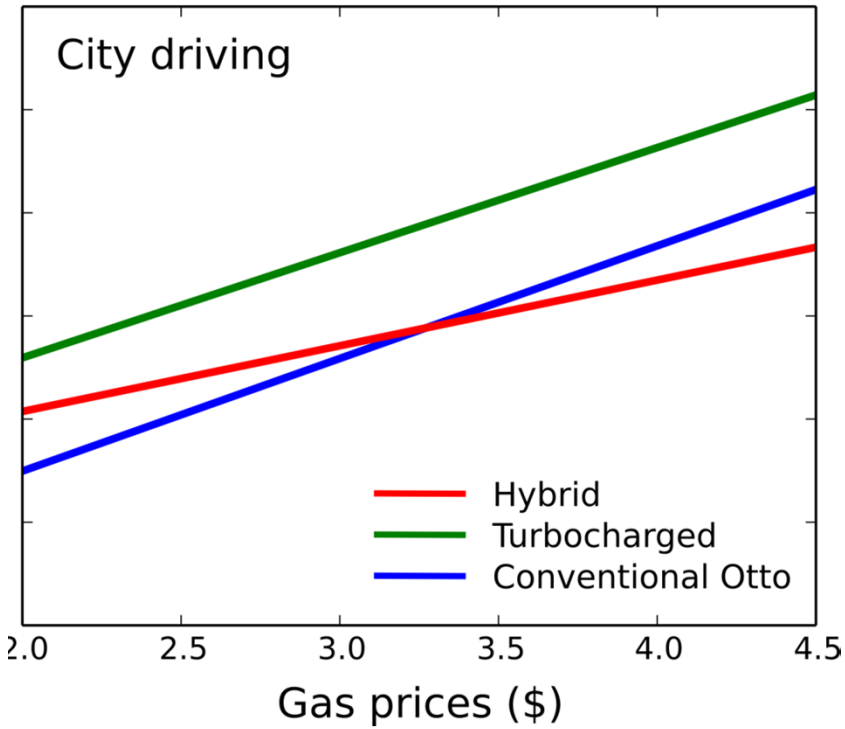






Back to our analogy





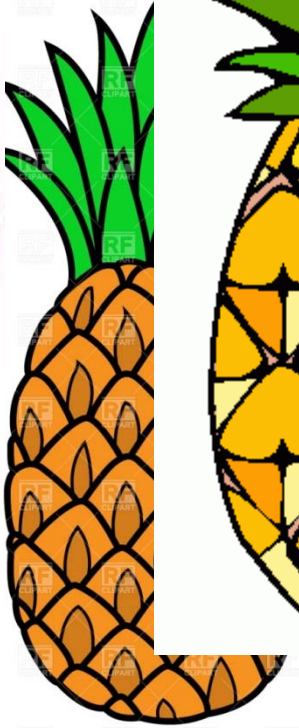
Conclusions

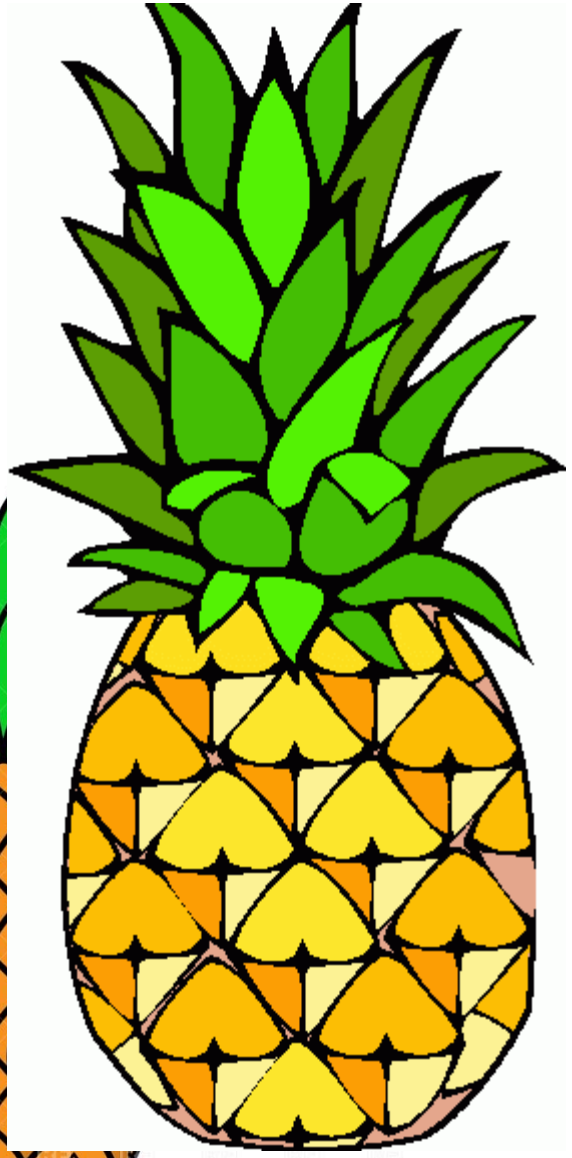
- Work in progress…
- Fascinating **interactions between plant and their environment** which are impacted by and in turn control the water cycle
- Important for **long term dynamics of soils**, biogeochemical cycles and landscape formation
- Optimizing our management of soil and water resources (**quantitative answers to the problem of sustainability**)

Thank you!

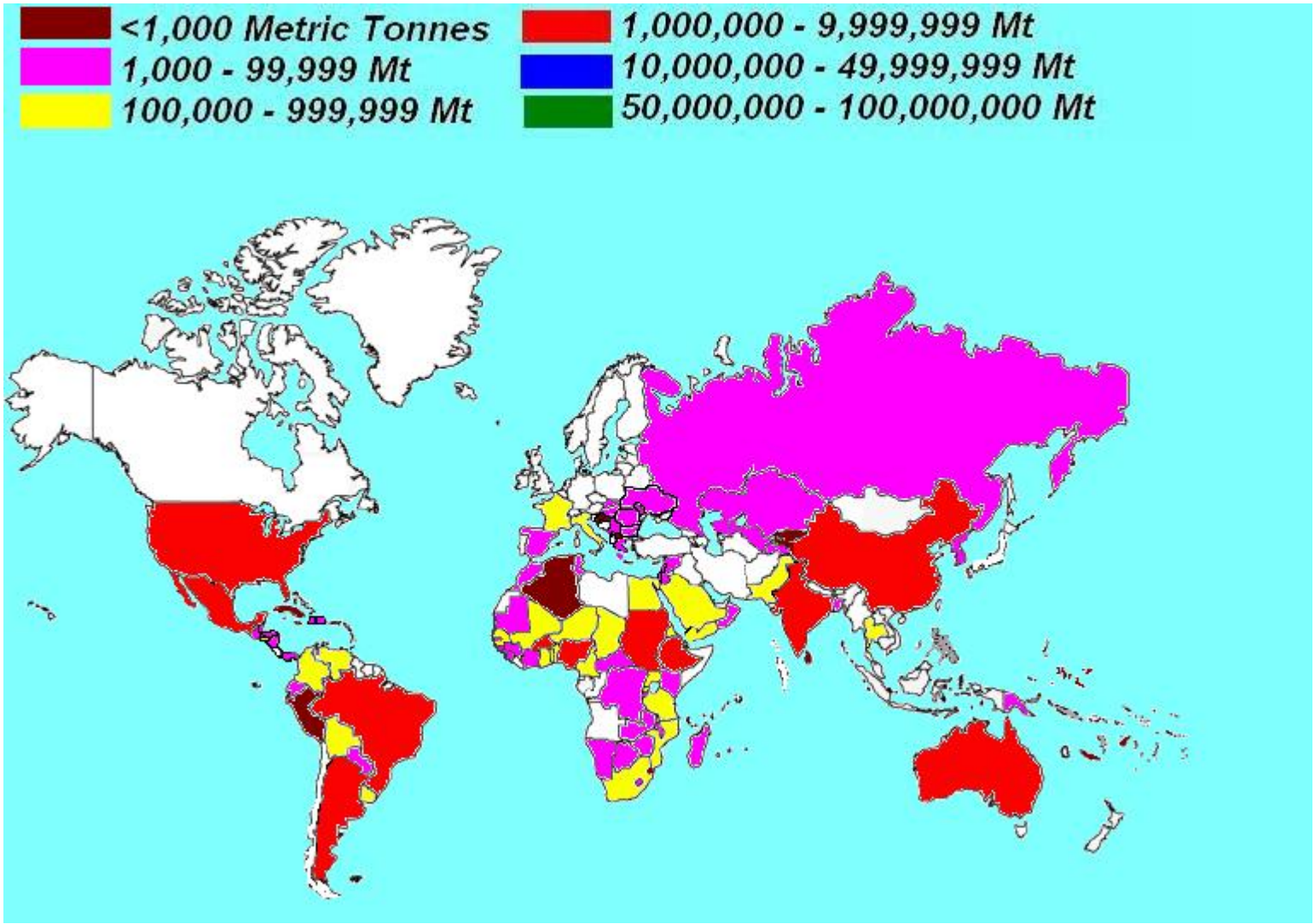
Opunthia ficus indica,
growing on an obelisk
in Ethiopia

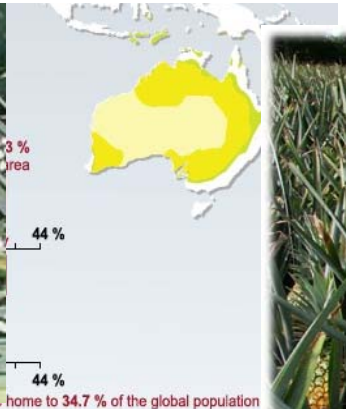
Photo:
courtesy of Paolo Inglese,
Univ. of Palermo, Italy





sorghum


<1,000 Metric Tonnes
1,000 - 99,999 Mt
100,000 - 999,999 Mt
1,000,000 - 9,999,999 Mt
10,000,000 - 49,999,999 Mt
50,000,000 - 100,000,000 Mt


3 %
rea
44 %
44 %
home to 34.7 % of the global population

e

uce

– anatomy)

- Improve comburent concentration → turbocharger