The Abdus Salam International Centre for Theoretical Physics

2444-14

College on Soil Physics - 30th Anniversary (1983-2013)

25 February - 1 March, 2013

Modeling for crop production

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BRAZIL

Modeling for crop production

College on Soil Physics 2013 – 30th Anniversary

Energy and mass balances at the Land-Water-Atmosphere continuum

Durval Dourado Neto

Crop Science Department, Esalq,
University of São Paulo

26 February 2013

Modeling: the philosophic procedure…

FACT

Observation

Abstraction

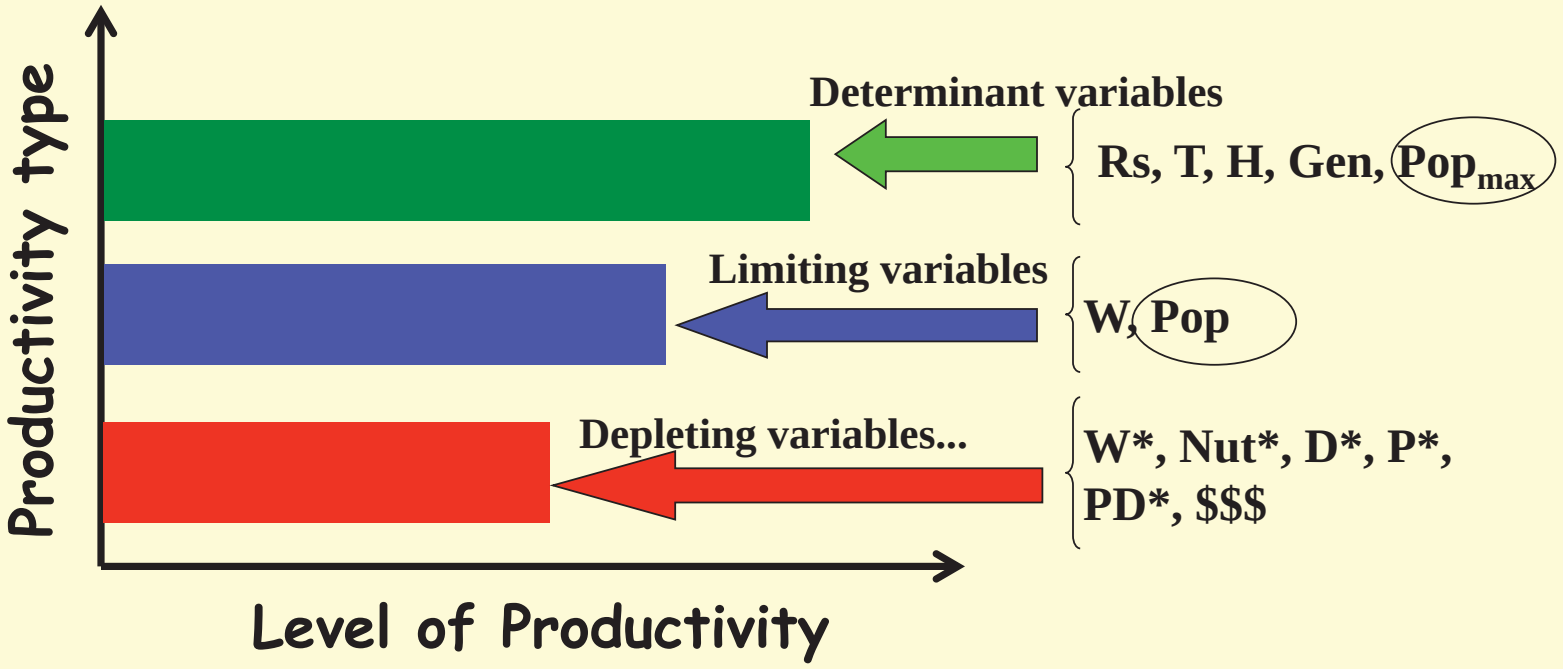
VALUE

The treatment applied to the **FACT** as function of experience and theoretical knowledge

RULE

Model as Resulted of **VALUE** applied to the **FACT**

Productivity



Potential Productivity (PP)

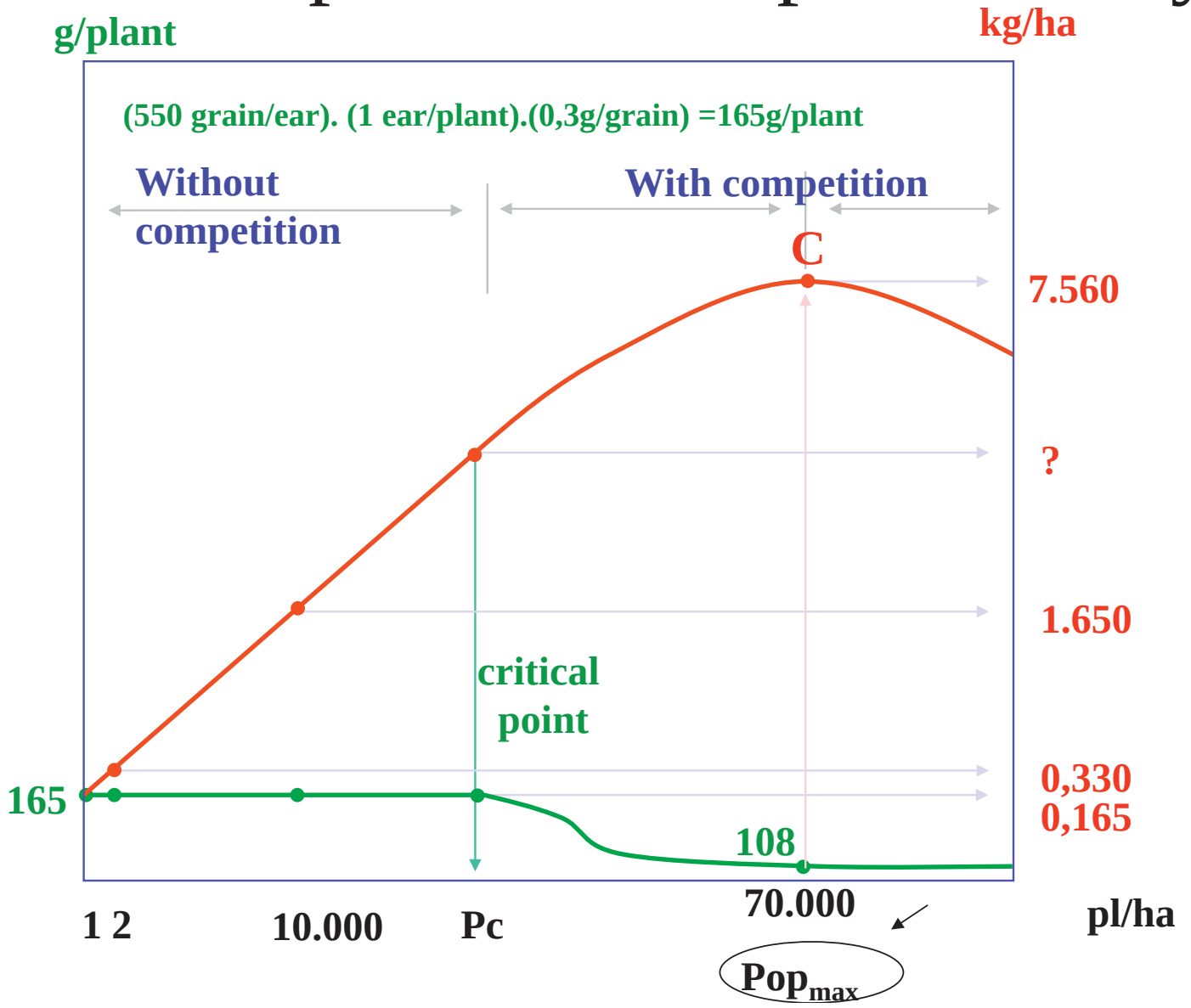
Obtainable Productivity

MINIMUM intervention…

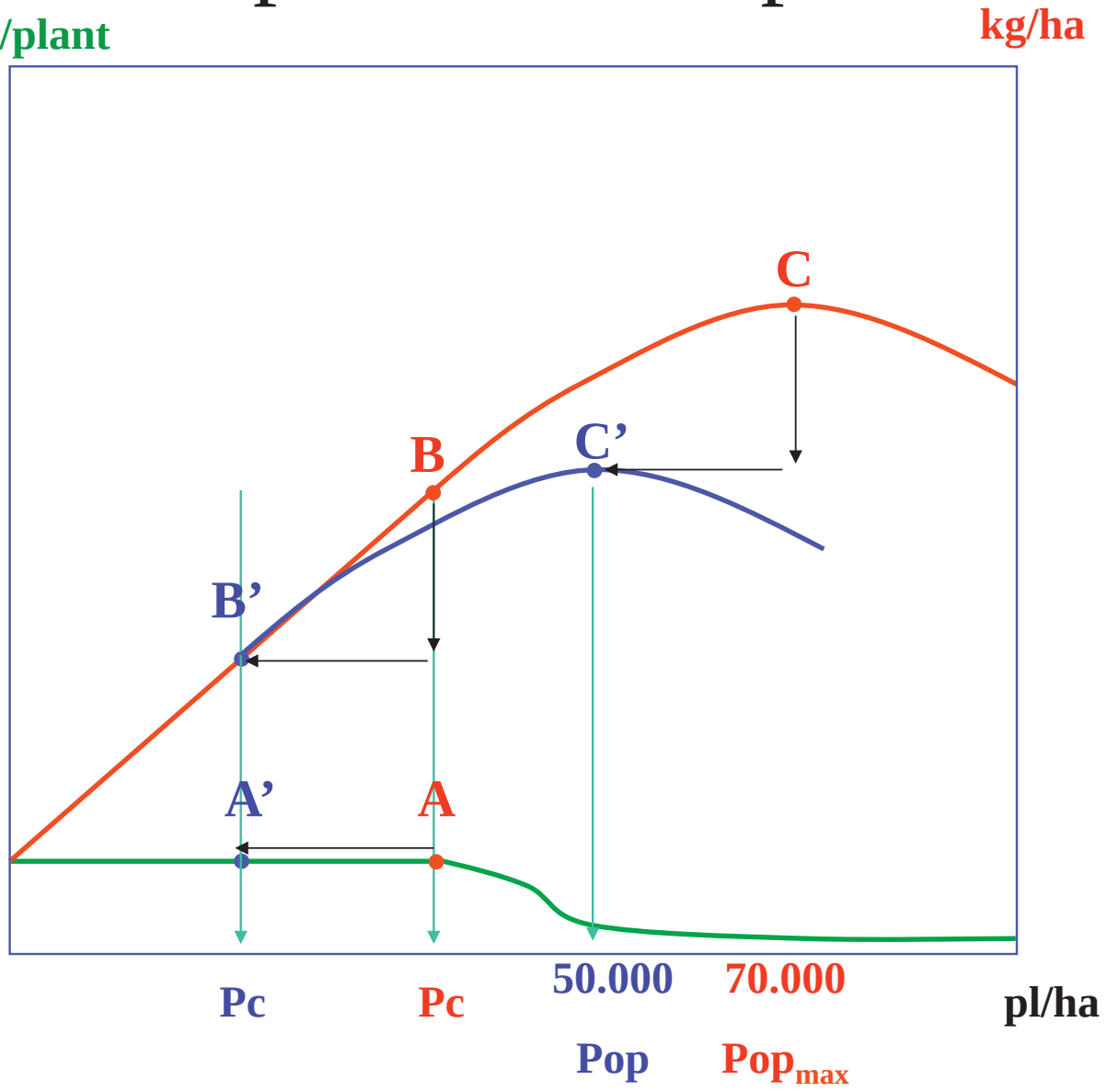
Maximum economical Productivity

WITH intervention…

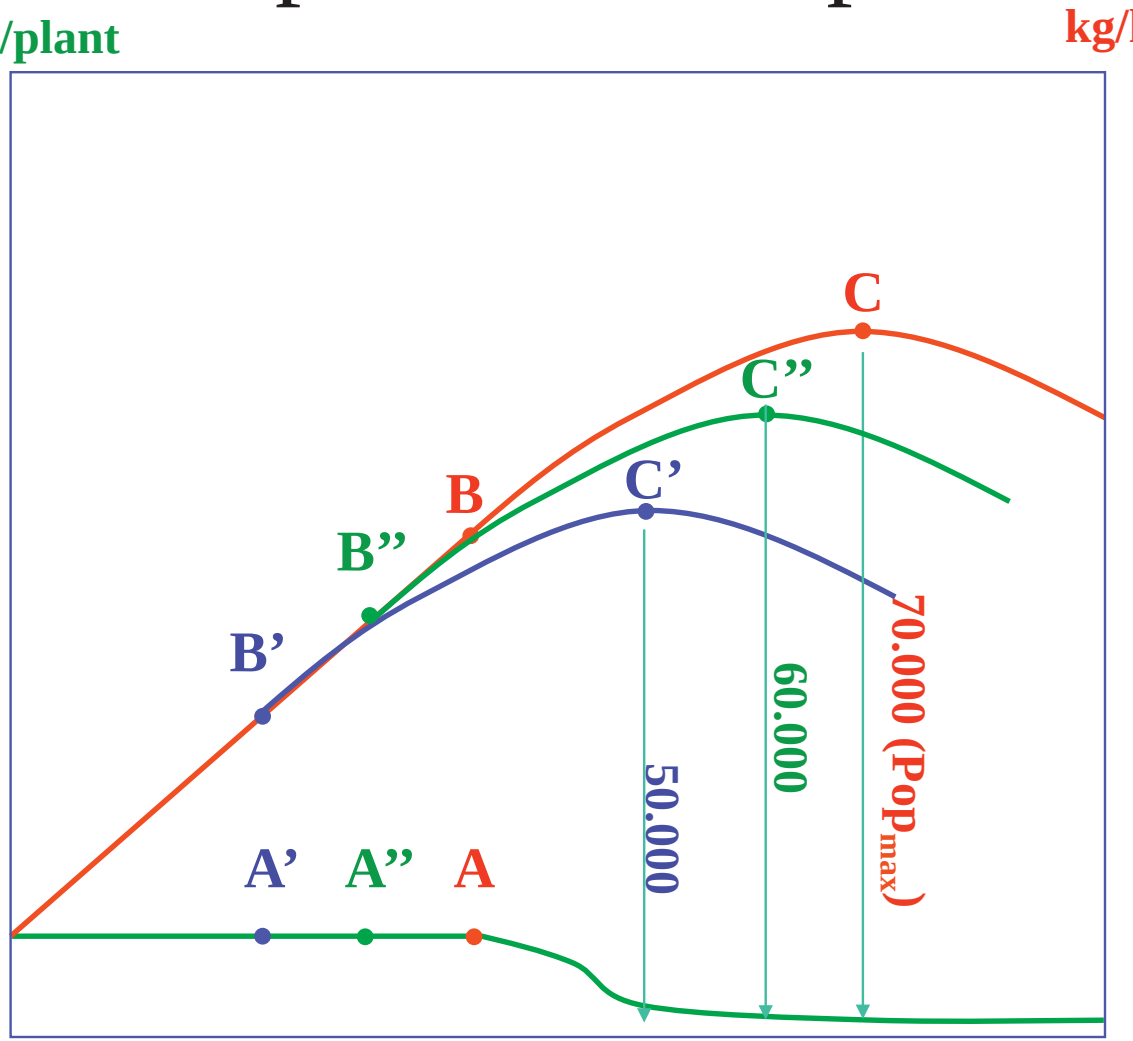
Corn Plant Population and productivity

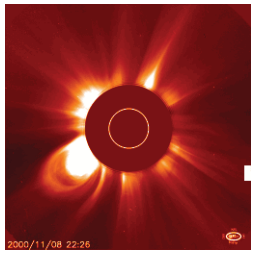


Corn Plant Population and productivity

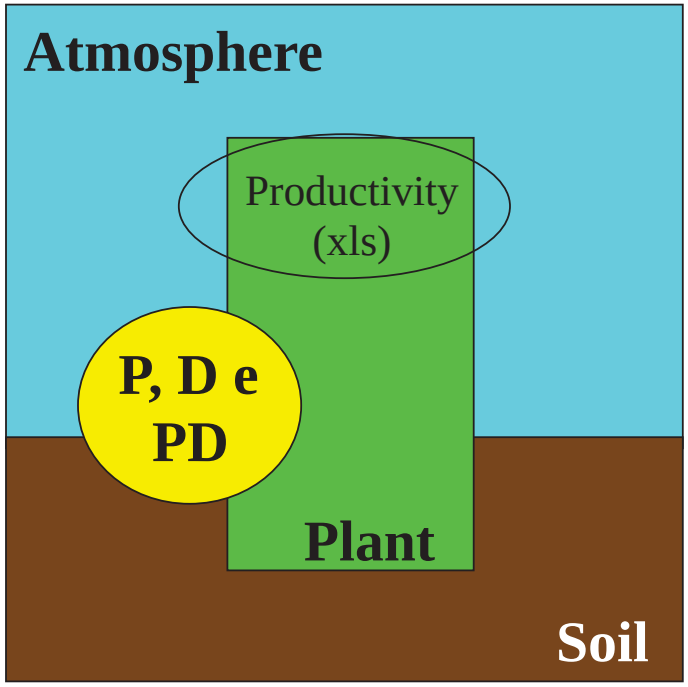


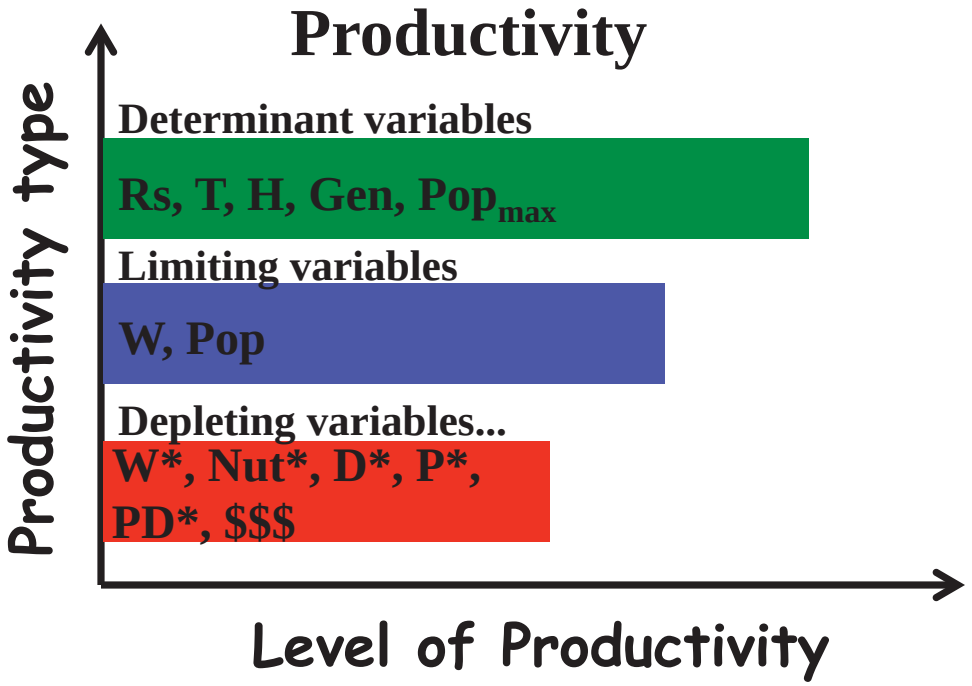
Corn Plant Population and productivity





Qo





De Wit

Potential Productivity (PP)

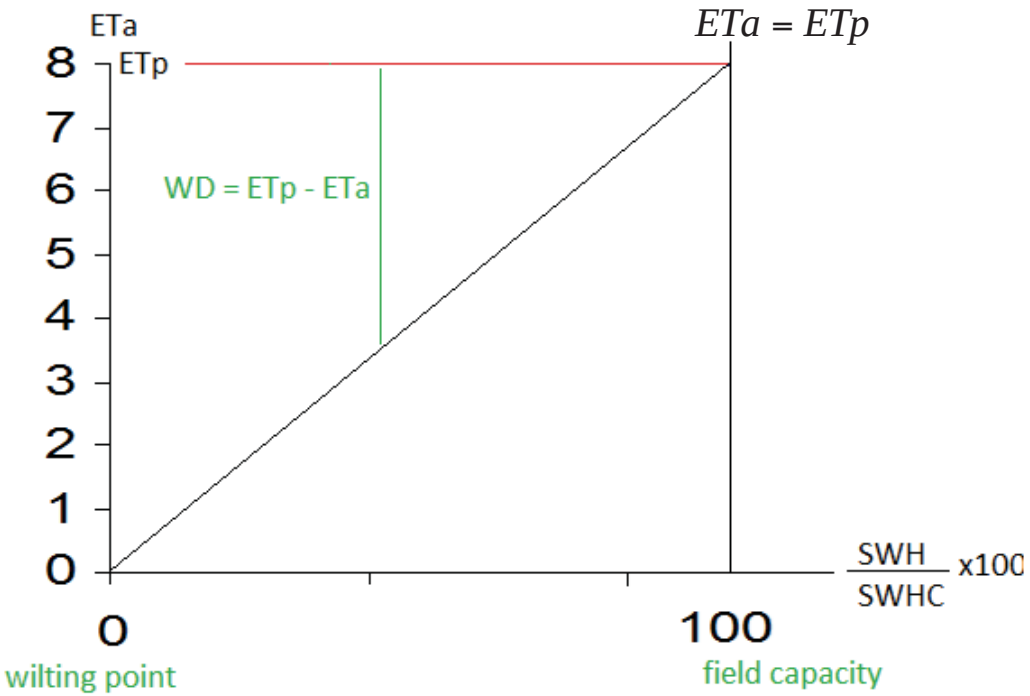
Obtainable Productivity

Maximum economical Productivity

Summary

1. What is water deficiency?
2. Genotype - Cultivar
   (a) Productivity (potential, attainable and actual productivity)
   (b) Photosynthesis
   (c) Leaf area index, row spacing and plant population
   (d) Carbon partition, Conversion efficiency, hormones and crop cycle
   (e) Light and carbon use efficiency
3. Environment
   (a) Soil water holding capacity and flux density
   (b) Water and nutrients use efficiency

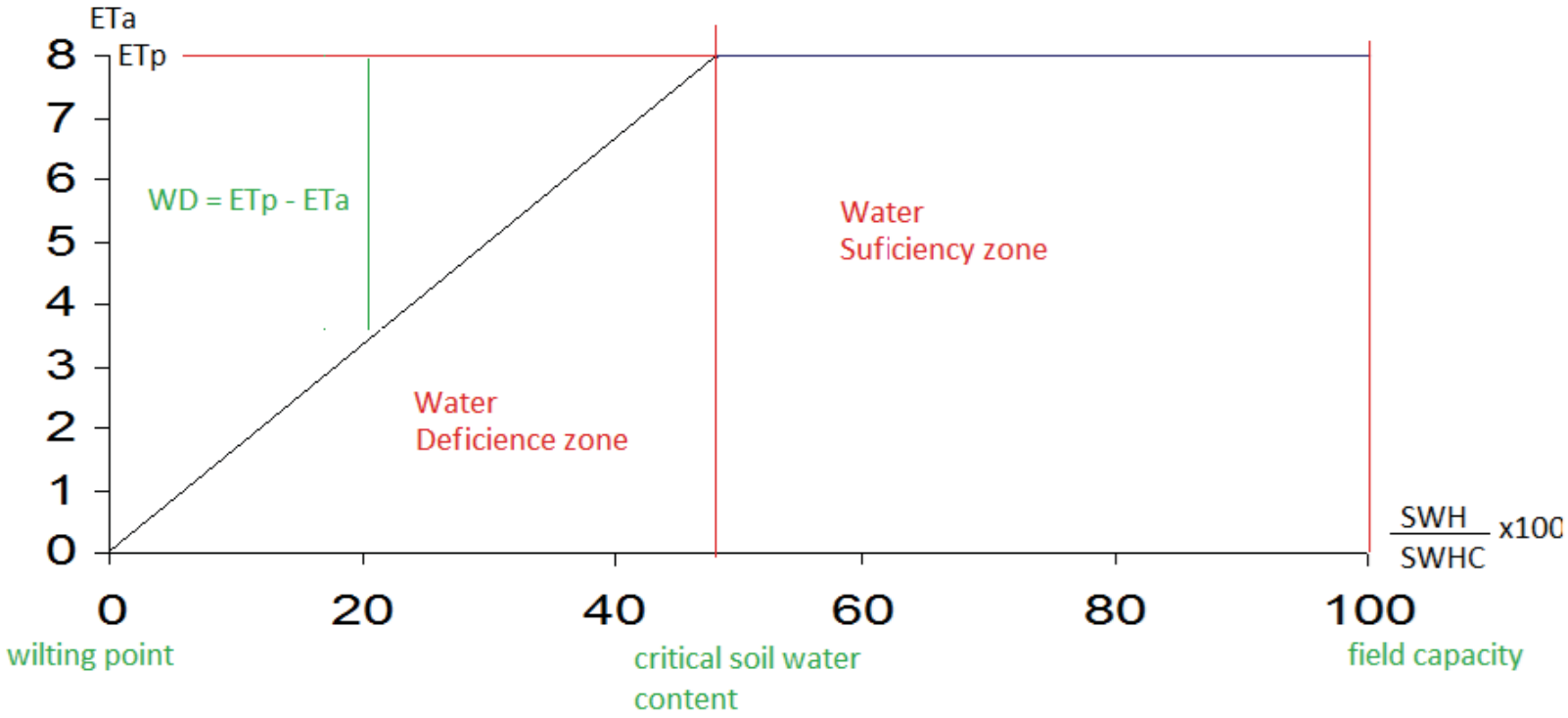
What is water deficiency?



$$ETa = ETp \frac{SWH}{SWHC}$$

Thornthwaite & Mather (1955)

What is water deficiency?



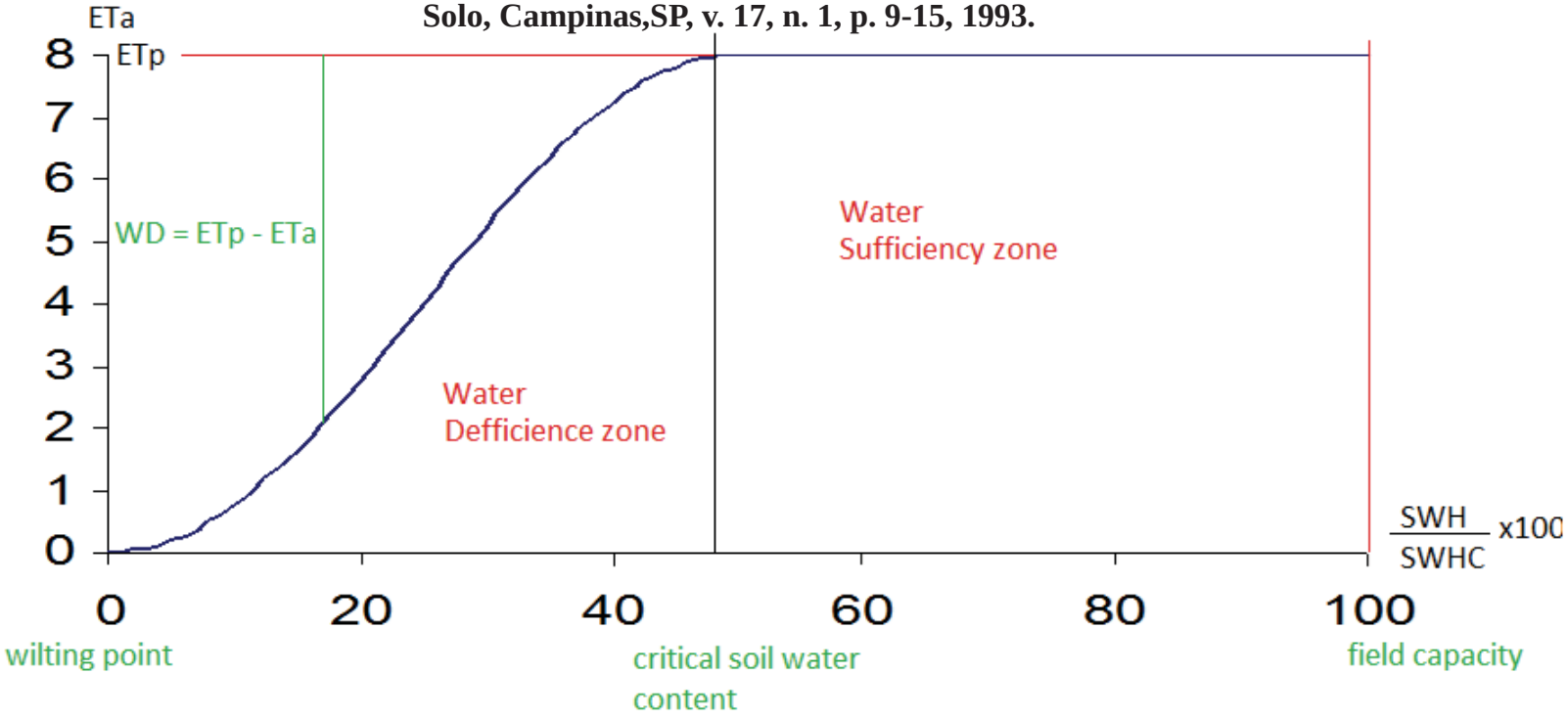
$$ETa = ETp \frac{SWH}{(1-p).SWHC}$$

$$ETa = ETp$$

Rijtema & Abouckhaled (1975)

What is water deficiency?

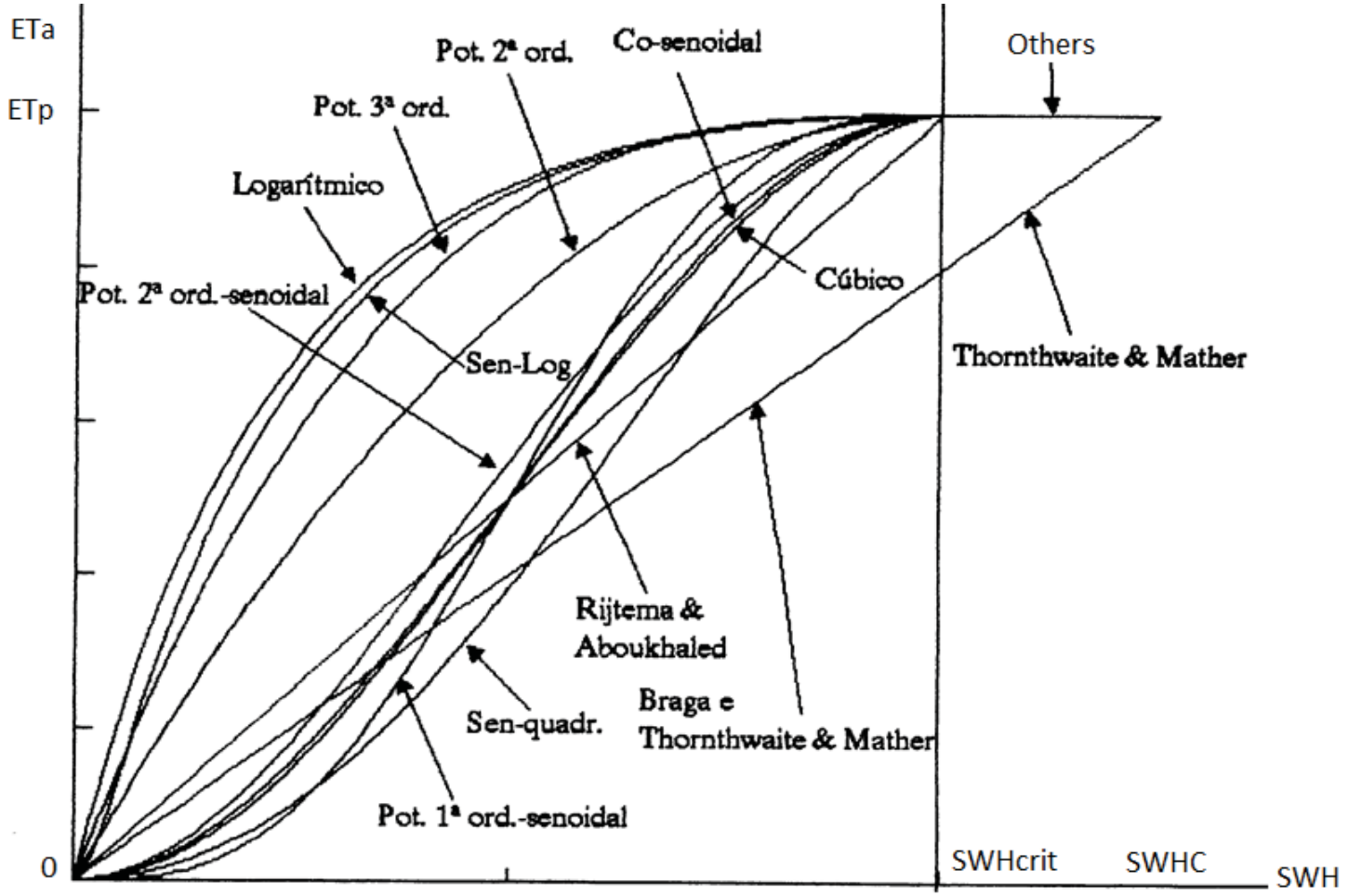
DOURADO NETO, Durval ; JONG VAN LIER, Q. Estimativa do armazenamento de água no solo para realização de balanço hídrico. Revista Brasileira de Ciência do Solo, Campinas,SP, v. 17, n. 1, p. 9-15, 1993.



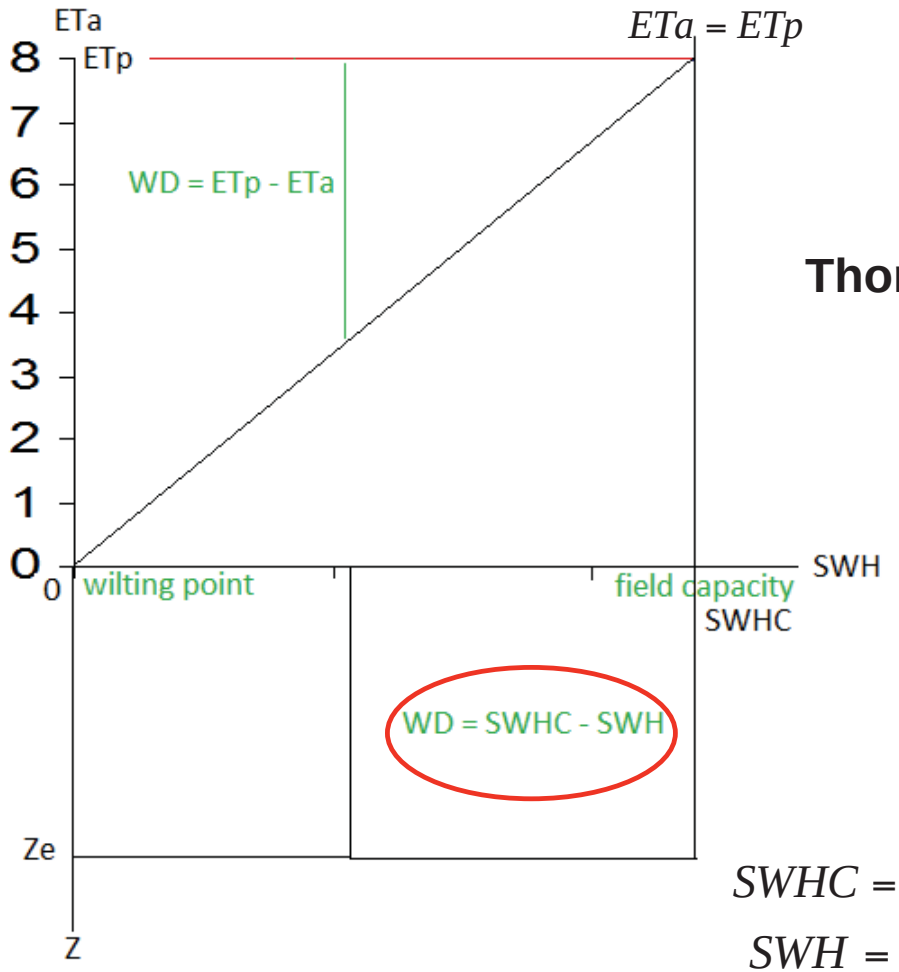
$$ETa = \frac{ETp}{2}\left[1 - \cos\left\{\frac{\pi . SWH}{(1-p).SWHC}\right\}\right] \qquad ETa = ETp$$

Dourado Neto & Jong van Lier (1993)

What is water deficiency?



What is water deficiency?



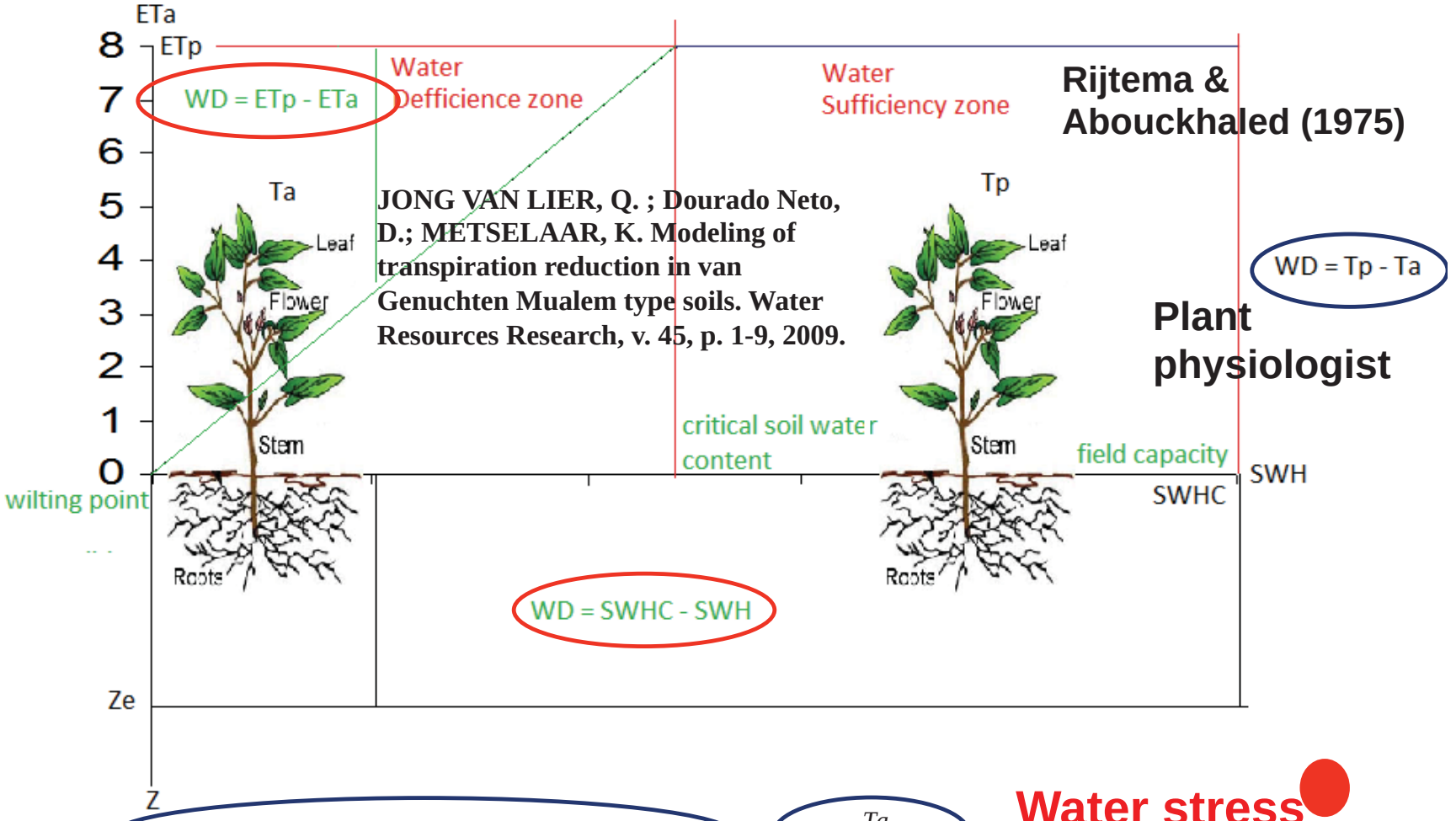
$ETa = ETp$

Thornthwaite & Mather (1955)

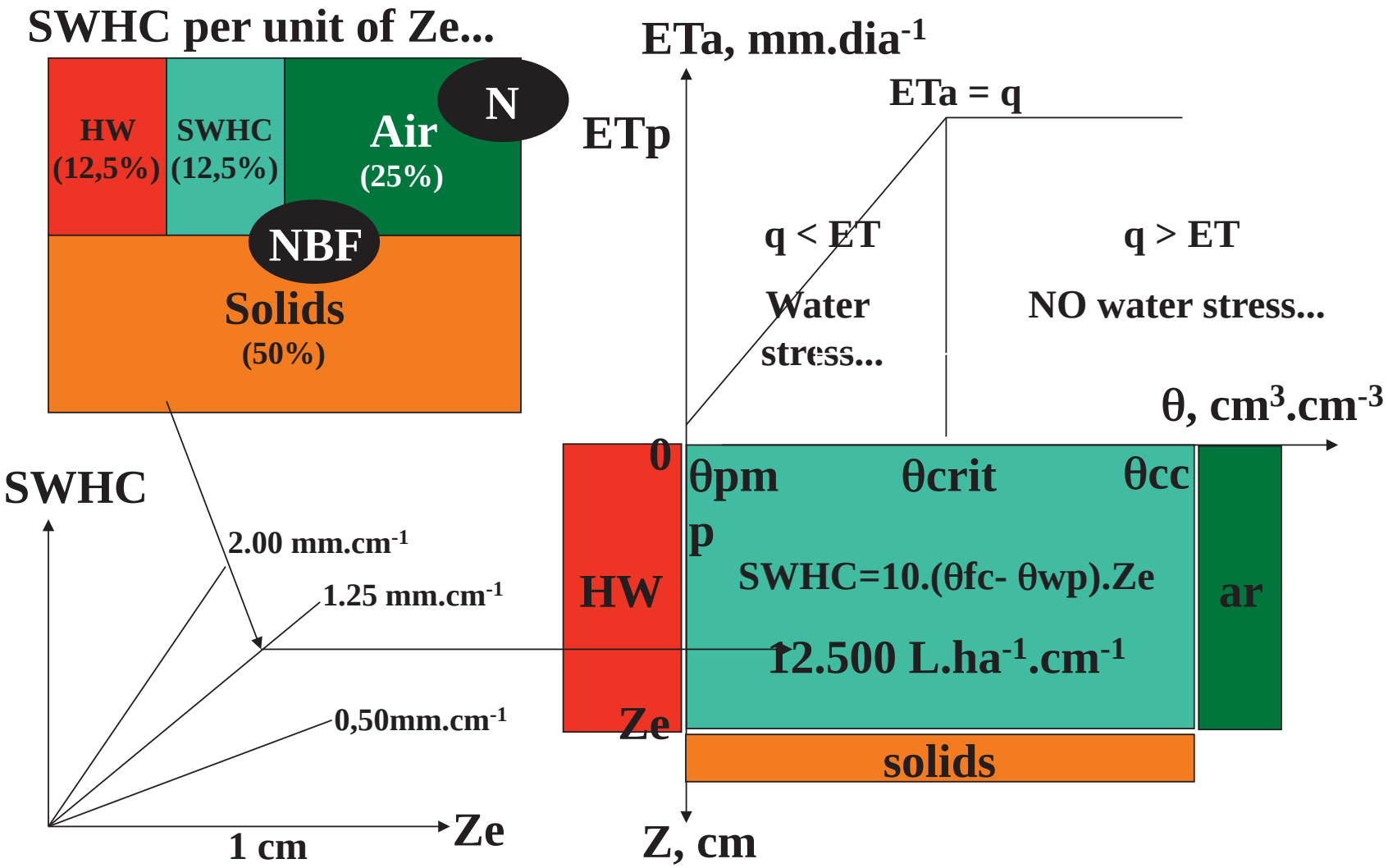
$$SWHC = 10(\theta_{fc} - \theta_{pwp})Ze$$

$$SWH = 10(\theta_{a} - \theta_{pwp})Ze$$

What is water deficiency?



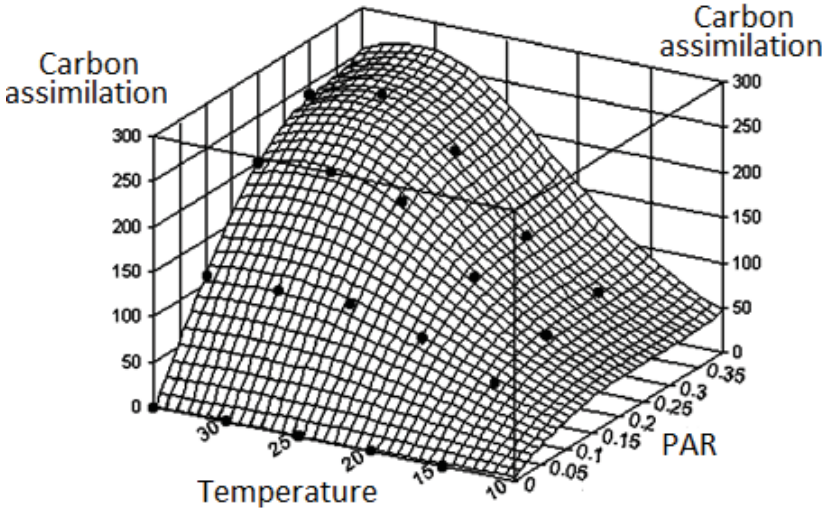
What is water deficiency?

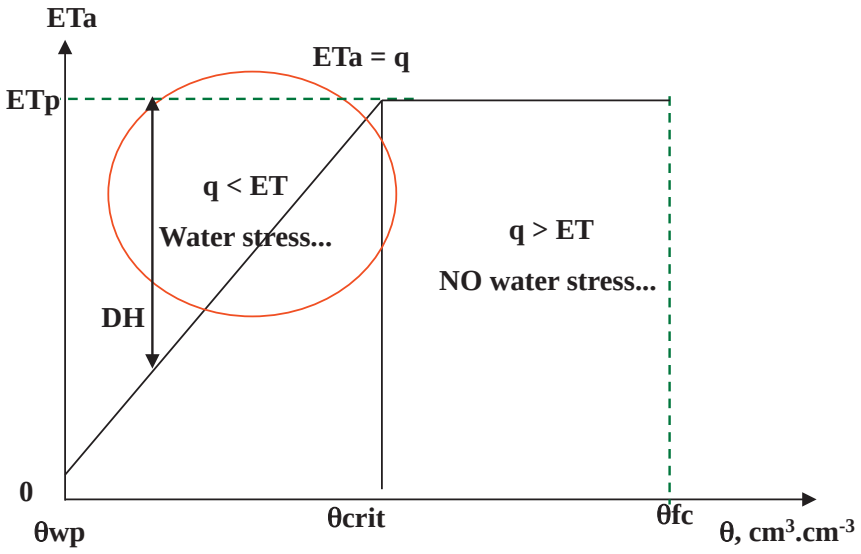


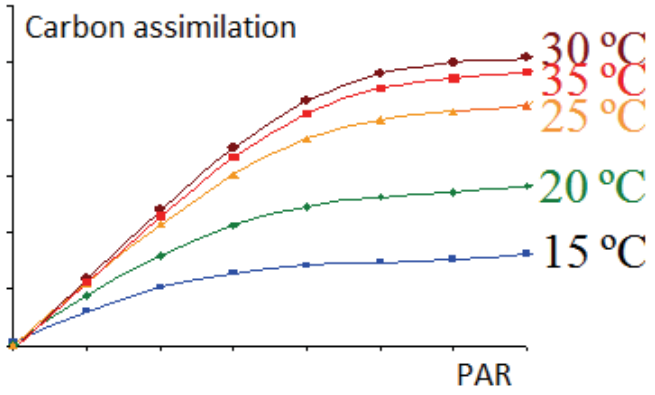
The effect of water deficiency on productivity

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

44g 18g 30g 32g



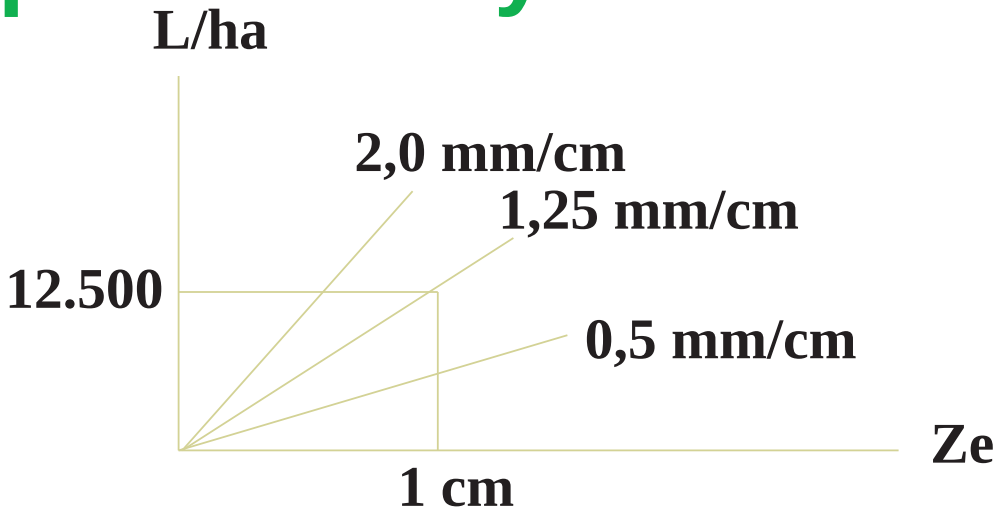




The effect of water deficiency on productivity

Less CO_2...
Less CH_2O...
Less Nutrients...
Less DM production...

...Less productivity



Comments about higher SWHC/Ze:

- Higher plant population

- Short dry season: less problem

- Superficial soil fertility: not impeditive to root growth

Water…

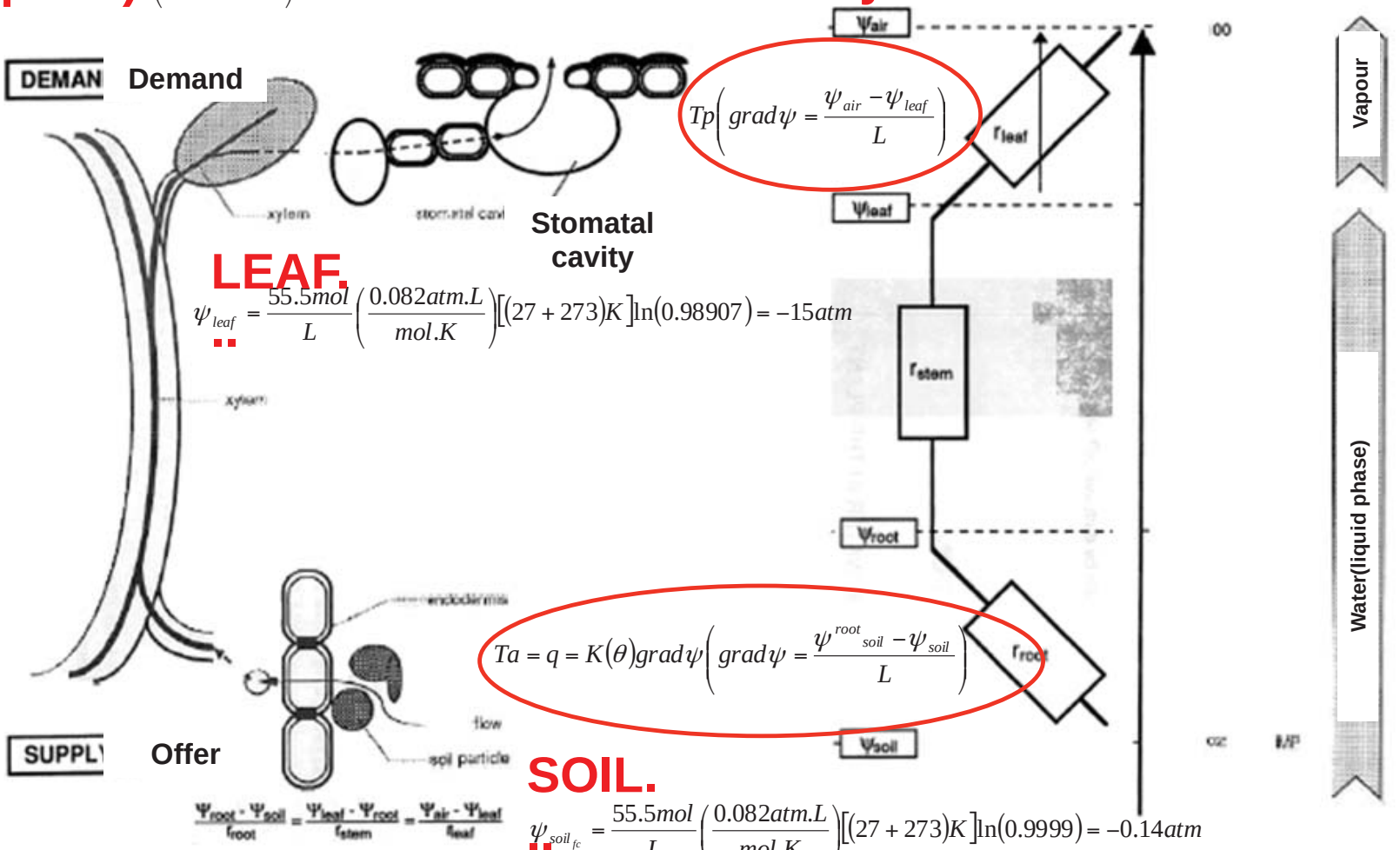
$$\psi = 55.5R(T+273)\ln(RH)$$

AIR: Night (Dew point)…

$$\psi_{air}^{2am} = \frac{55.5mol}{L}\left(\frac{0.082atm.L}{mol.K}\right)\left[(18+273)K\right]\ln(1) = 0atm$$

AIR: Day…

$$\psi_{air}^{2pm} = \frac{55.5mol}{L}\left(\frac{0.082atm.L}{mol.K}\right)\left[(27+273)K\right]\ln(0.5) = -946atm$$



$$Tp\left(grad\psi = \frac{\psi_{air} - \psi_{leaf}}{L}\right)$$

LEAF…

$$\psi_{leaf} = \frac{55.5mol}{L}\left(\frac{0.082atm.L}{mol.K}\right)\left[(27+273)K\right]\ln(0.98907) = -15atm$$

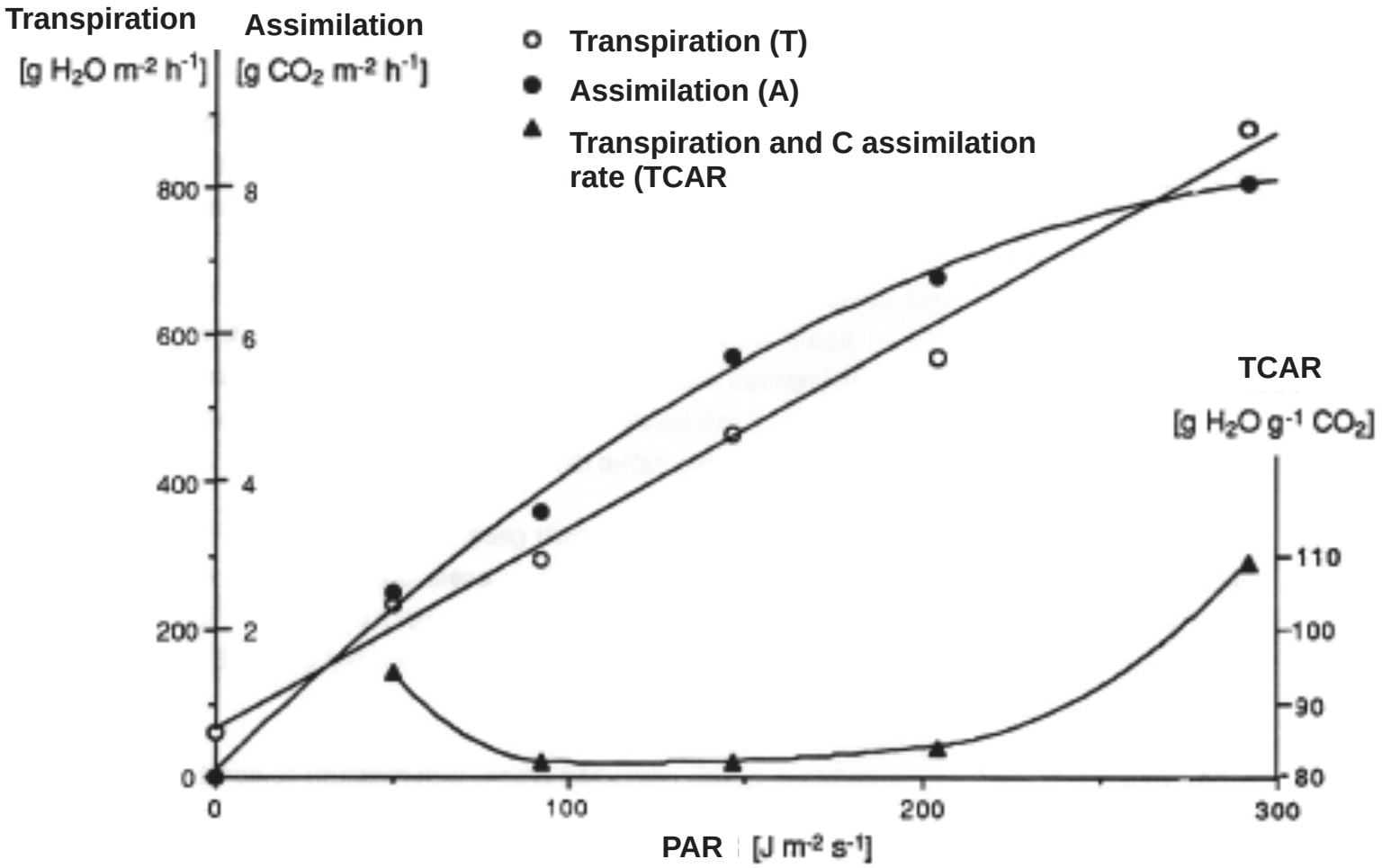
$$Ta = q = K(\theta)grad\psi\left(grad\psi = \frac{\psi^{root}{}_{soil} - \psi_{soil}}{L}\right)$$

$$\frac{\Psi_{root} - \Psi_{soil}}{r_{root}} = \frac{\Psi_{leaf} - \Psi_{root}}{r_{stem}} = \frac{\Psi_{air} - \Psi_{leaf}}{r_{leaf}}$$

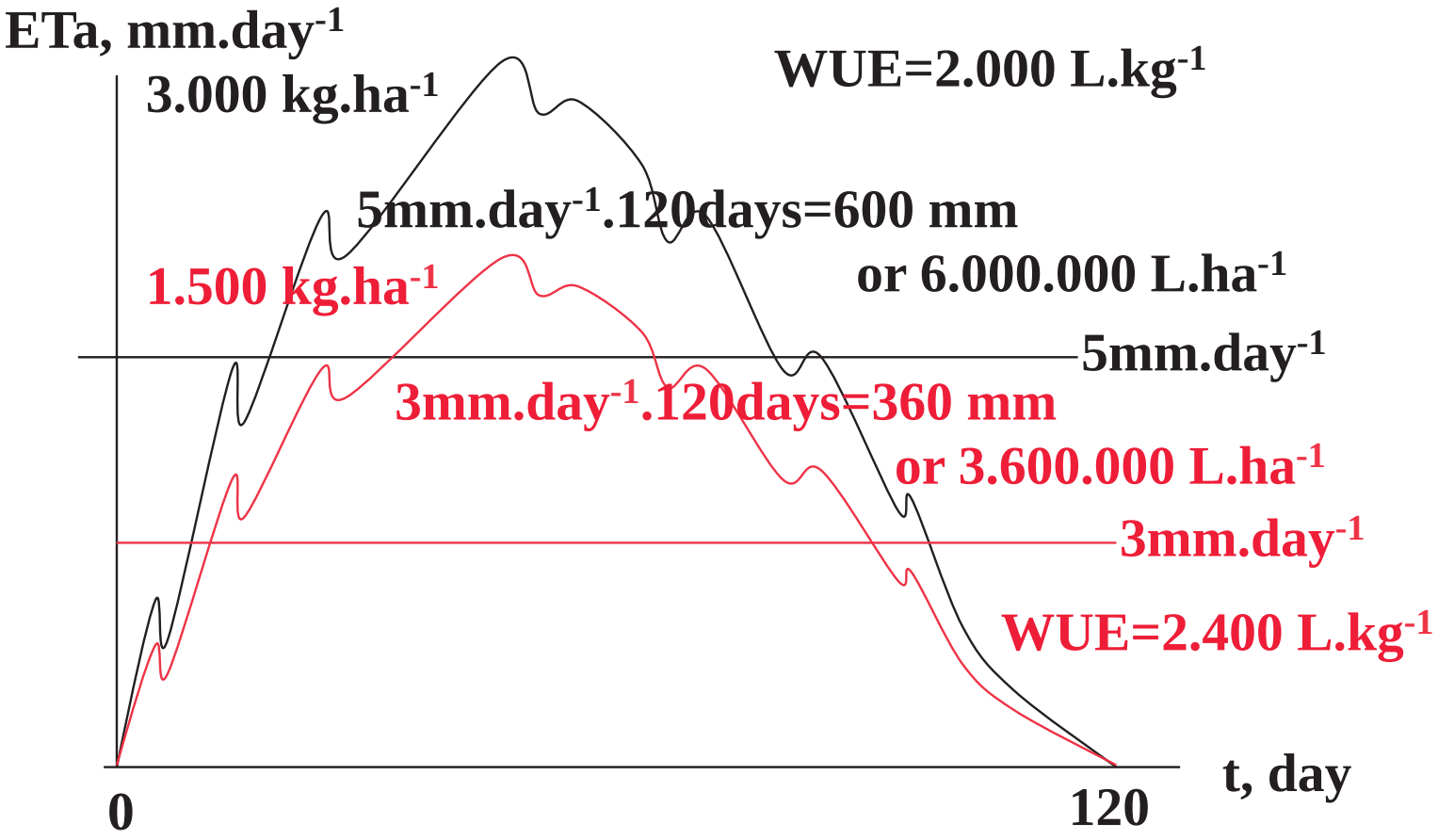
SOIL…

$$\psi_{soil\ fc} = \frac{55.5mol}{L}\left(\frac{0.082atm.L}{mol.K}\right)\left[(27+273)K\right]\ln(0.9999) = -0.14atm$$

Transpiration and C assimilation

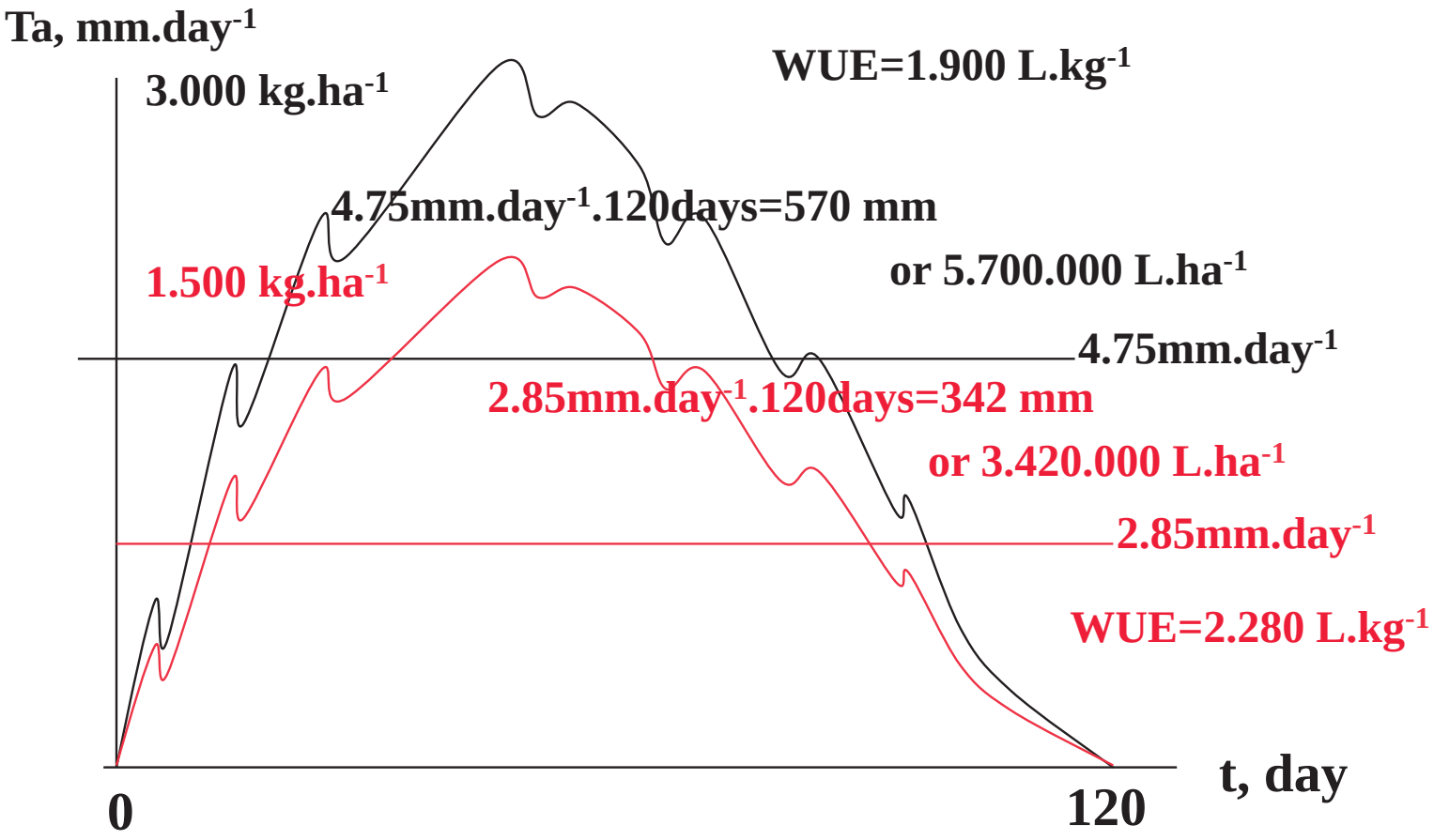


Evapotranspiration



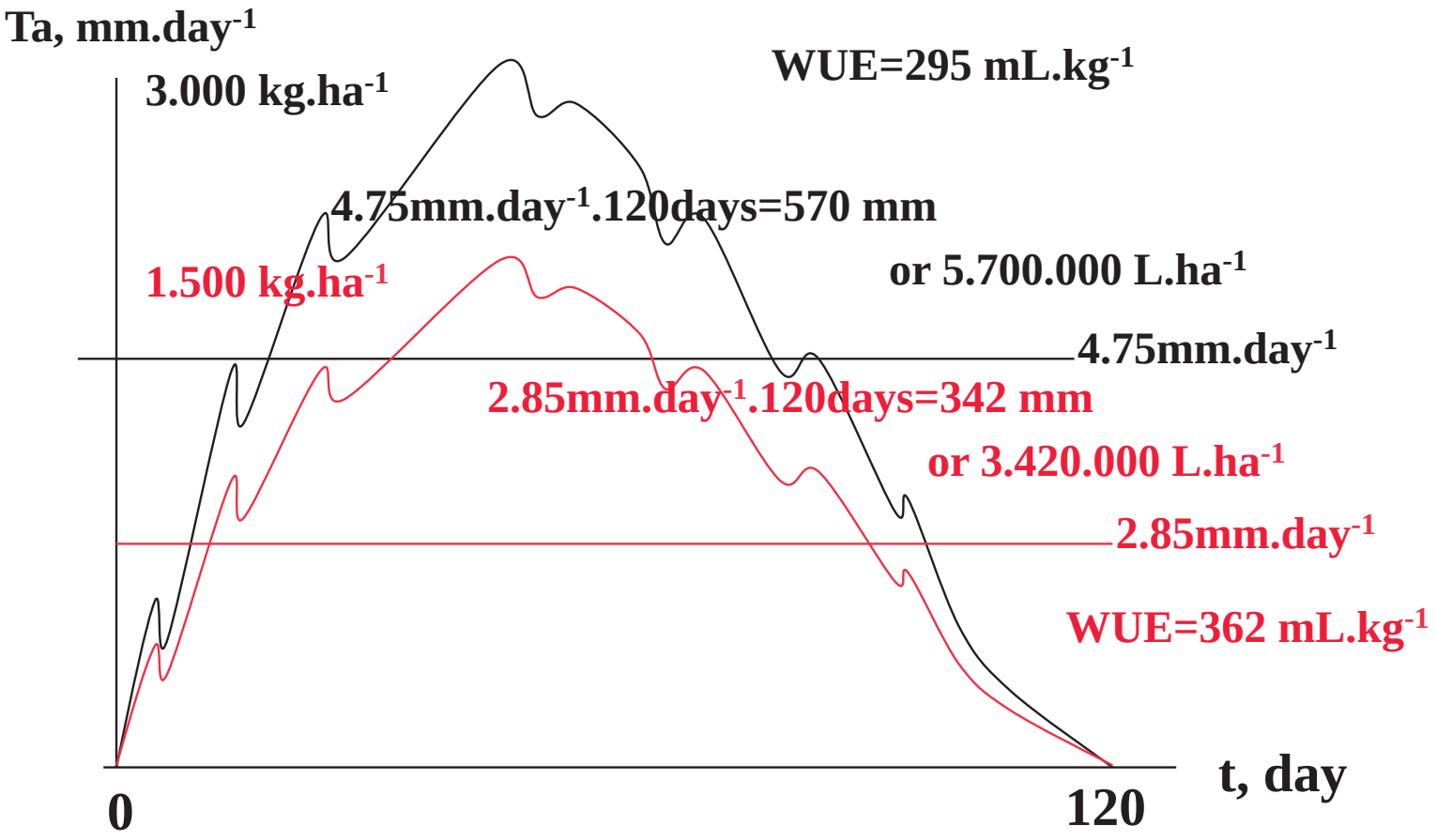
Transpiration

E=0.05xETa

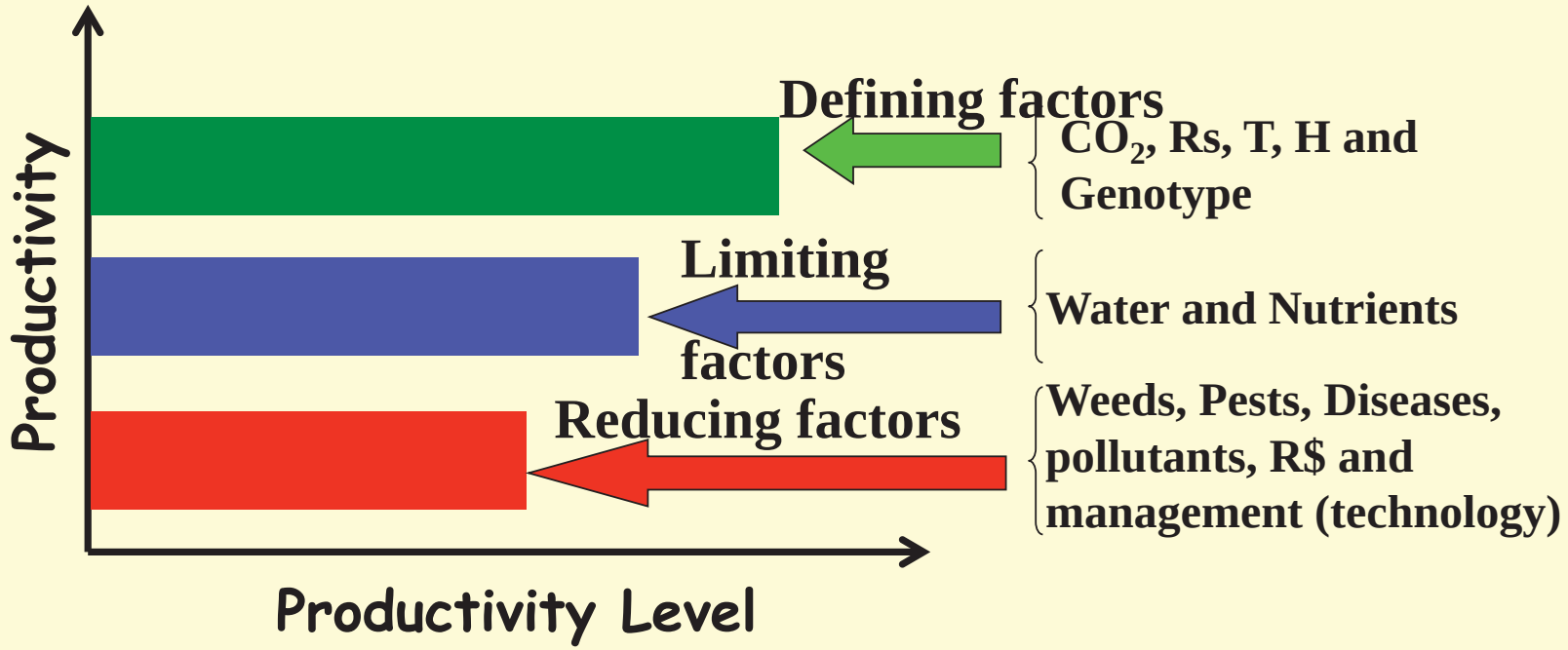


Water in the TDM and exported by grain

E=0.05xETa
HI=0.25/0.35 kg/kg
u=0.13 g/g



Productivity

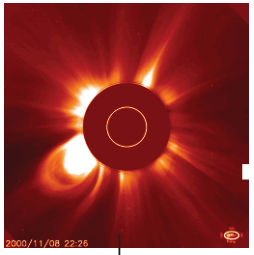


Potential productivity

Attainable productivity

Actual productivity

Productivity



Solar radiation

Atmosphere

Pests

Diseases

Weeds

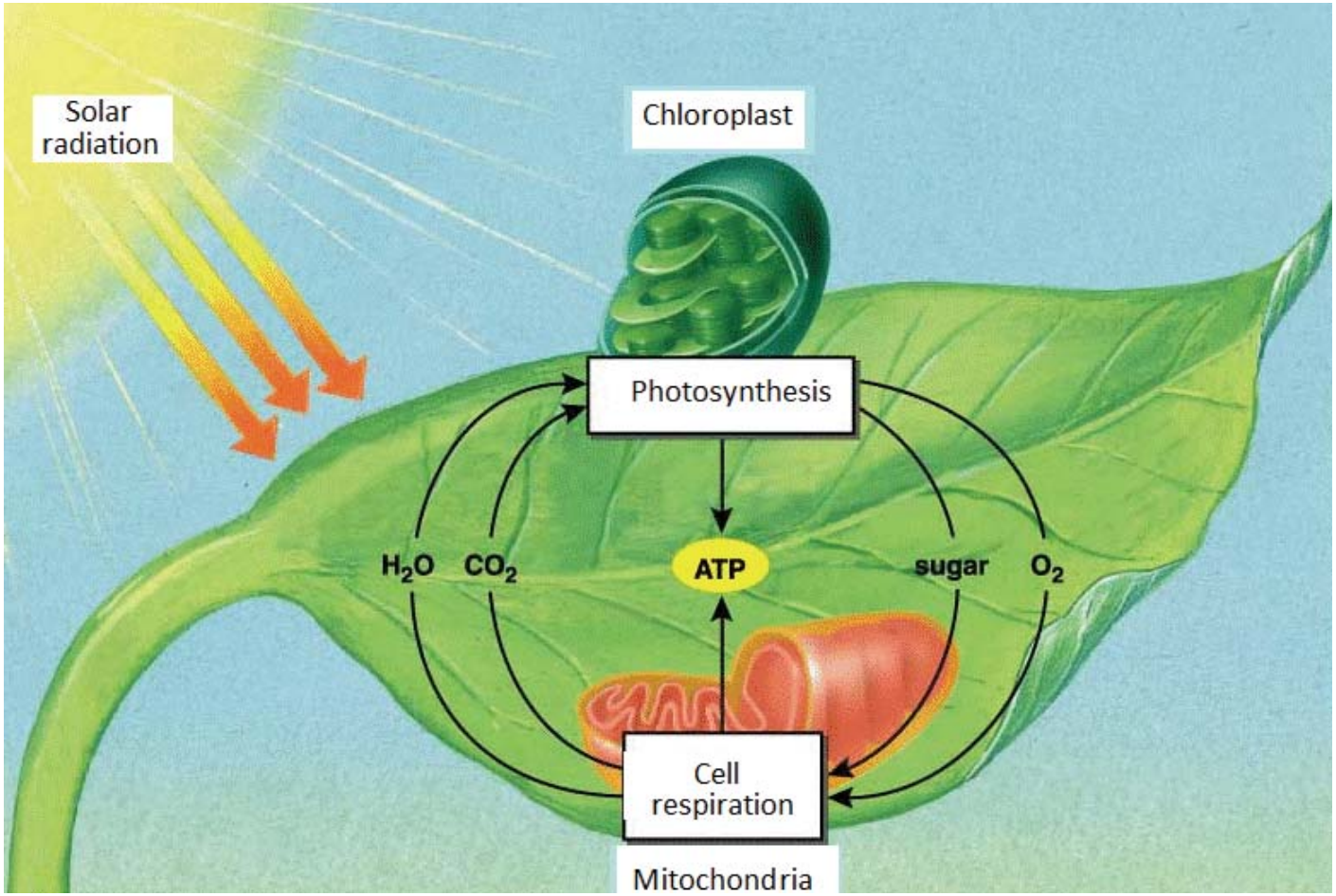
Plant

Soil

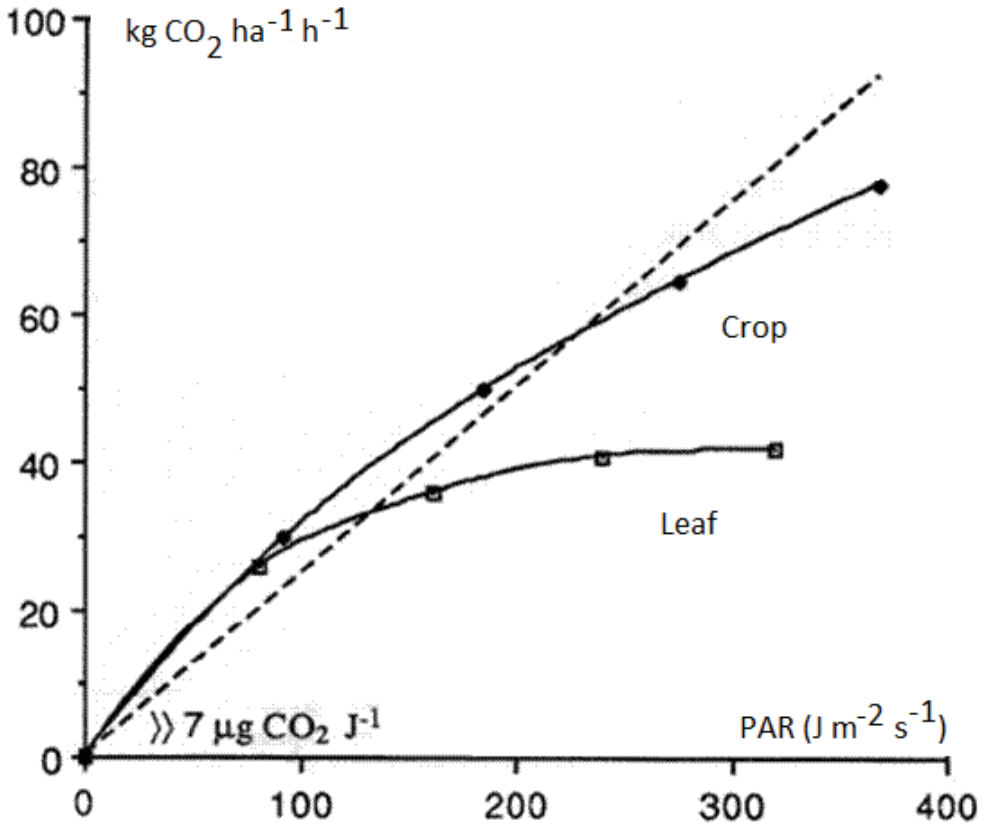
Productivity depends on:

- **Environment**
  - **Sowing date**
    - **Solar radiation, temperature and photoperiod**
    - **Rainfall**
  - **Soil type**
    - **Soil water holding capacity and Flux density**
- **Genotype – Soybean cultivar**
- **Crop management**
  - **Based on phenology and economic decision**

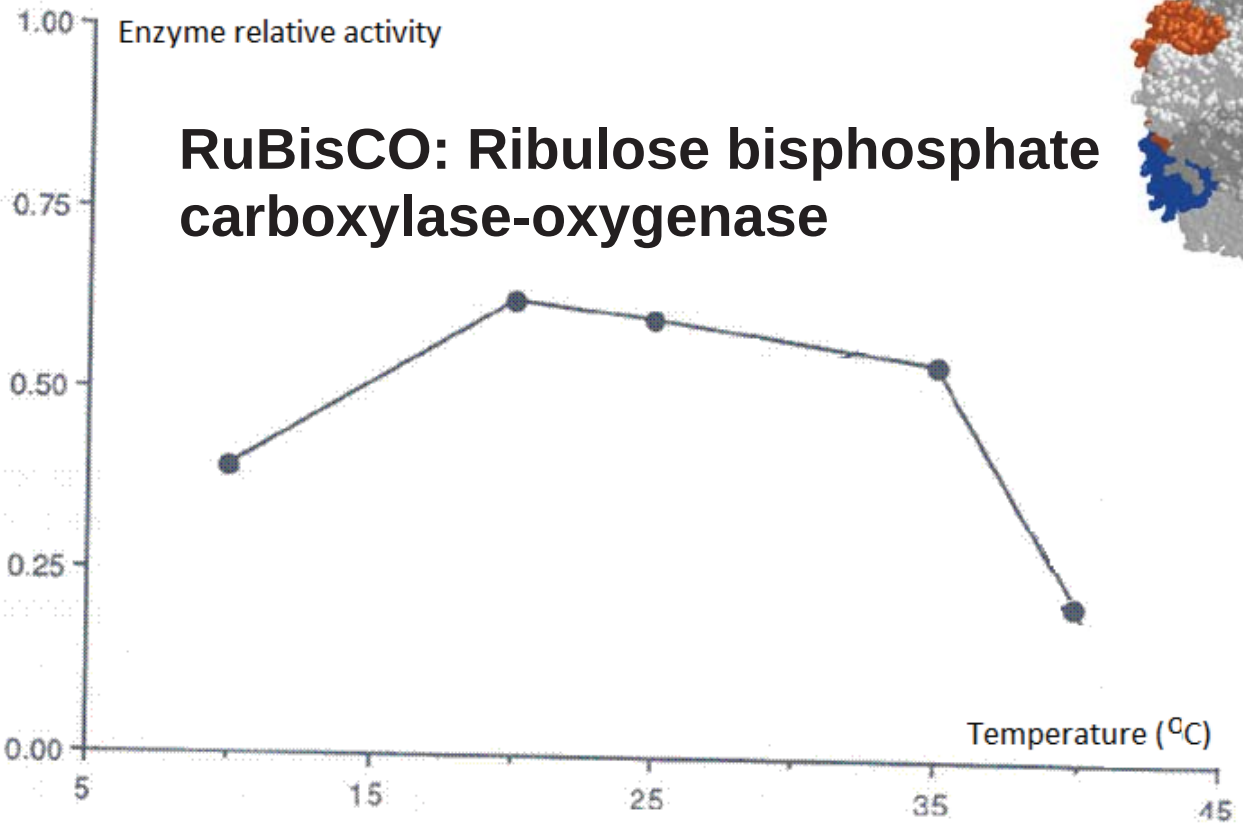
Photosynthesis



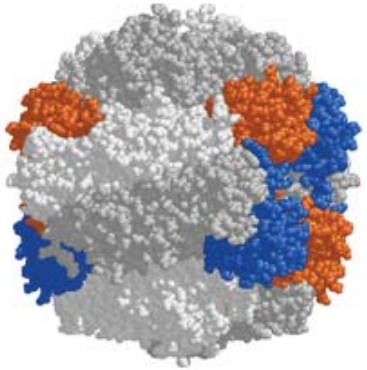
Gross photosynthesis



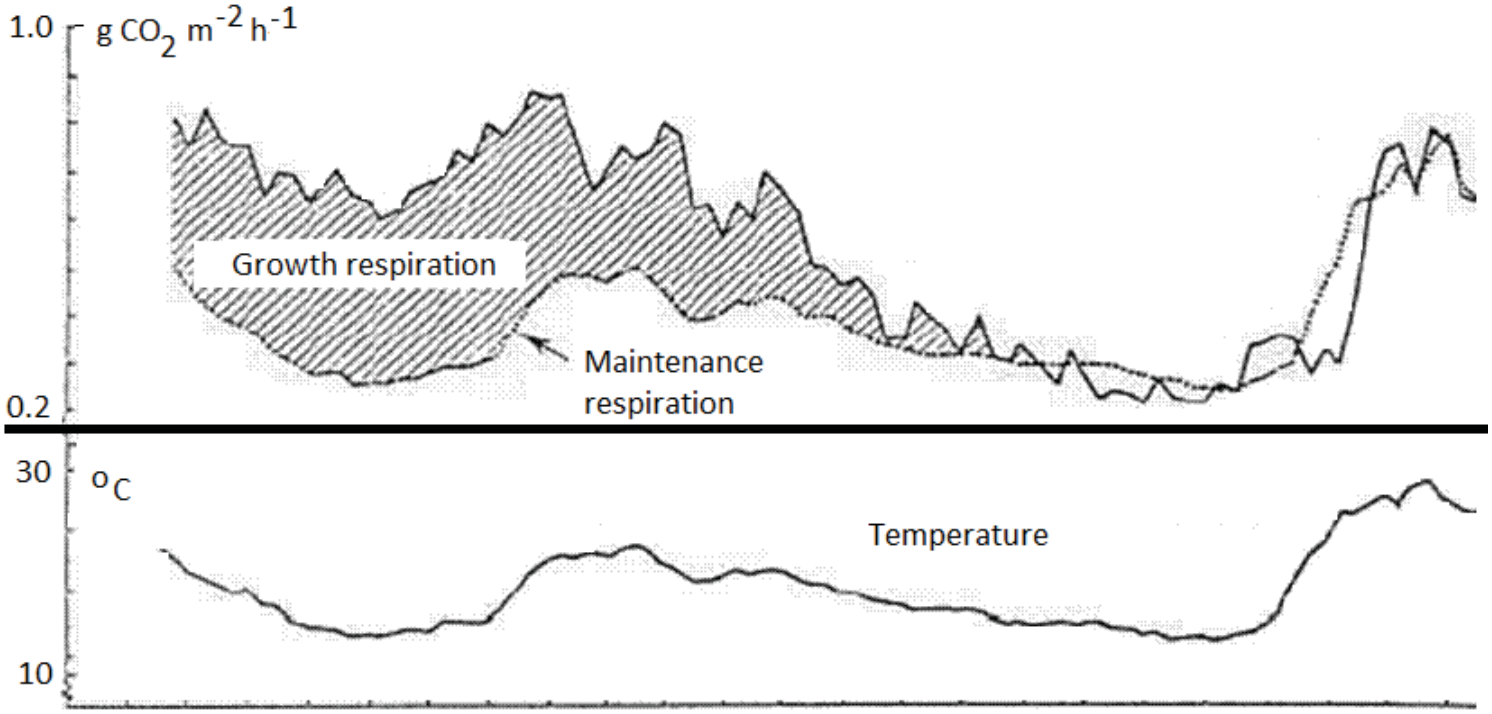
Enzyme activity



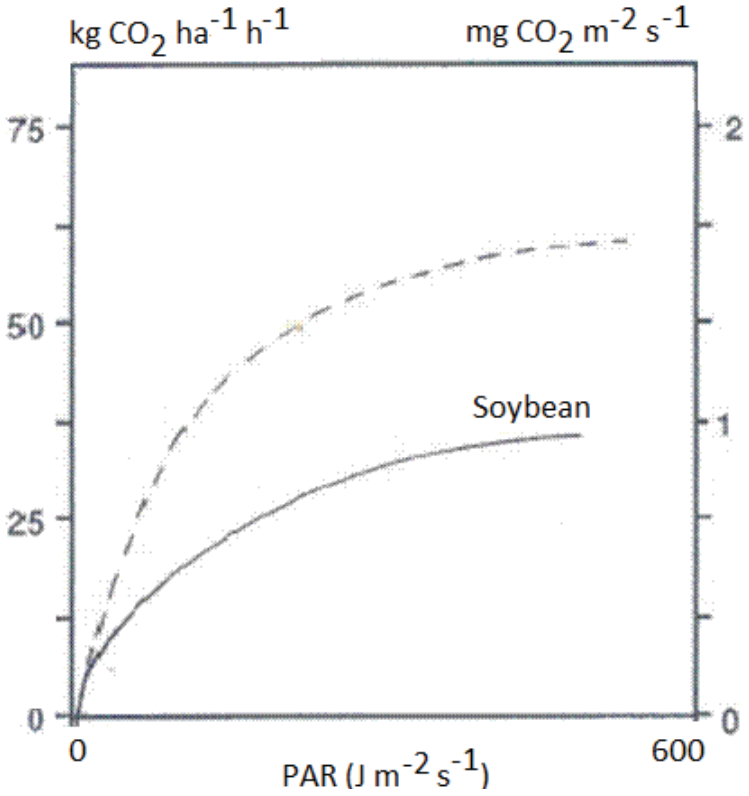
RuBisCO: Ribulose bisphosphate carboxylase-oxygenase

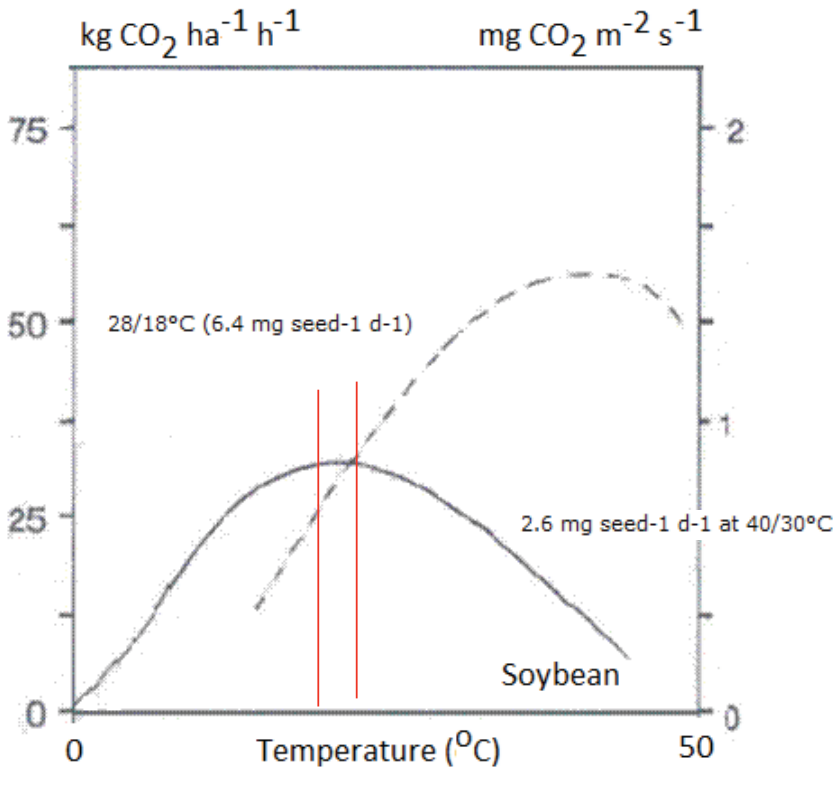


Respiration



Net photosynthesis



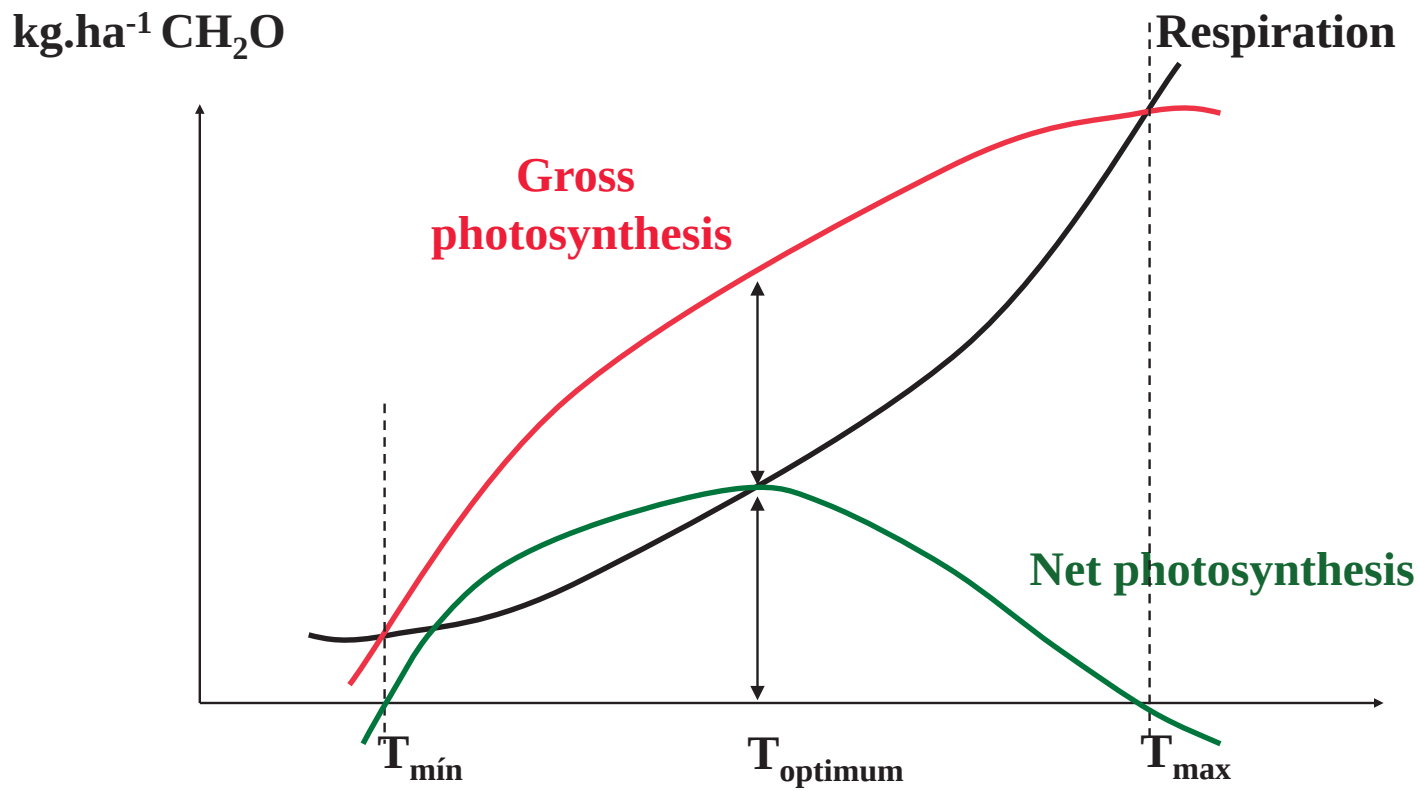


Elevated Temperature Delays Onset of Reproductive Growth and Reduces Seed Growth Rate of Soybean

Jean M.G. Thomas, Kenneth J. Boote, Deyun Pan, Leon Hartwell Allen

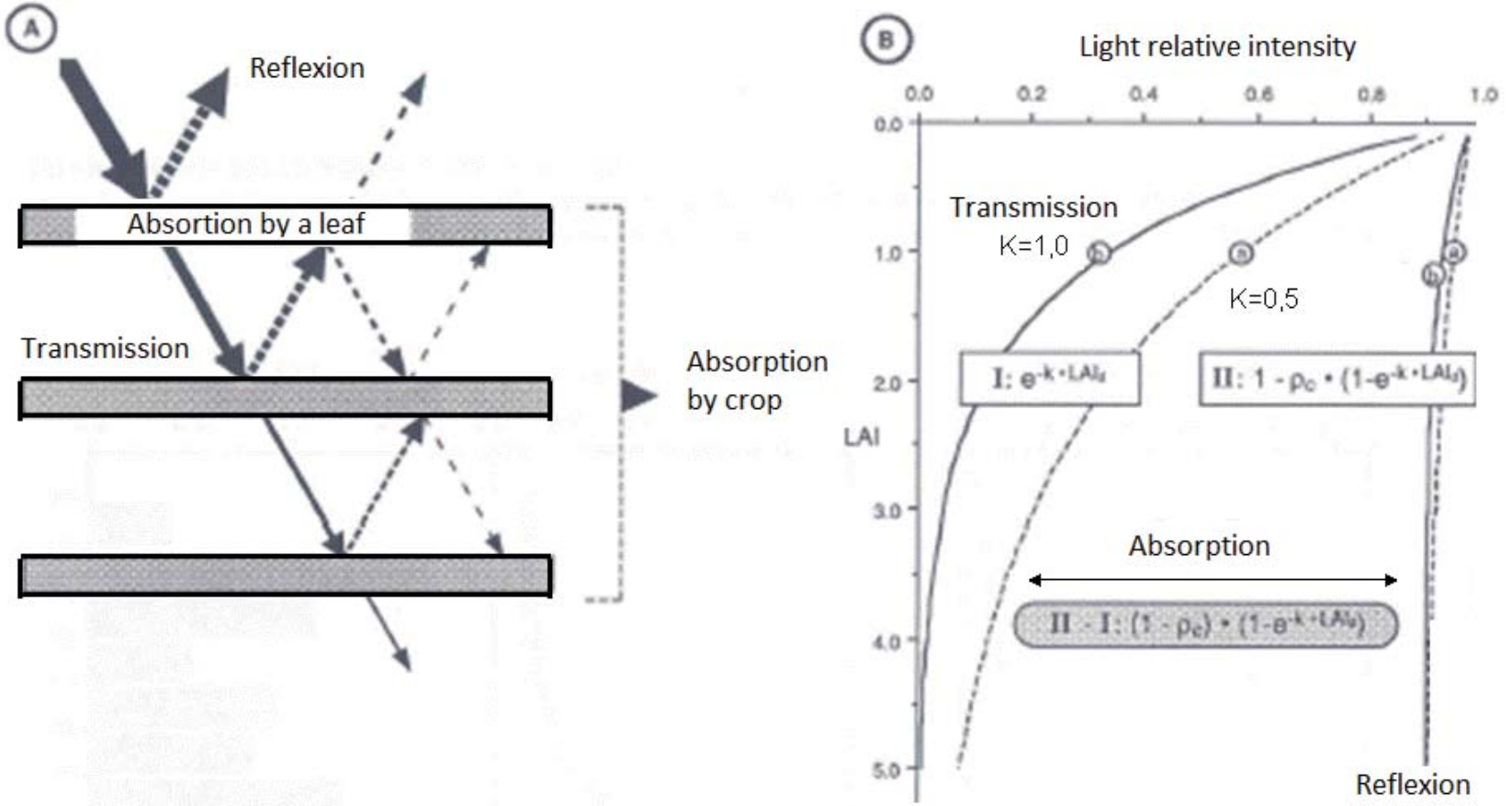
Journal of Agro Crop Science, Vol 1, No 1 (2010)

Net photosynthesis

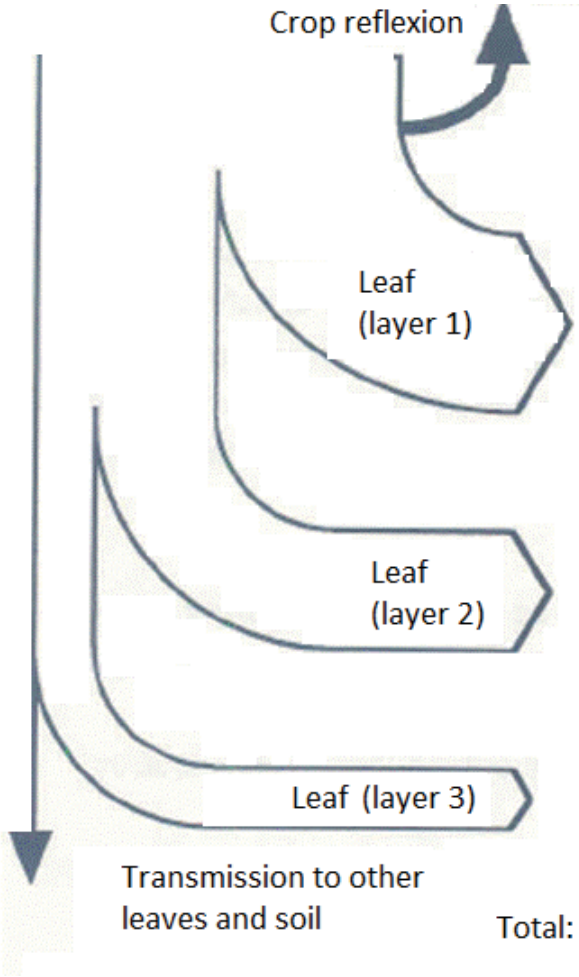


Genotype definition…

Leaf Area Index (LAI, $m^2.m^{-2}$)

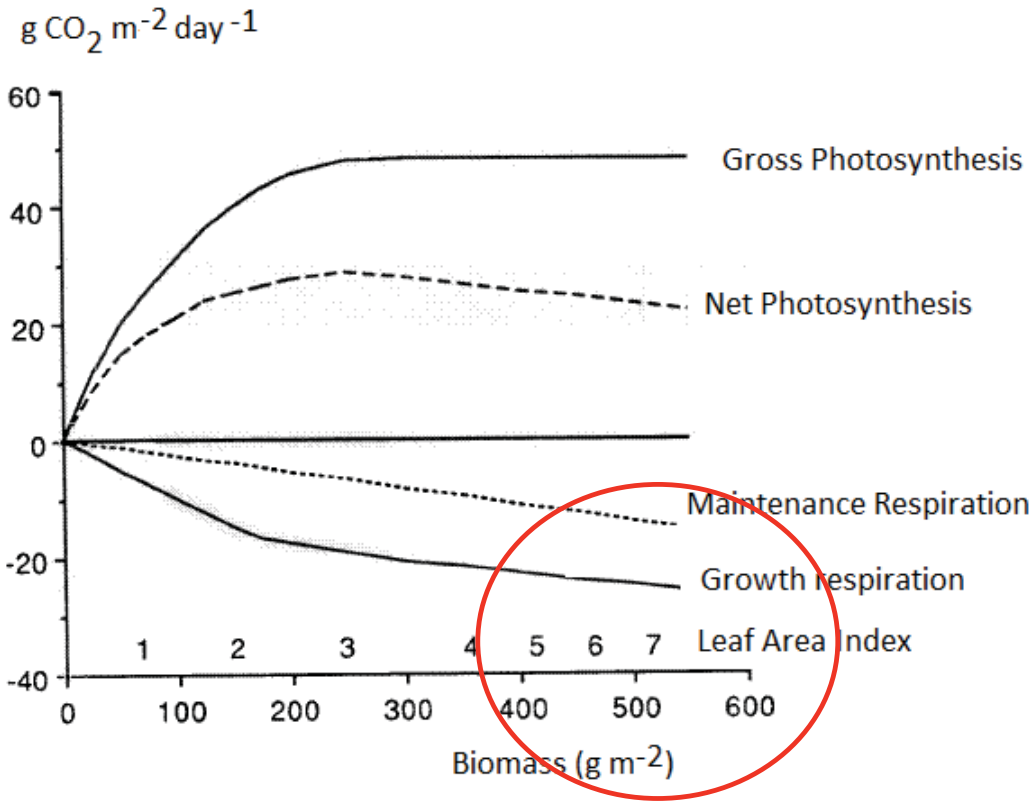


Leaf Area Index (LAI, $m^2.m^{-2}$)

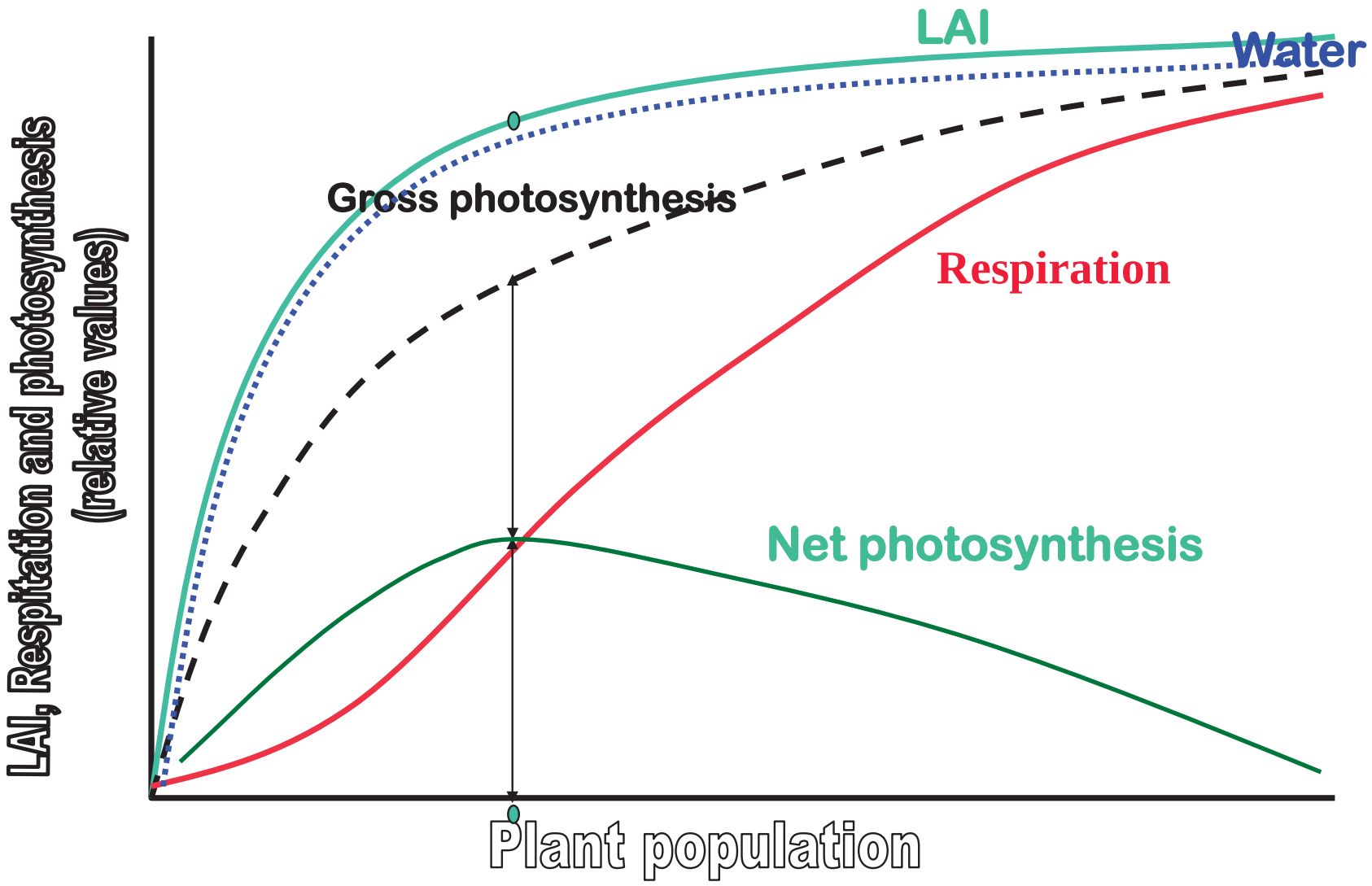


	100 J m^{-2} s^{-1}				500 J m^{-2} s^{-1}			
	PAR_{inc}	PAR_{abs}	A_{gross}	LUE	PAR_{inc}	PAR_{abs}	A_{gross}	LUE
Leaf (layer 1)	92.00	46.31	16.24	0.35	460.00	231.57	37.04	0.16
Leaf (layer 2)	45.69	23.00	9.12	0.40	228.43	114.99	29.03	0.25
Leaf (layer 3)	22.69	11.42	4.82	0.42	113.44	57.10	18.96	0.33
Total:		80.73	30.18	0.37		403.67	85.03	0.21

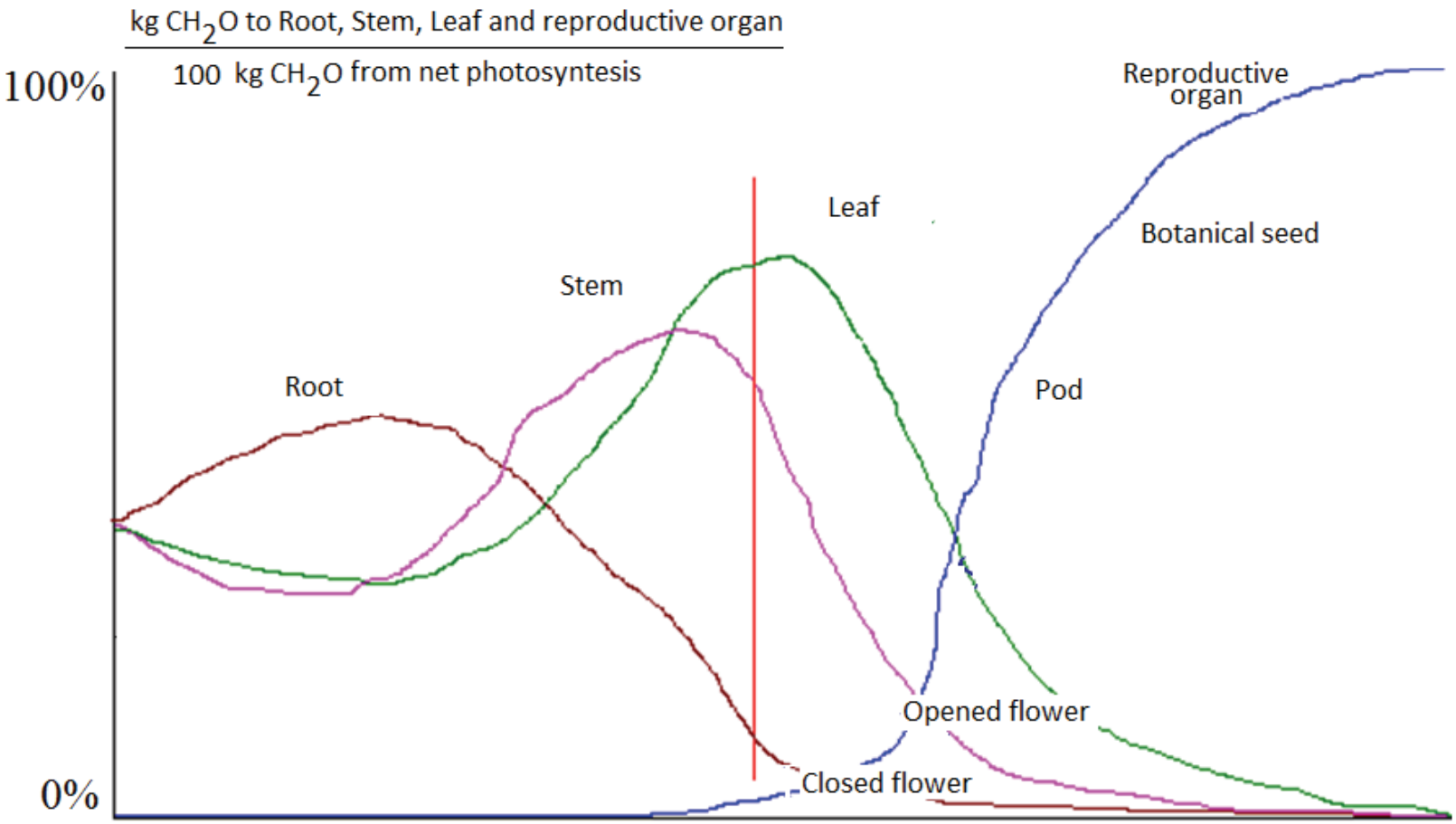
Biomass and CO_2 assimilation



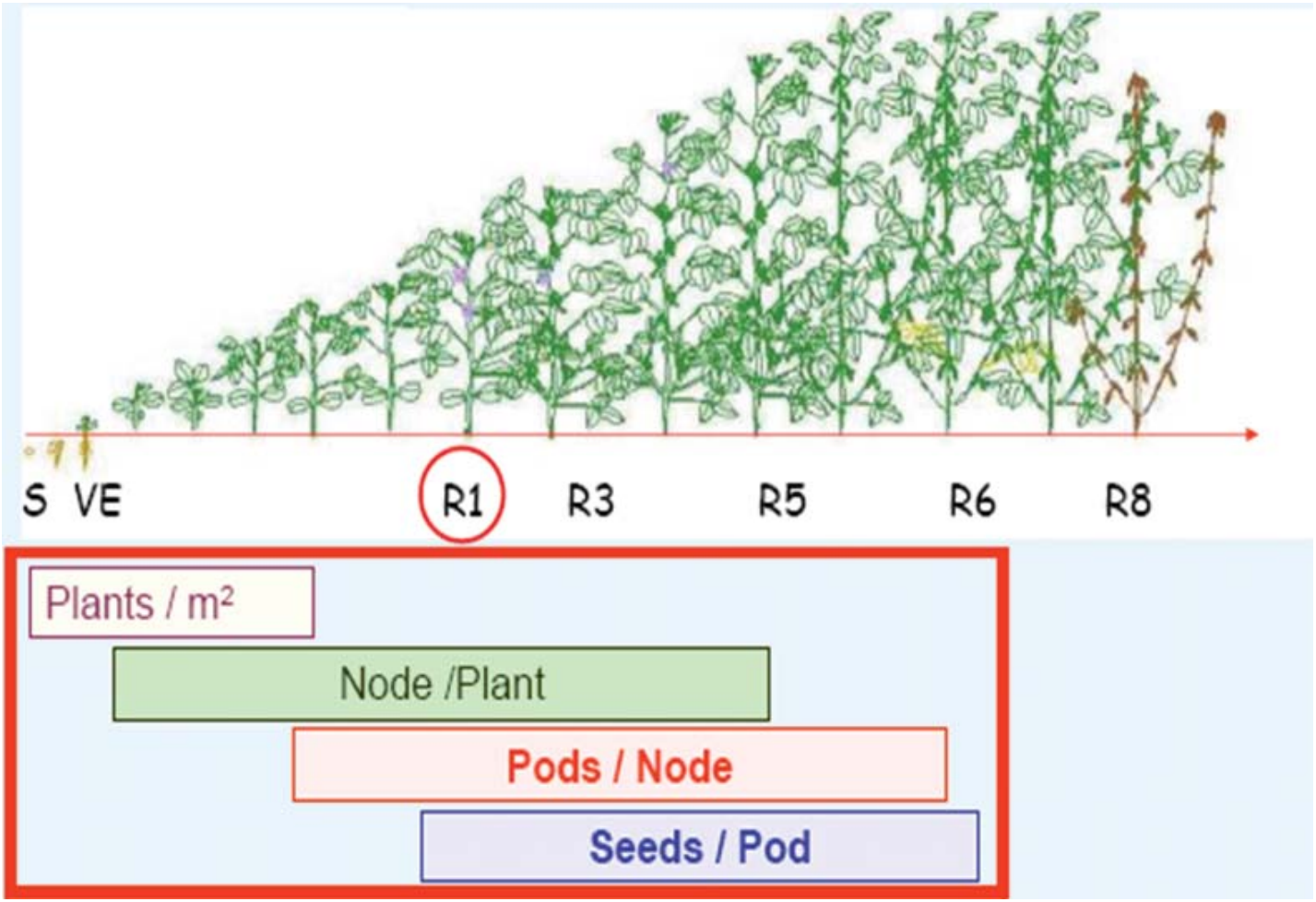
Plant population



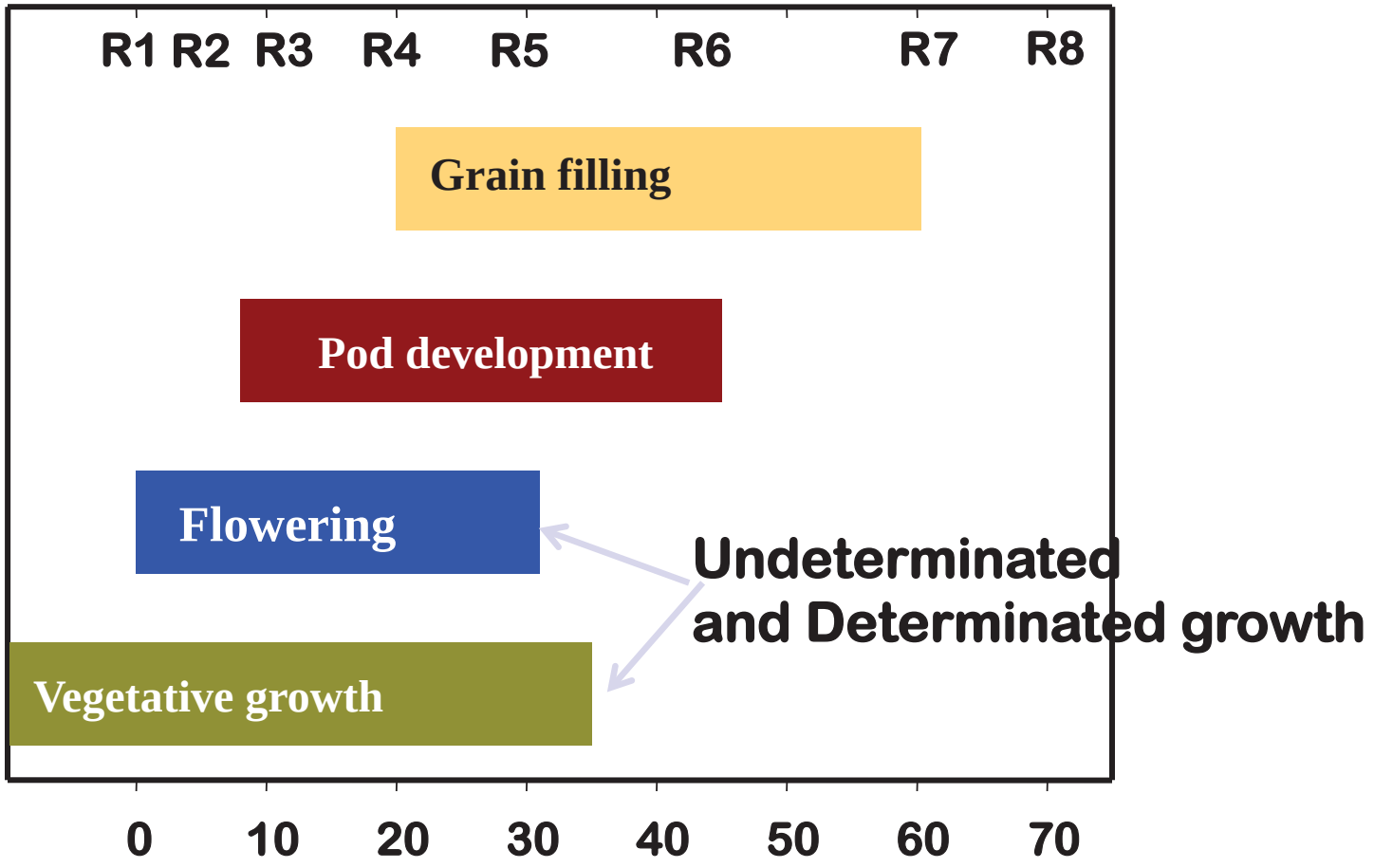
Carbon Partition



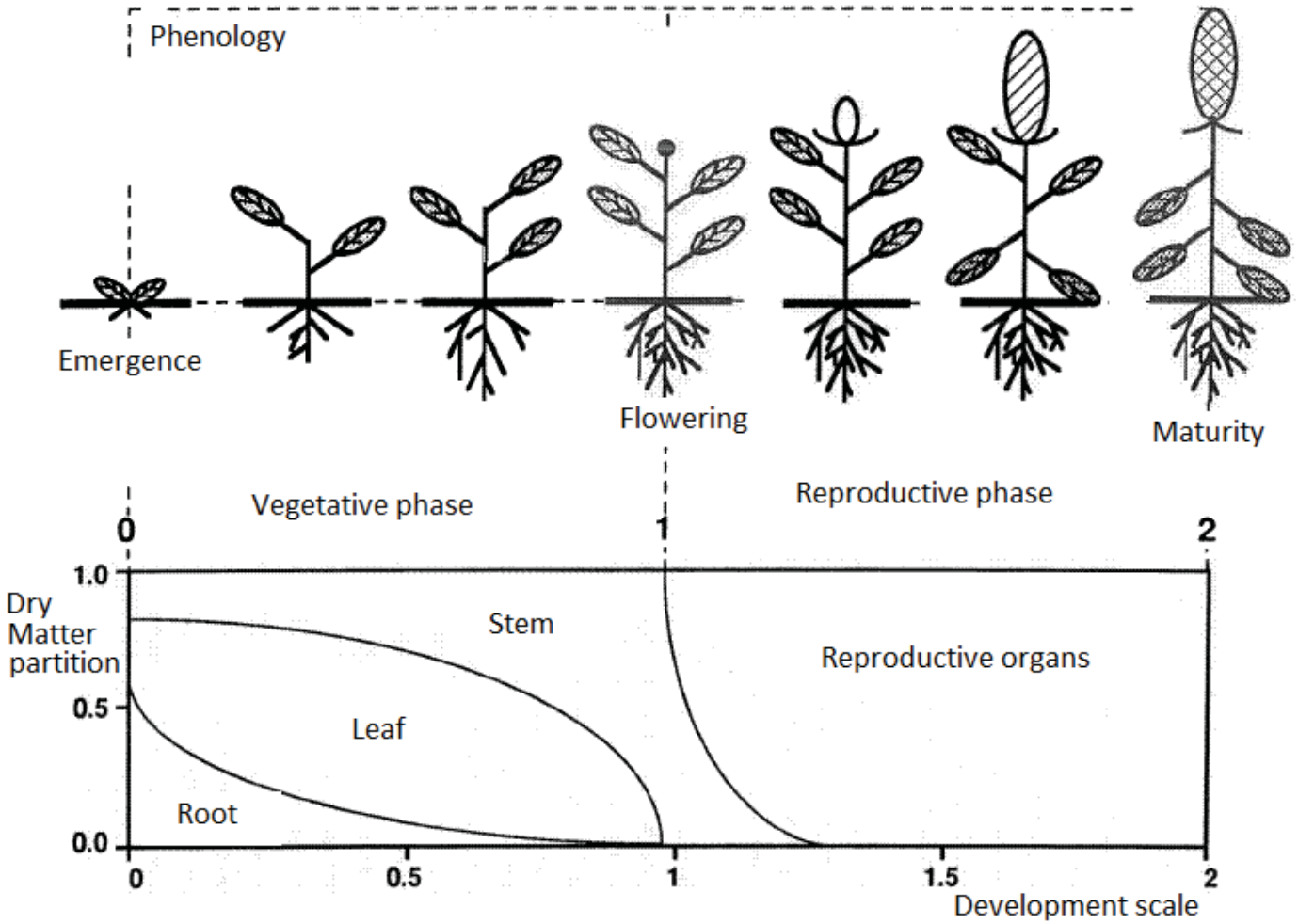
Soybean phenology and critical periods



Reproductive phase



Dry Matter Partition

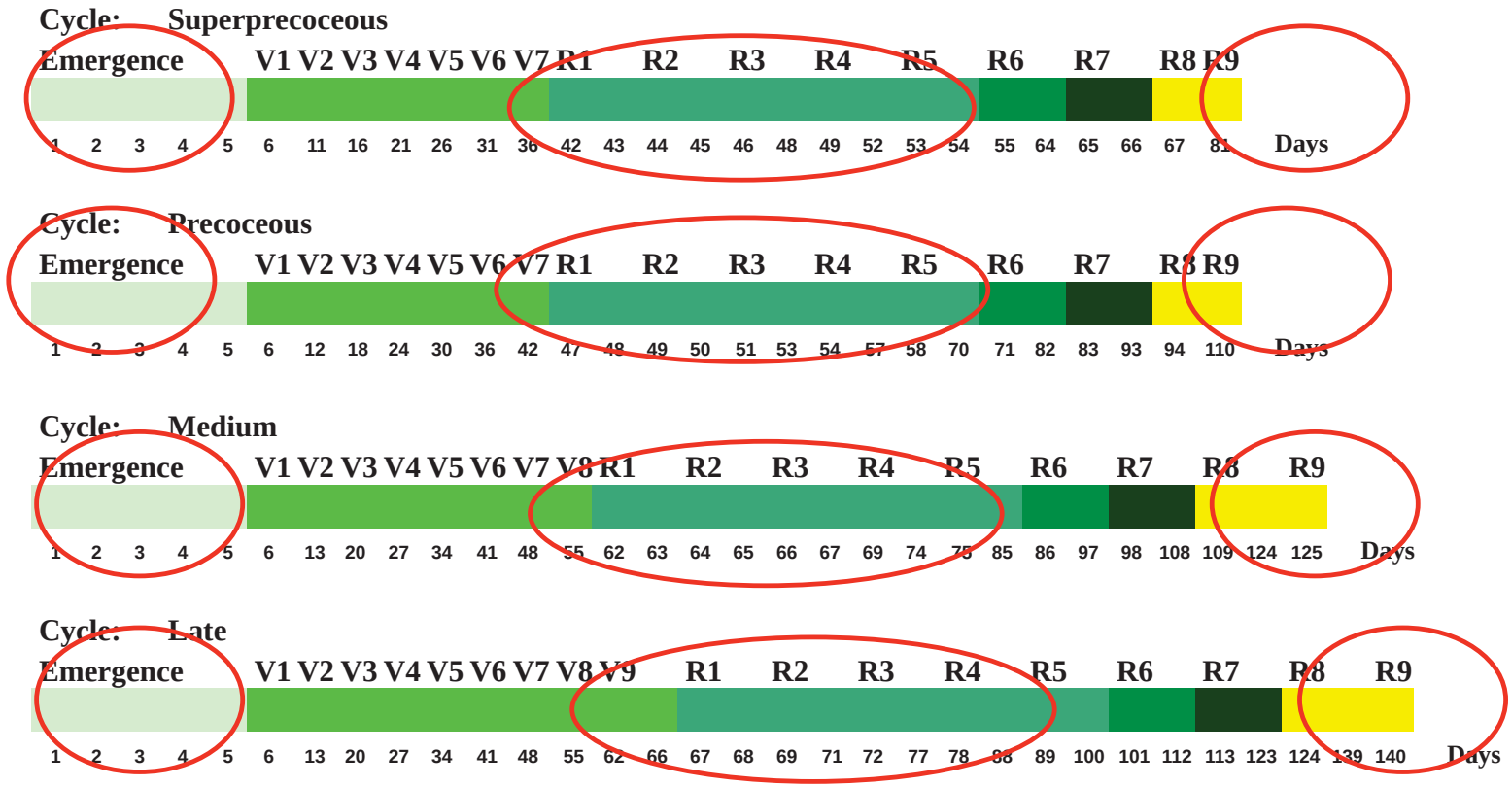


Phenology – critical periods

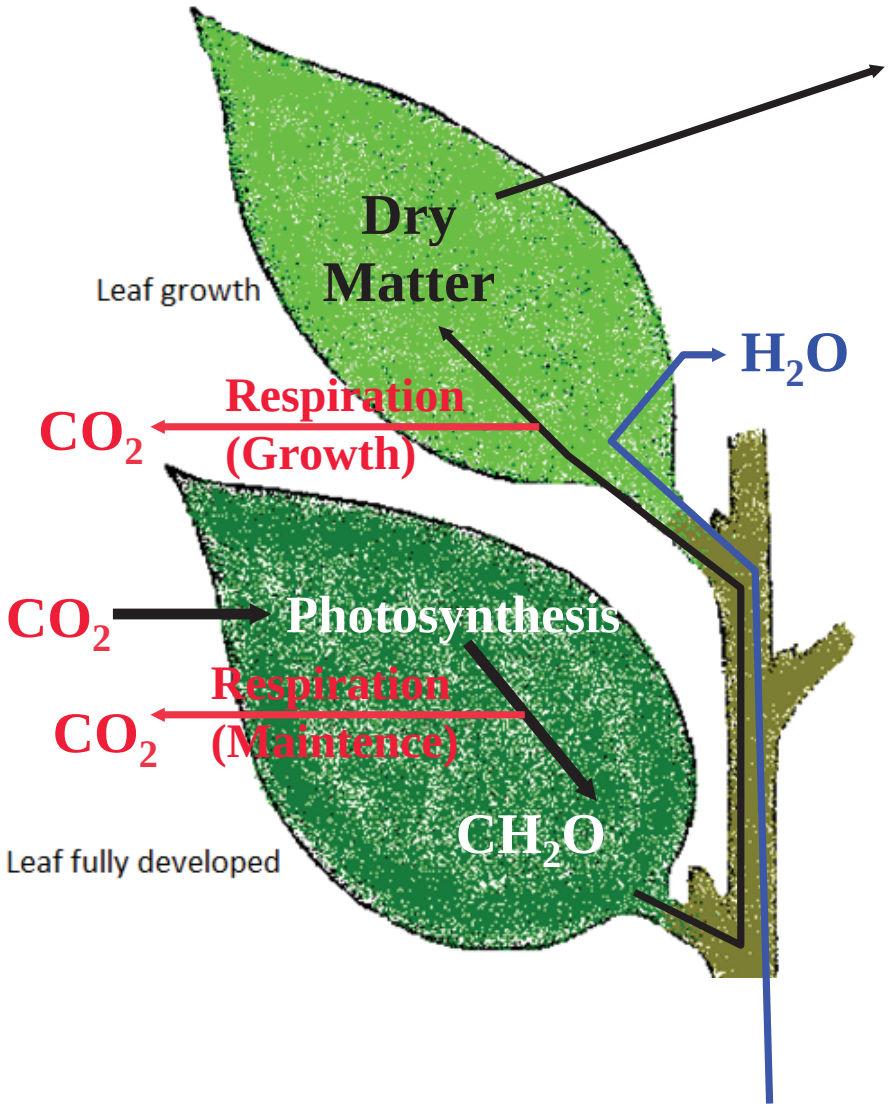
Water for stablishment

Water during critical period

No water for harvesting



Conversion efficiency



Dry Matter composition:

- Fats
- Lignins
- Proteins
- Carbohydrates
- Organic acids
- Minerals

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

45% C	
45% O	
6% H	
96.00%	
3.50%	N,P,K,Ca,Mg,S
0.03%	B,Cl,Cu,Fe,Mn,Mo,Zn
0.47%	others
100.00%	

N

Macronutrientes e nutrientes orgânicos		ppm	Nutriente	%
Nutrientes orgânicos				
C = Carbon 450,000 ppm	C = Carbon 450,000 ppm	450,000	C	45.00
H = Hydrogen 60,000 ppm	H = Hydrogen 60,000 ppm	60,000	H	6.00
O = Oxygen 450,000 ppm	O = Oxygen 450,000 ppm	450,000	O	45.00
SUBTOTAL				**96.00**
Macronutrientes				
P = Phosphorus 2,000 ppm	P = Phosphorus 2,000 ppm	2,000	P	0.20
K = Potassium 10,000 ppm	K = Potassium 10,000 ppm	10,000	K	1.00
N = Nitrogen 15,000 ppm	N = Nitrogen 15,000 ppm	15,000	N	1.50
S = Sulfur 1,000 ppm	S = Sulfur 1,000 ppm	1,000	S	0.10
Ca = Calcium 5,000 ppm	Ca = Calcium 5,000 ppm	5,000	Ca	0.50
Mg = Magnesium 2000 ppm	Mg = Magnesium 2000 ppm	2,000	Mg	0.20
SUBTOTAL				**3.50**
Microutrientes				
Fe = Iron 100 ppm	Fe = Iron 100 ppm	100	Fe	0.01000
Mo = Molybdenum 0.1 ppm	Mo = Molybdenum 0.1 ppm	0.1	Mo	0.00001
B = Boron 20 ppm	B = Boron 20 ppm	20	B	0.00200
Cu = Copper 6 ppm	Cu = Copper 6 ppm	6	Cu	0.00060
Mn = Manganese 50 ppm	Mn = Manganese 50 ppm	50	Mn	0.00500
Zn = Zinc 20 ppm	Zn = Zinc 20 ppm	20	Zn	0.00200
Cl = Chlorine 100 ppm	Cl = Chlorine 100 ppm	100	Cl	0.01000
SUBTOTAL				**0.03**
SUBTOTAL		995,296		
TOTAL		1,000,000		
Outros		**4,704**		**0.47**

Conversion efficiency

compound	A biosynthesis costs g gluc.g^{-1} prod	B transport costs g gluc g^{-1} prod	C = A + B conversion costs g gluc g^{-1} prod	D = 1/C CVF g prod g^{-1} gluc
fats	3.030	0.159	3.189	0.31
lignin	2.119	0.112	2.231	0.45
proteins	1.824	0.096	1.920	0.52
carbohydrates	1.211	0.064	1.275	0.78
organic acids	0.906	0.048	0.954	1.05
minerals (K,Ca,P, S)	0.0	0.120	0.120	(8.3)

Soybean composition:

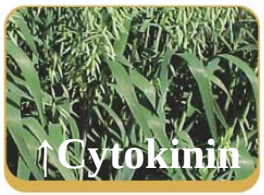
- **Protein = 40 %**
- **Oil = 20 %**

1 kg of CH_2O from Net Photosynthesis produces

0.55 kg of Dry Matter of seeds

Soybean: environment and plant physiology

Promotor and inhibitor hormones and effect of Ca, B and enzymes



↑RuBisCO

↑ division and cell expansion

↑Leaf DM and LAI

↓ABA (Abscisic Acid)

↓Ethylene

↓Senecence

↑Leaf DM and LAI

↑IAA (Indole Acetic Acid)

↓Senescence

↑division and cell expansion

↑activity of POD, SOD and CAT enzymes

↓

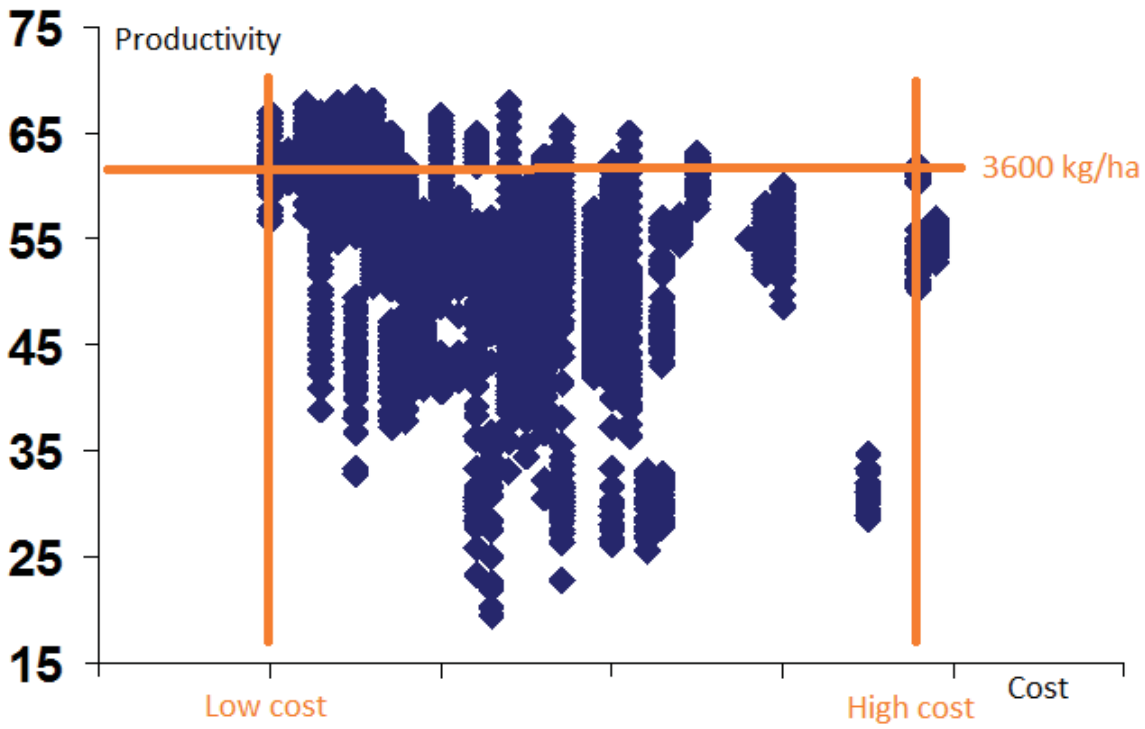
Antioxidant effect (↓ROS): Keep membrane integrity and inhibit the premature senescence and damage on DNA

↓Chlorophyl degradation

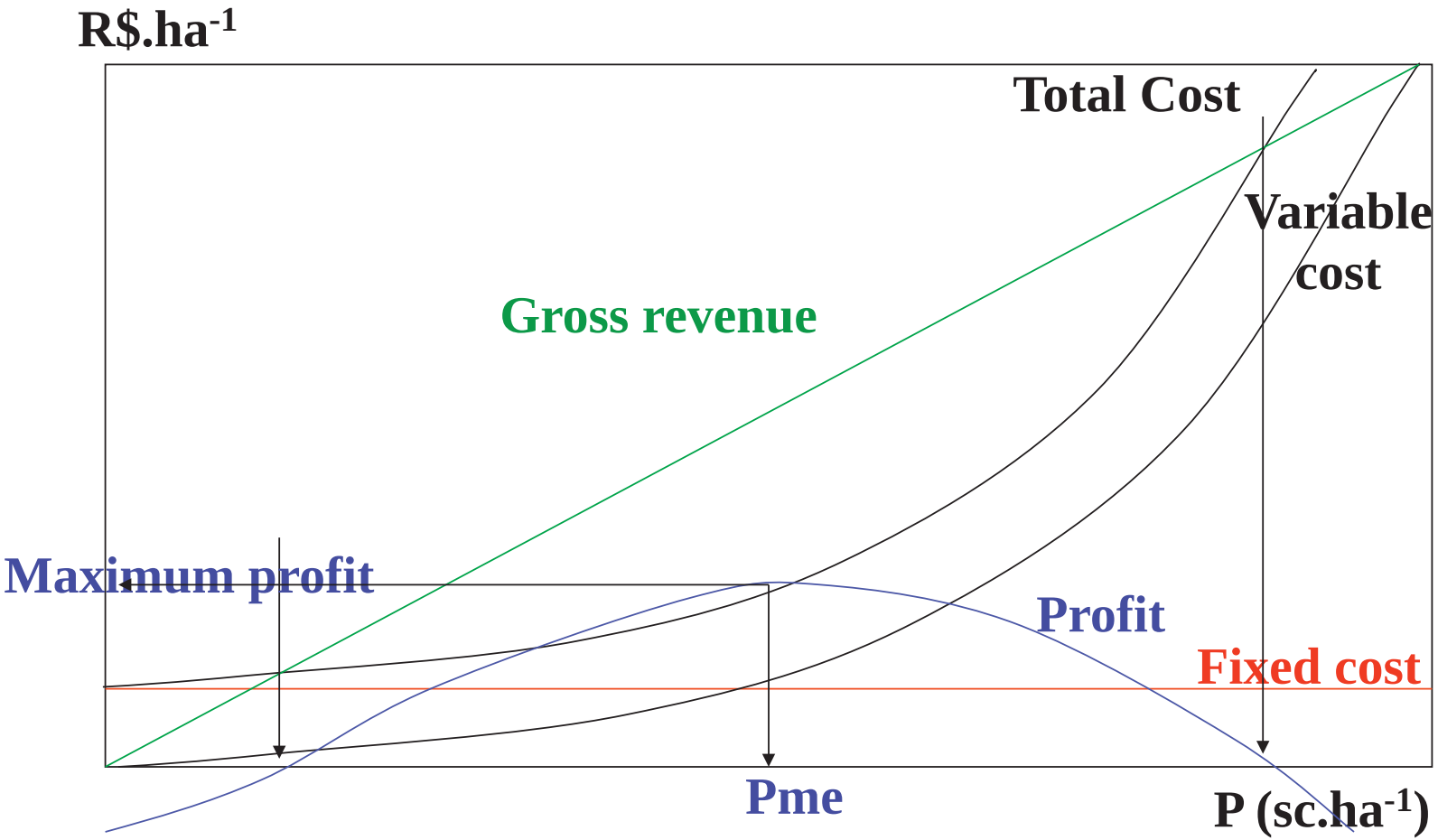
↑division and cell expansion

Ca and B: less flower aborption

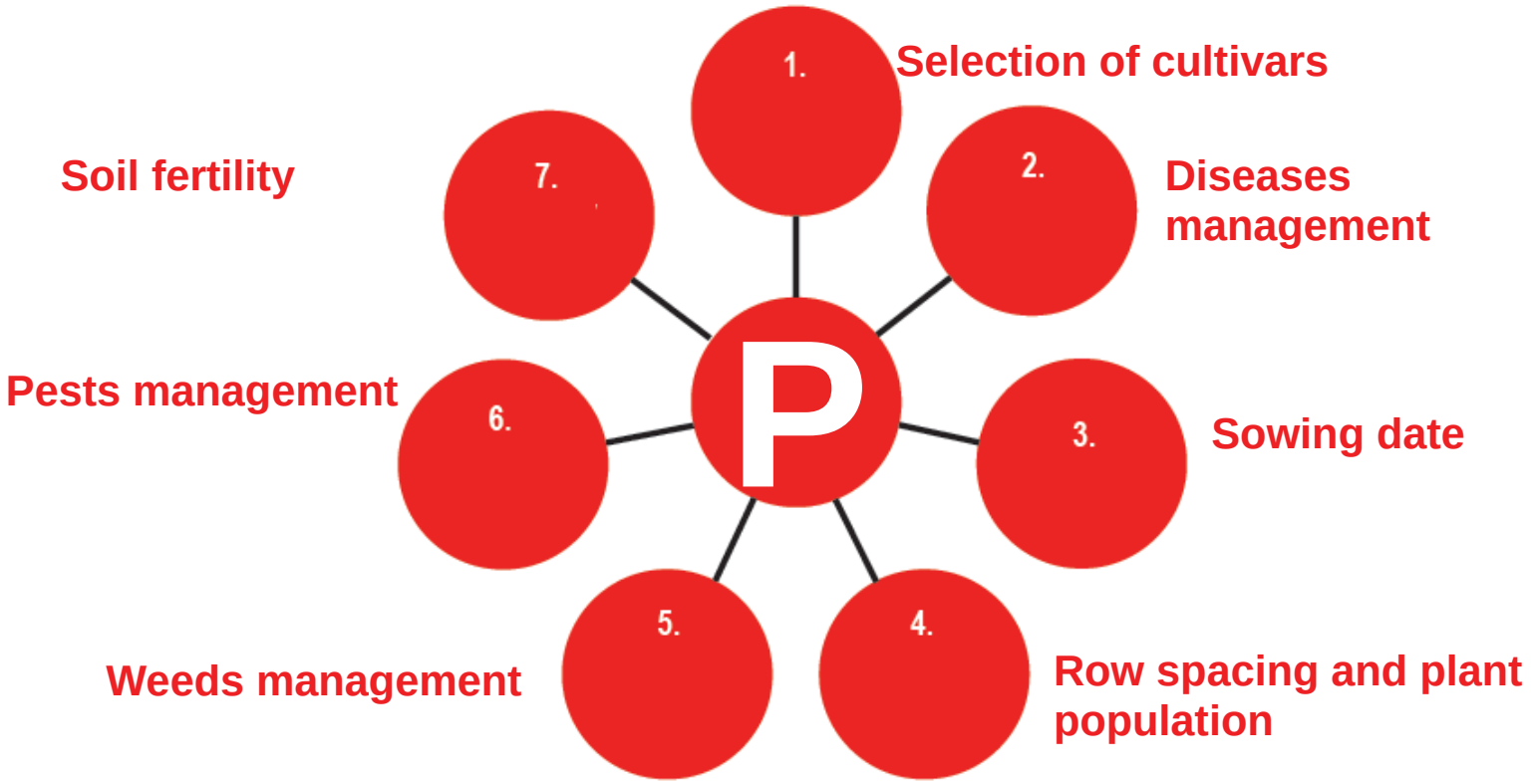
Soybean - USA


75
65
55
45
35
25
15
Productivity
3600 kg/ha
Low cost
High cost
Cost

The economical actual productivity defines TECHNOLOGY (Pme, sc.ha^{-1})



Management for high productivity (P)



Iwoa State University

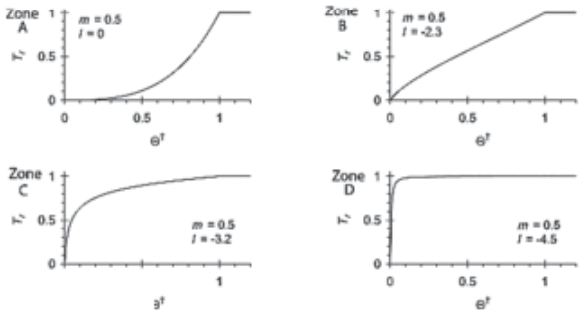
Higher productivities: 6000 kg/ha in Whiting, Iowa

4800 kg/ha - Est of Iwoa

3900 to 4200 kg/ha in Des Moines, Iwoa

Final consideration

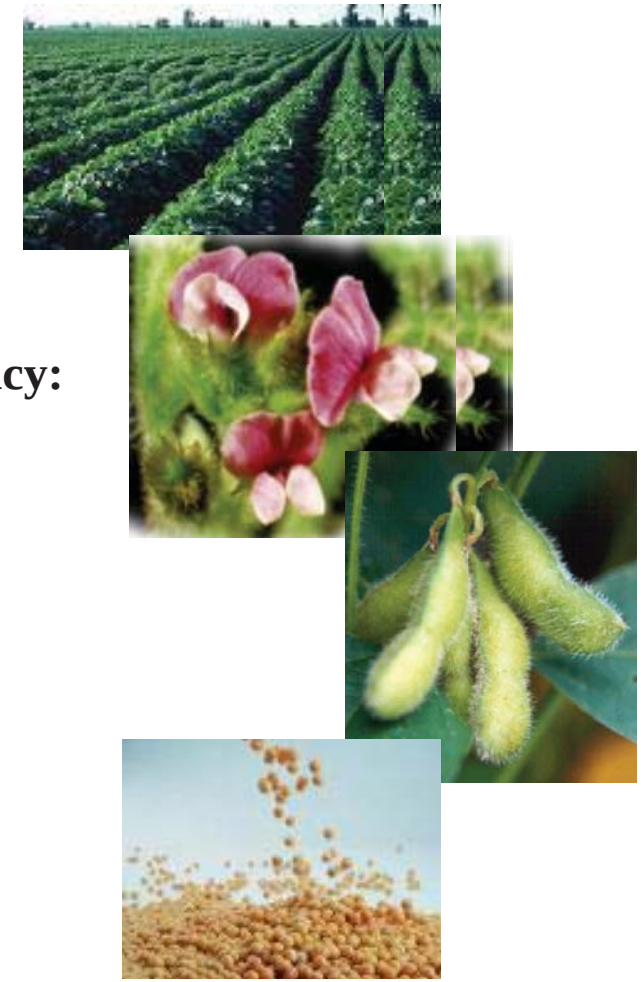
Water deficiency



1. Limiting values (*h* or θ) of macroscopic root water extraction models are a function of potential transpiration rate, soil hydraulic properties and root density.
2. $h_{mean,lim}$ and $\theta_{mean,lim}$ can be calculated from the matric flux potential at 0.53 r_m, which is a function of transpiration rate and root density and which depends on a soil-specific $K(h)$ function.

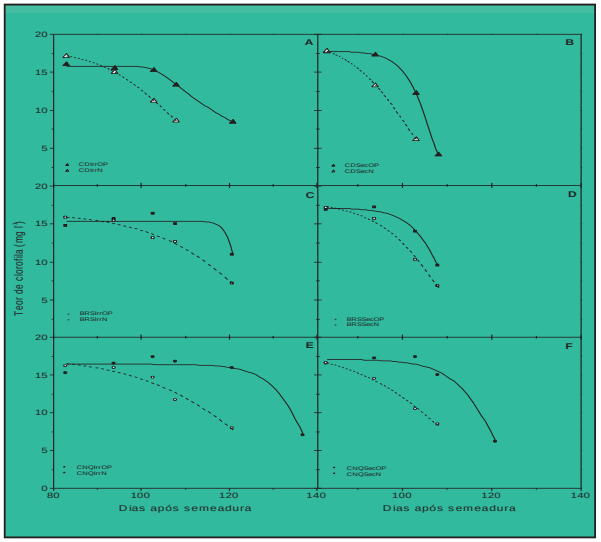
Final consideration

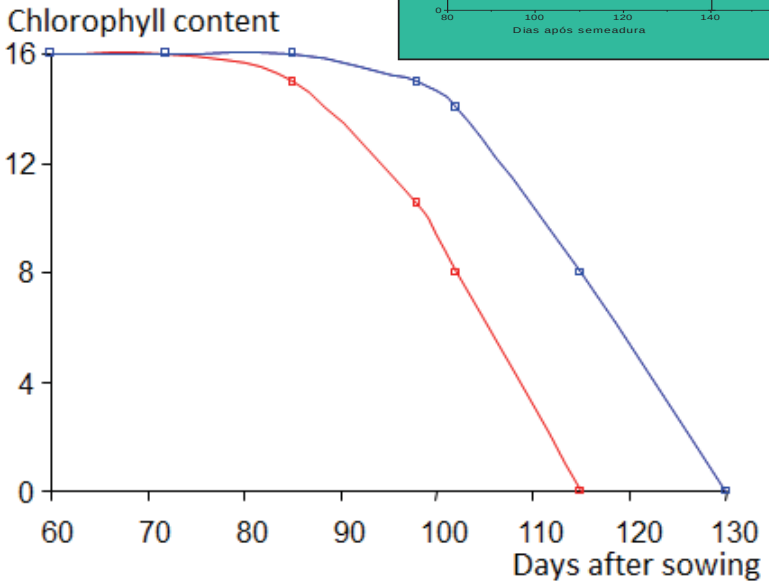
1. **Water use efficiency**
2. **Nutrients use efficiency**
3. **Genotype**
   - **(a) Chlorophyll content – water and N**
   - **(b) Leaf area index**
   - **(c) Carbon partition and Conversion efficiency: Total dry matter**
   - **(d) Hormones (ethylene)**
   - **(e) Crop cycle duration**
   - **(f) Productivity**
4. **Knowledge and technology**



Final consideration

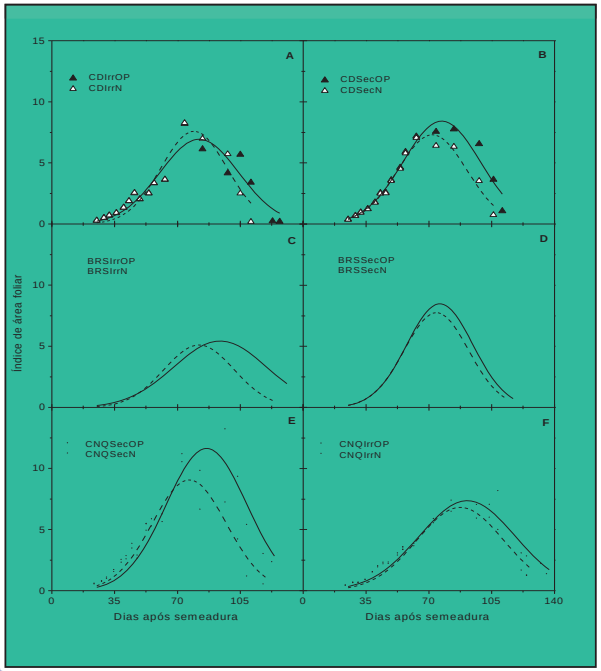
Chlorophyll content: water and N

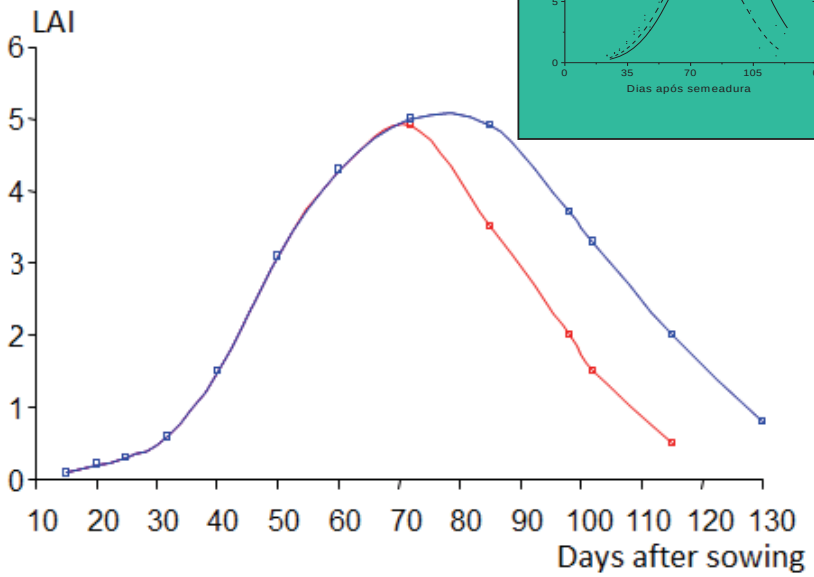




Final consideration

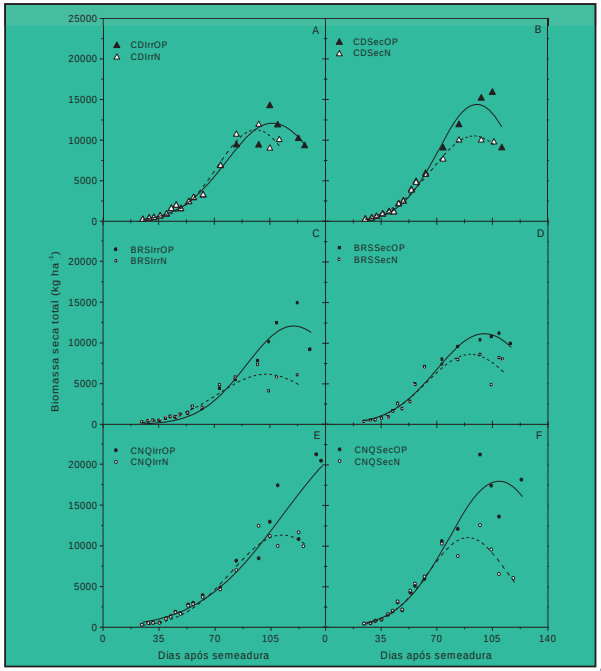
Leaf area index

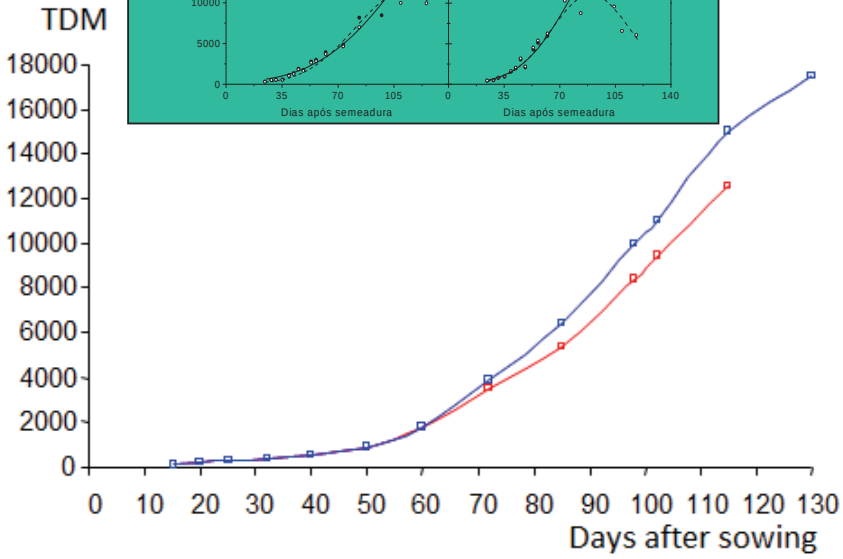




Final consideration

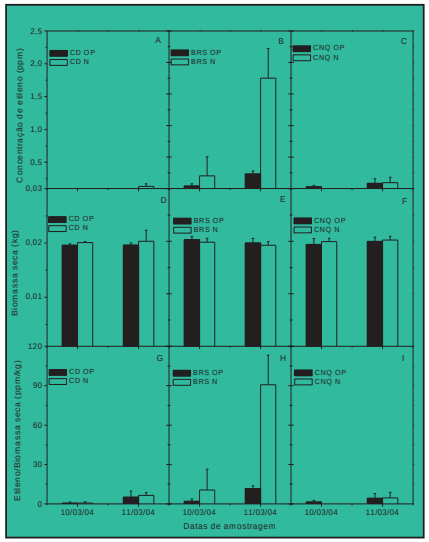
Total Dry Matter

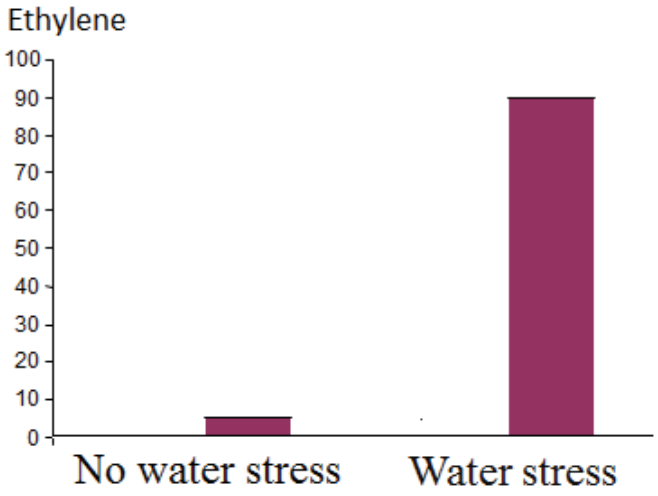




Final consideration

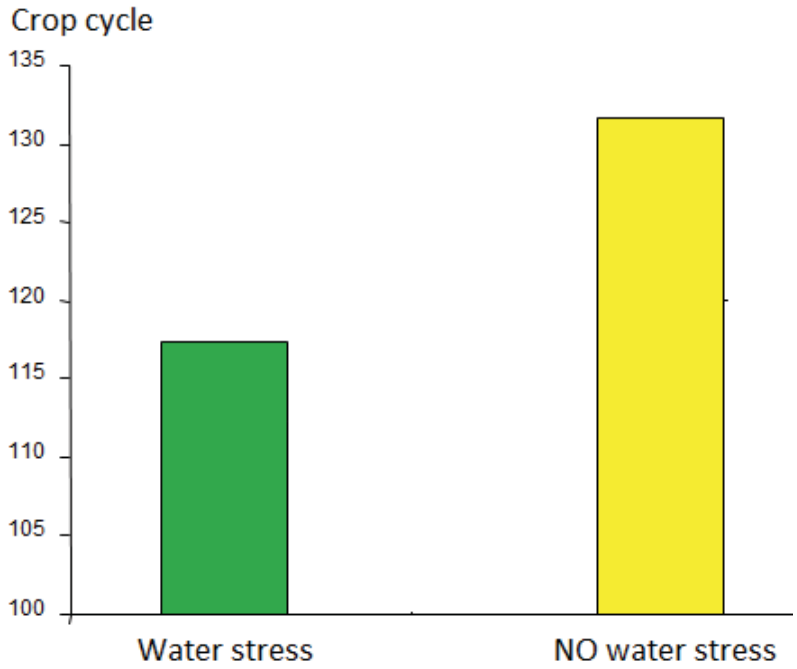
Ethylene





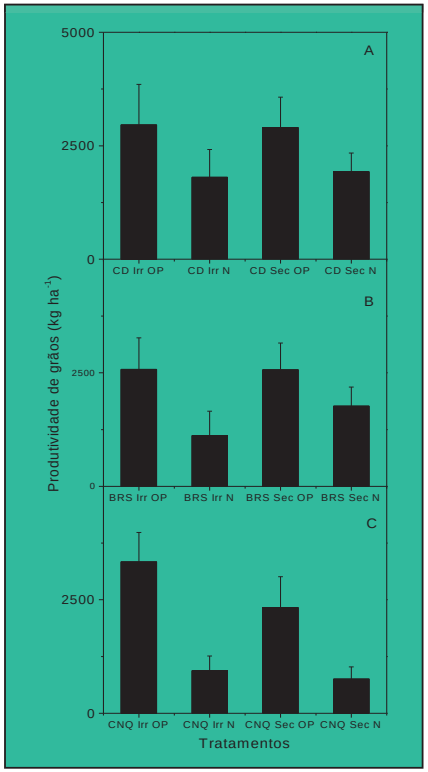
Final consideration

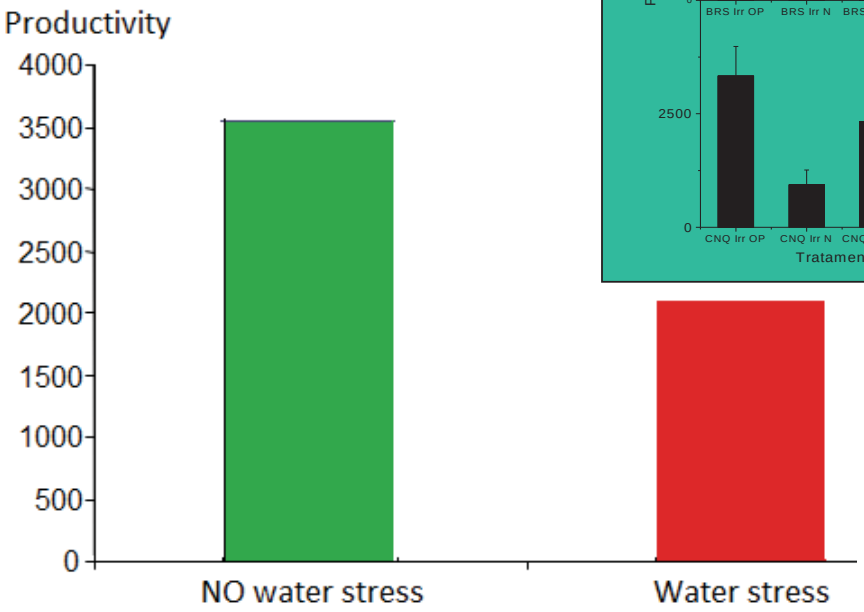
Crop cycle



Final consideration

Productivity





Final consideration

Light and carbon use efficiency

Actual (observed) efficiency

100		**Total solar radiation (incident)**
	→ 55	Not photosynthetically active (incident)
45		**Photosynthetically active (incident)**
	→ 7	Canopy albedo
38		**Absorbed by leaves**
	→ 3	Inactive absorption
35		**Absorbed by photosynthetic pigments**
	→ 31	Lost as heat (and fluorescence)
4.0		**Assimilated in photosynthesis**
	→ 1.0	Maintenance respiration
3.0		**Available for growth**
	→ 0.8	Growth respiration
2.2		**New free energy in phytomass**

New Phytologist — Review

Tansley review

From sunlight to phytomass: on the potential efficiency of converting solar radiation to phyto-energy

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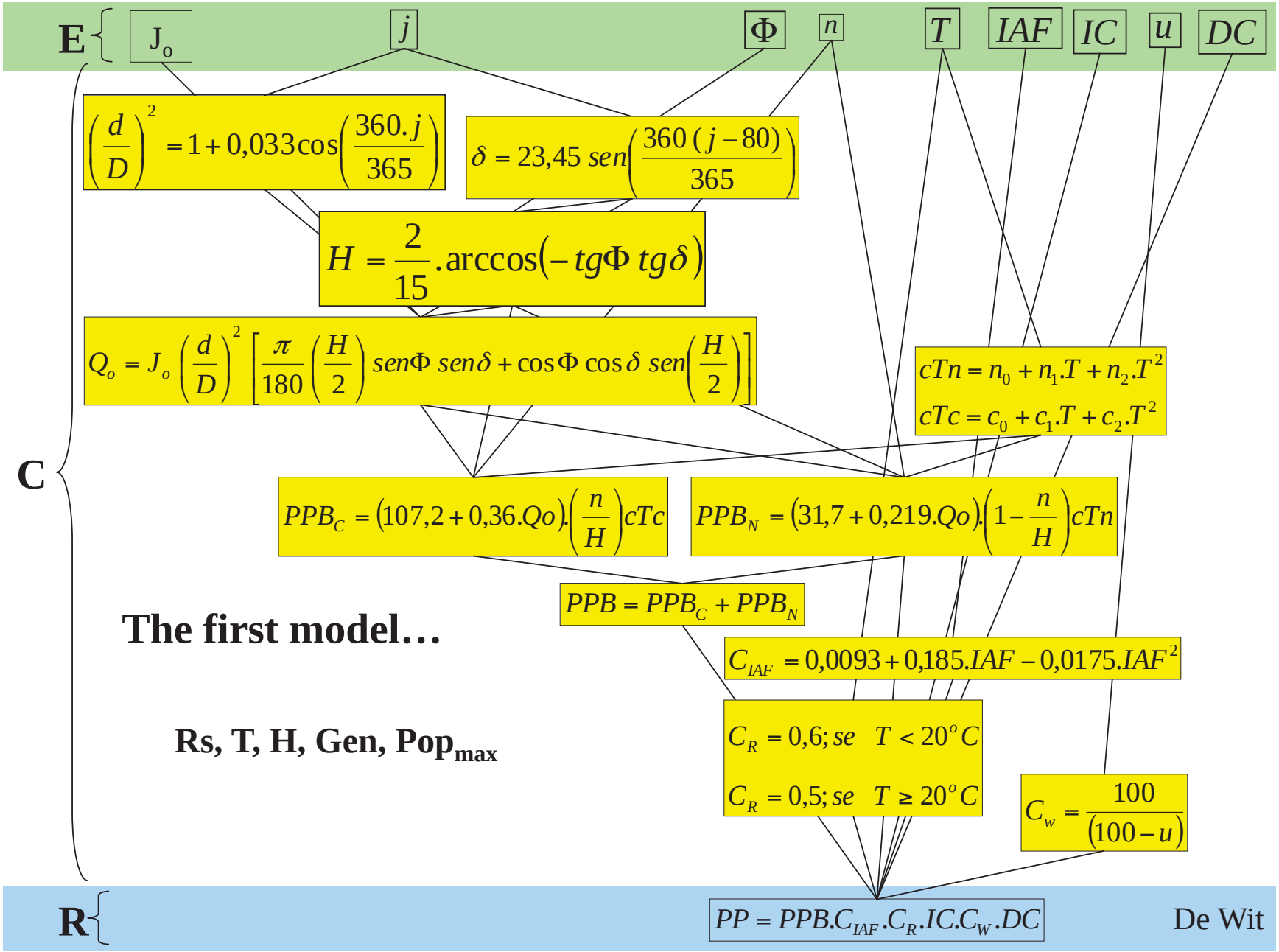
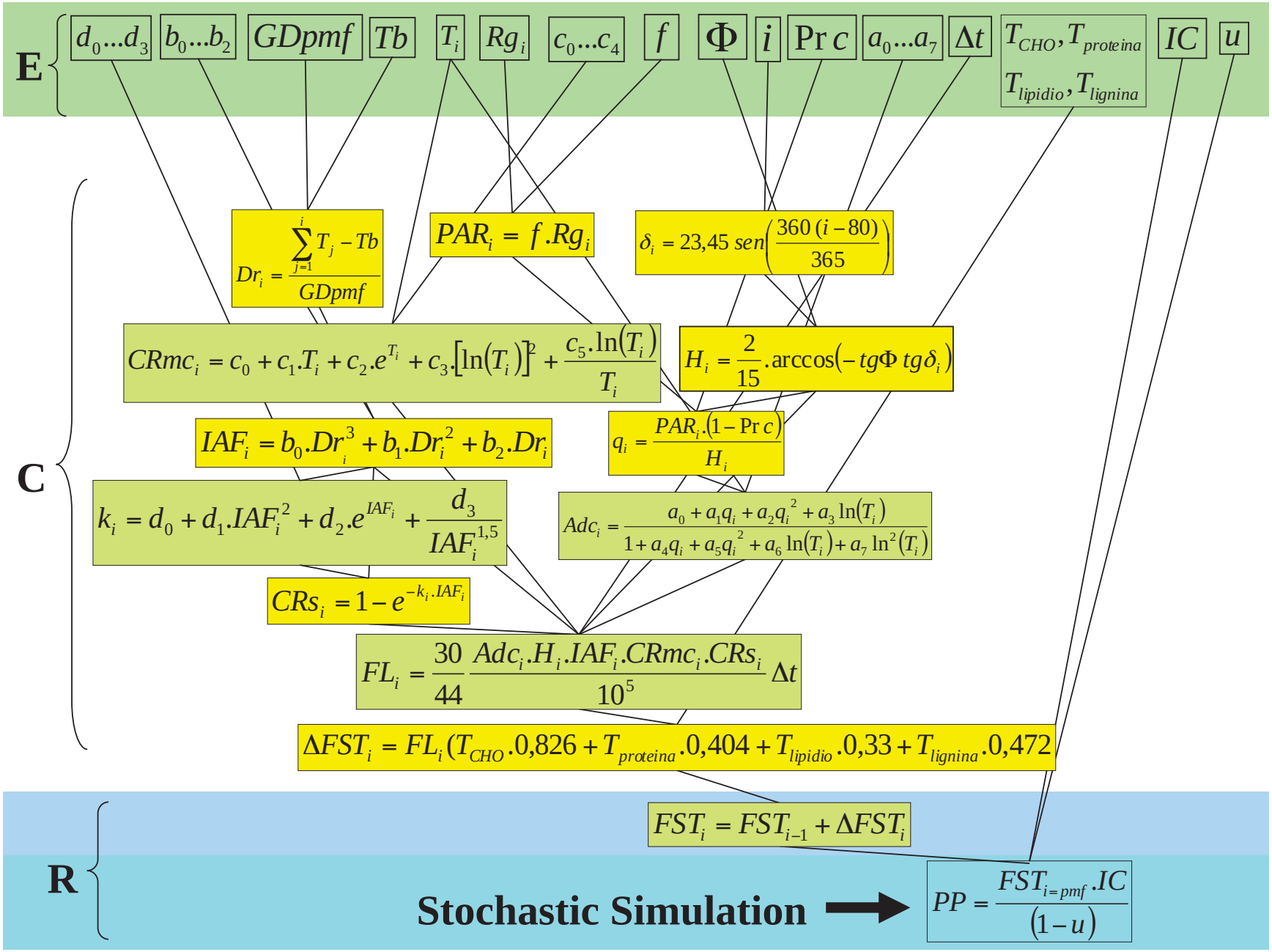

E
J_o
j
Φ
n
T
IAF
IC
u
DC
$\left(\frac{d}{D}\right)^2 = 1 + 0{,}033\cos\left(\frac{360.j}{365}\right)$
$\delta = 23{,}45\ sen\left(\frac{360\,(j-80)}{365}\right)$
$H = \frac{2}{15}.\arccos\left(-tg\Phi\ tg\delta\right)$
$Q_o = J_o\left(\frac{d}{D}\right)^2\left[\frac{\pi}{180}\left(\frac{H}{2}\right)sen\Phi\ sen\delta + \cos\Phi\cos\delta\ sen\left(\frac{H}{2}\right)\right]$
$cTn = n_0 + n_1.T + n_2.T^2$
$cTc = c_0 + c_1.T + c_2.T^2$
C
$PPB_C = (107{,}2 + 0{,}36.Qo).\left(\frac{n}{H}\right)cTc$
$PPB_N = (31{,}7 + 0{,}219.Qo).\left(1 - \frac{n}{H}\right)cTn$
$PPB = PPB_C + PPB_N$
The first model…
Rs, T, H, Gen, Pop_{max}
$C_{IAF} = 0{,}0093 + 0{,}185.IAF - 0{,}0175.IAF^2$
$C_R = 0{,}6;\ se\quad T < 20^oC$
$C_R = 0{,}5;\ se\quad T \geq 20^oC$
$C_w = \frac{100}{(100-u)}$
R
$PP = PPB.C_{IAF}.C_R.IC.C_W.DC$
De Wit


E
$d_0 ... d_3$
$b_0 ... b_2$
$GDpmf$
Tb
T_i
Rg_i
$c_0 ... c_4$
f
Φ
i
$\Pr c$
$a_0 ... a_7$
Δt
$T_{CHO}, T_{proteina}$
$T_{lipidio}, T_{lignina}$
IC
u
C
$Dr_i = \frac{\sum_{j=1}^{i} T_j - Tb}{GDpmf}$
$PAR_i = f.Rg_i$
$\delta_i = 23{,}45\ sen\left(\frac{360\,(i-80)}{365}\right)$
$CRmc_i = c_0 + c_1.T_i + c_2.e^{T_i} + c_3.\left[\ln(T_i)\right]^2 + \frac{c_5.\ln(T_i)}{T_i}$
$H_i = \frac{2}{15}.\arccos(-tg\Phi\ tg\delta_i)$
$IAF_i = b_0.Dr_i^3 + b_1.Dr_i^2 + b_2.Dr_i$
$q_i = \frac{PAR_i.(1-\Pr c)}{H_i}$
$k_i = d_0 + d_1.IAF_i^2 + d_2.e^{IAF_i} + \frac{d_3}{IAF_i^{1,5}}$
$Adc_i = \frac{a_0 + a_1 q_i + a_2 q_i^2 + a_3 \ln(T_i)}{1 + a_4 q_i + a_5 q_i^2 + a_6 \ln(T_i) + a_7 \ln^2(T_i)}$
$CRs_i = 1 - e^{-k_i.IAF_i}$
$FL_i = \frac{30}{44}\frac{Adc_i.H_i.IAF_i.CRmc_i.CRs_i}{10^5}\Delta t$
$\Delta FST_i = FL_i(T_{CHO}.0{,}826 + T_{proteina}.0{,}404 + T_{lipidio}.0{,}33 + T_{lignina}.0{,}472$
R
$FST_i = FST_{i-1} + \Delta FST_i$
Stochastic Simulation
$PP = \frac{FST_{i=pmf}.IC}{(1-u)}$

Modeling for crop production

Final Consideration

Science and Technology

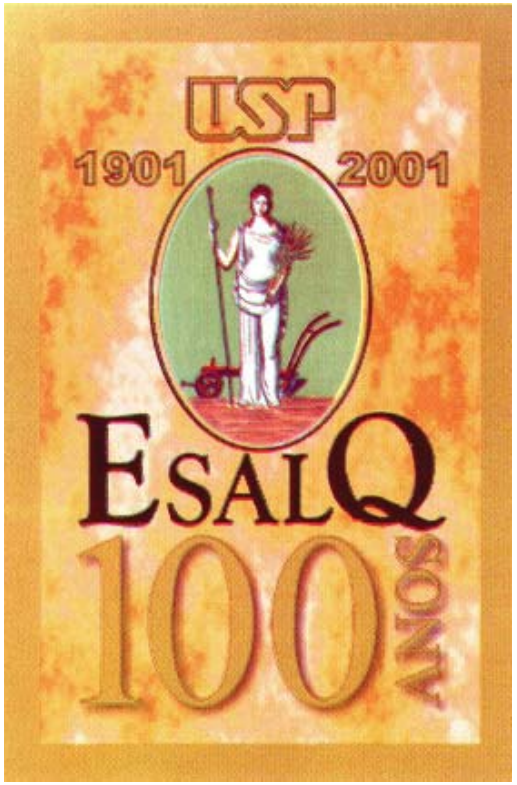
Agriculture and Environment

- ✓ **Correct Techniques**
- ✓ **Economically feasible**
- ✓ **Social justice**
- ✓ **Environmental sustainability**

"... 85% of future growth in food production must come from already used agricultural areas."

Dr. Norman Borlaug (1914 -)
1970: Nobel Prieze (Peace)

“The essence of scientific knowledge is its practical application”.



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