EXCHANGE VELOCITY APPROACH AND OBT FORMATION IN PLANTS DURING THE DAYTIME

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THE DRIVING EQUATIONS FOR TRITIUM TRANSFER IN ATMOSPHERE - SOIL- PLANT CONTINUUM

Driving equation for the HTO transfer from atmosphere to leaves:

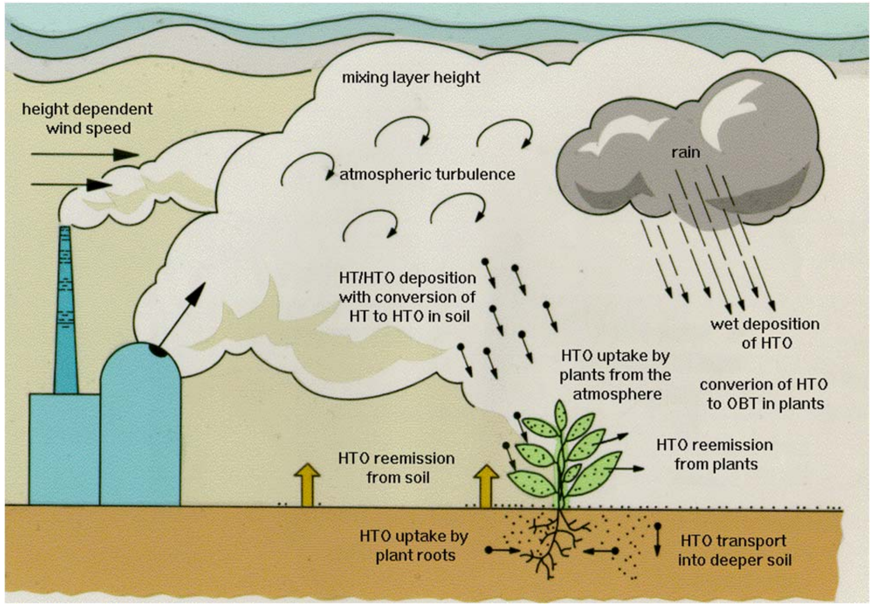
depends on canopy resistance

↙

$$\frac{dC}{dt} = \frac{V_{exc}}{M_w}(C_{air} - 0.91\rho_s C) + \underbrace{\frac{V_{exc}}{M_w}(\rho_s - \rho)C_s}_{\text{the transpiration flux}}$$

C – HTO concentration in plant water (Bq/kg);
C_{air} – HTO concentration in air (Bq/m^3);
C_s - HTO concentration in the sap water (Bq/kg);
ρ_s - saturated air humidity at vegetation temp. (kg/m^3);
ρ - air humidity at reference level (kg/m^3);
M_w – water mass in plant on a unit soil surface (kg/m^2);
V_{exc} – exchange velocity from atmosphere to canopy (m/s)

- used for all canopy, ignoring the transfer of air HTO to steam, because the exchange velocity is smaller with one order of magnitude;
- Ignores the initial diffusion of leaf water to steams



The tritium dynamics at soil surface:

depends on soil resistance

↙

$$\frac{dC_{sw,1}}{dt} = \frac{V_{ex,s}}{M_{ws}}(C_{air} - 0.91\rho_{sat}(T_s)C_{sw,1}) - DF$$

$C_{sw,1}$ - HTO concentration in the first soil layer at the (Bq/kg);
$V_{ex,s}$ - exchange velocity from atmosphere to soil (m/s);
ρ_{sat}(Ts) - saturated air humidity at soil surface temp. (kg/m^3);
M_{ws} – water mass in the surface soil layer;
DF - HTO net flux at the bottom interface of the first soil layer

SIMPLIFIED EQUATION FOR TRITIUM TRANSFER BETWEEN AIR AND PLANTS

If C_{air} = ct and V_{exc} = ct and ignoring the soil tritium transfer, a simple equation is obtained:

$$C_{TFWT} = C_{\infty}(1 - e^{-k.t})$$

C_{TFWT} - HTO concentration in plant at the considered time t (Bq L^{-1});
C_{∞} - steady-state TFWT concentration (Bq L^{-1});
k - constant rate for HTO uptake (h^{-1});
t - time after the beginning of exposure (h);

$$C_{\infty} = 1.1 * \rho_a / \rho_s C_{ah}$$

ρ_s - water vapour density in leaf stomatal pore (g /m^3);
ρ_a - the water vapour density in atmosphere (g /m^3);
C_{ah} is the air water HTO concentration (Bq/L)

$$k = \rho_s /(1.1 * W * r)$$

W - water content of leaf (g /m^2);
r - leaf resistance to water transport (h/m)

The above relationships were used to explain the experimental data for various plants and environmental conditions.

M. Andoh Atarashi et al., 1997

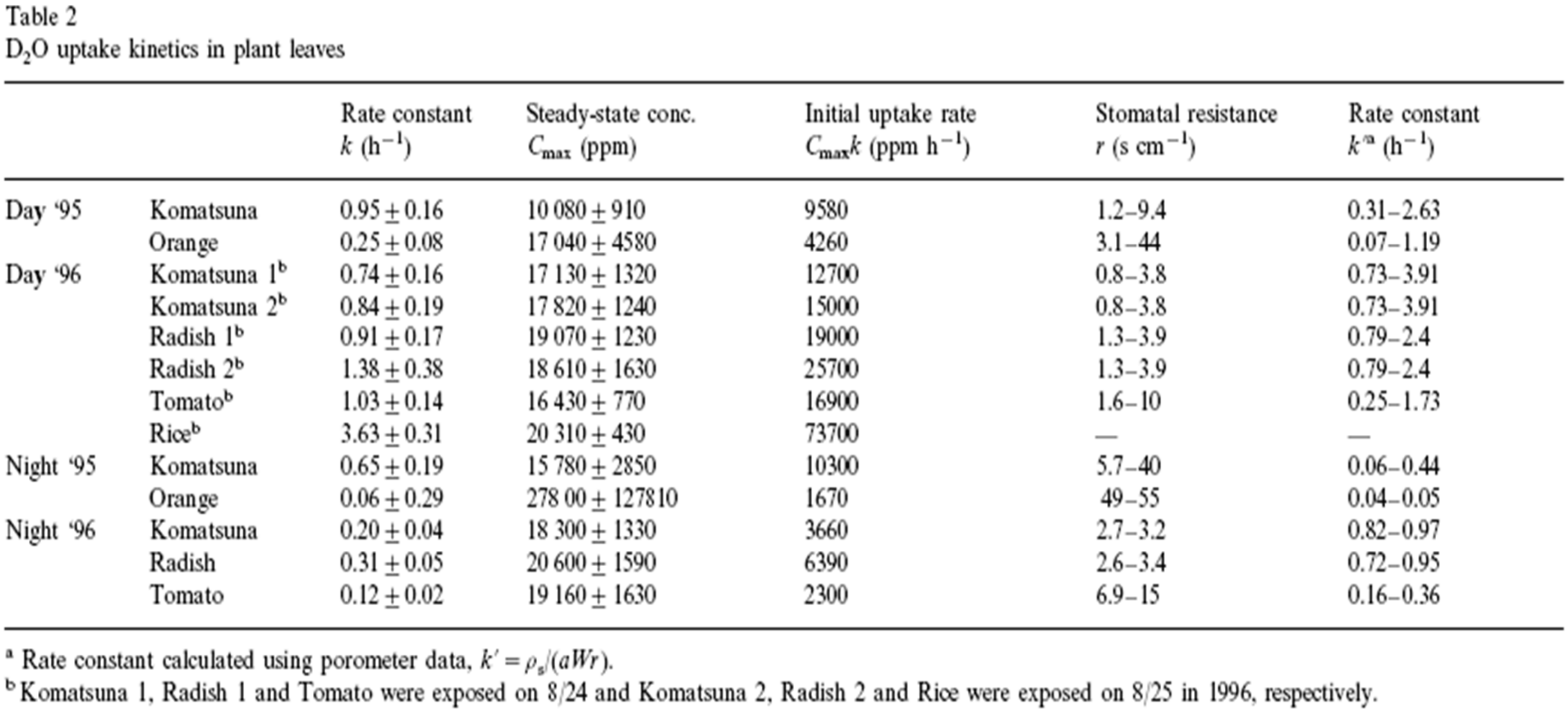


Table 2
D_2O uptake kinetics in plant leaves

		Rate constant k (h^{-1})	Steady-state conc. C_{max} (ppm)	Initial uptake rate $C_{max}k$ (ppm h^{-1})	Stomatal resistance r (s cm^{-1})	Rate constant k'^{a} (h^{-1})
Day '95	Komatsuna	0.95 ± 0.16	10 080 ± 910	9580	1.2–9.4	0.31–2.63
	Orange	0.25 ± 0.08	17 040 ± 4580	4260	3.1–44	0.07–1.19
Day '96	Komatsuna 1[b]	0.74 ± 0.16	17 130 ± 1320	12700	0.8–3.8	0.73–3.91
	Komatsuna 2[b]	0.84 ± 0.19	17 820 ± 1240	15000	0.8–3.8	0.73–3.91
	Radish 1[b]	0.91 ± 0.17	19 070 ± 1230	19000	1.3–3.9	0.79–2.4
	Radish 2[b]	1.38 ± 0.38	18 610 ± 1630	25700	1.3–3.9	0.79–2.4
	Tomato[b]	1.03 ± 0.14	16 430 ± 770	16900	1.6–10	0.25–1.73
	Rice[b]	3.63 ± 0.31	20 310 ± 430	73700	—	—
Night '95	Komatsuna	0.65 ± 0.19	15 780 ± 2850	10300	5.7–40	0.06–0.44
	Orange	0.06 ± 0.29	278 00 ± 127810	1670	49–55	0.04–0.05
Night '96	Komatsuna	0.20 ± 0.04	18 300 ± 1330	3660	2.7–3.2	0.82–0.97
	Radish	0.31 ± 0.05	20 600 ± 1590	6390	2.6–3.4	0.72–0.95
	Tomato	0.12 ± 0.02	19 160 ± 1630	2300	6.9–15	0.16–0.36

[a] Rate constant calculated using porometer data, $k' = \rho_s/(aWr)$.
[b] Komatsuna 1, Radish 1 and Tomato were exposed on 8/24 and Komatsuna 2, Radish 2 and Rice were exposed on 8/25 in 1996, respectively.

Large variability between plants and environmental conditions → Need to consider the variability of exchange velocity

Y. Ichimasa et al., 1990, 1991, 1992

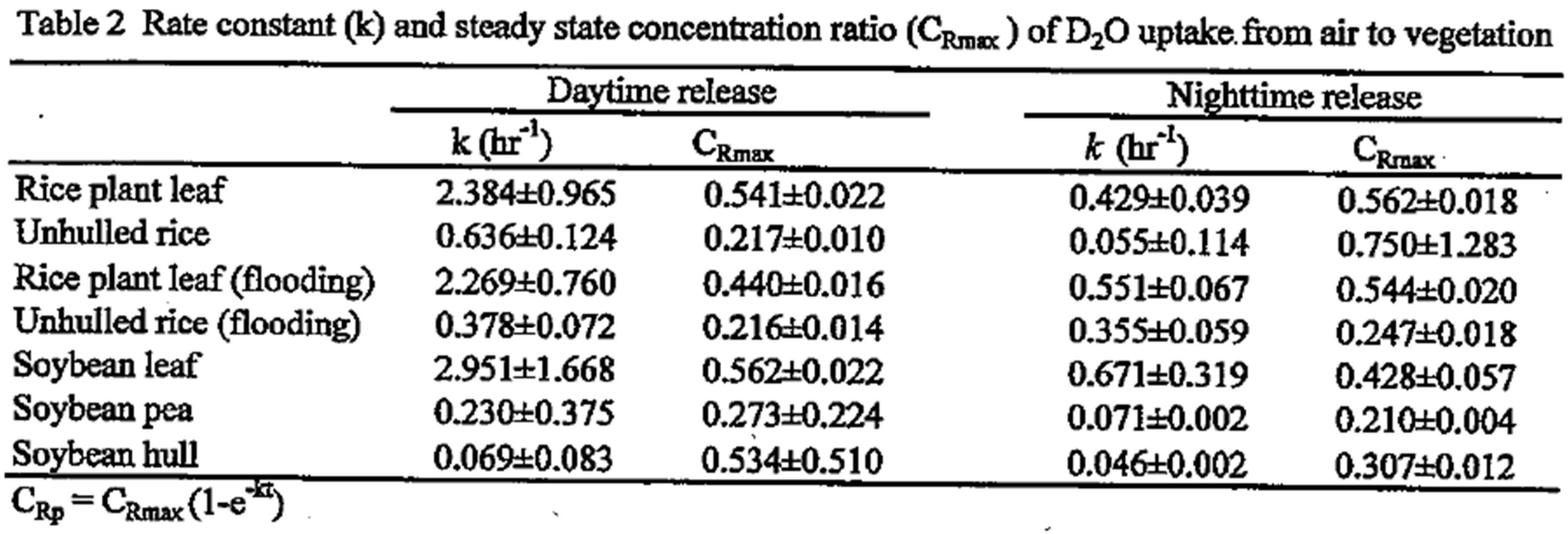


Table 2 Rate constant (k) and steady state concentration ratio (C_{Rmax}) of D_2O uptake from air to vegetation

	Daytime release		Nighttime release	
	k (hr^{-1})	C_{Rmax}	*k* (hr^{-1})	C_{Rmax}
Rice plant leaf	2.384±0.965	0.541±0.022	0.429±0.039	0.562±0.018
Unhulled rice	0.636±0.124	0.217±0.010	0.055±0.114	0.750±1.283
Rice plant leaf (flooding)	2.269±0.760	0.440±0.016	0.551±0.067	0.544±0.020
Unhulled rice (flooding)	0.378±0.072	0.216±0.014	0.355±0.059	0.247±0.018
Soybean leaf	2.951±1.668	0.562±0.022	0.671±0.319	0.428±0.057
Soybean pea	0.230±0.375	0.273±0.224	0.071±0.002	0.210±0.004
Soybean hull	0.069±0.083	0.534±0.510	0.046±0.002	0.307±0.012

$C_{Rp} = C_{Rmax}(1-e^{-kt})$

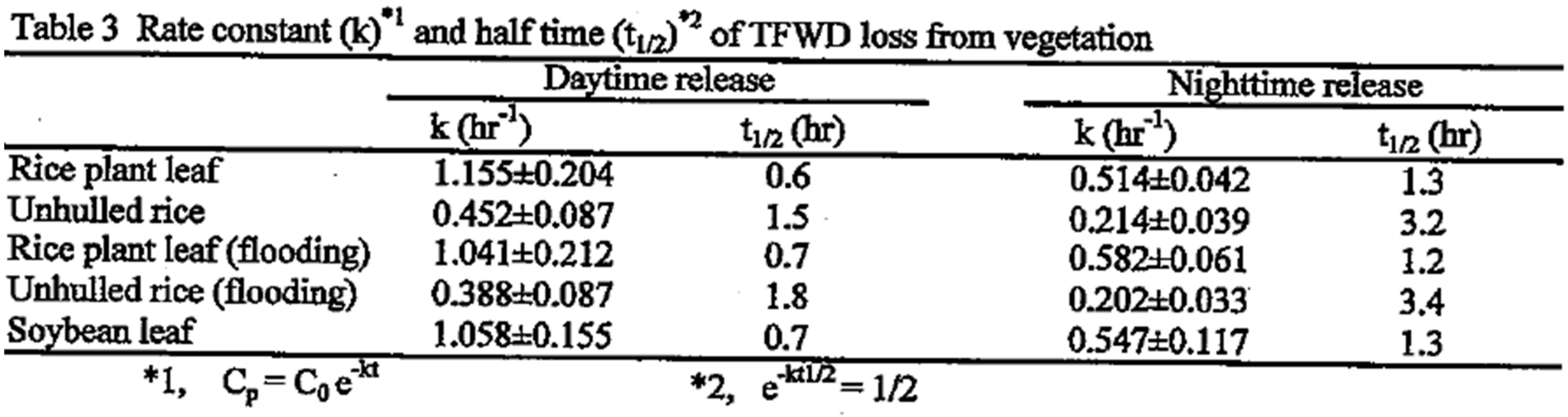


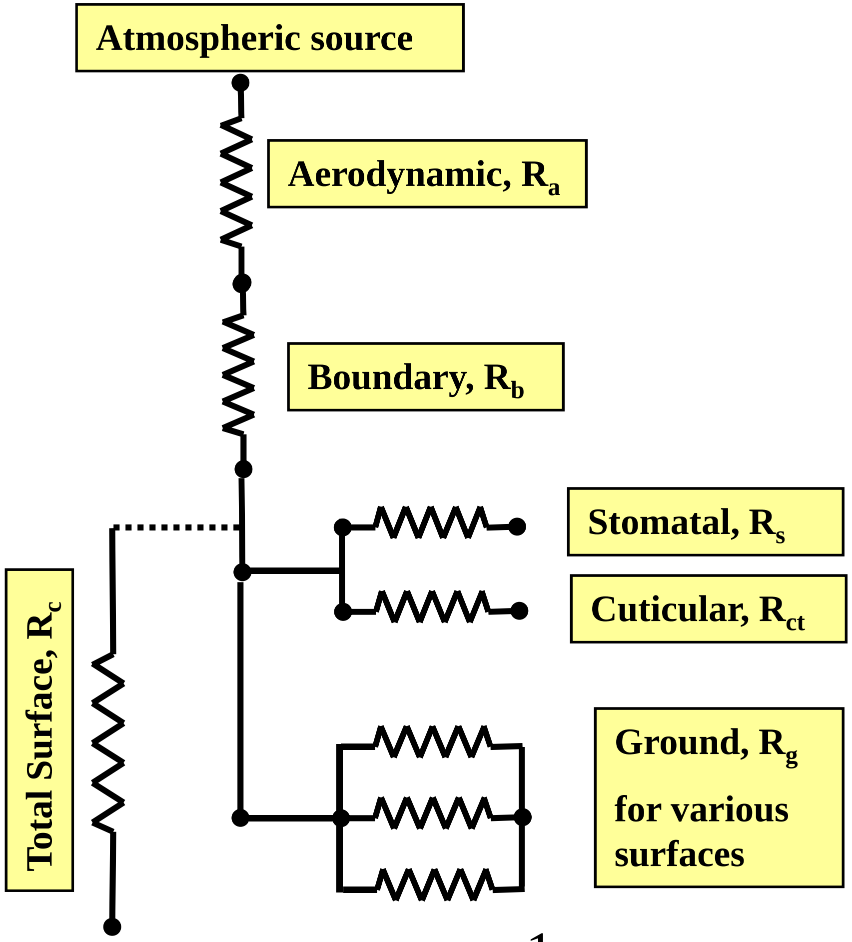
Table 3 Rate constant (k)[*1] and half time ($t_{1/2}$)[*2] of TFWD loss from vegetation

	Daytime release		Nighttime release	
	k (hr^{-1})	$t_{1/2}$ (hr)	k (hr^{-1})	$t_{1/2}$ (hr)
Rice plant leaf	1.155±0.204	0.6	0.514±0.042	1.3
Unhulled rice	0.452±0.087	1.5	0.214±0.039	3.2
Rice plant leaf (flooding)	1.041±0.212	0.7	0.582±0.061	1.2
Unhulled rice (flooding)	0.388±0.087	1.8	0.202±0.033	3.4
Soybean leaf	1.058±0.155	0.7	0.547±0.117	1.3

*1, $C_p = C_0 e^{-kt}$ *2, $e^{-kt_{1/2}} = 1/2$

Large variability between plants and environmental conditions → Need to consider the variability of exchange velocity

Resistance Approaches for Deposition and Exchange



$$V_{ex} = \frac{1}{R_a + R_b + R_c}$$

↓

exchange velocity at air to plant (soil) interface

- Similitude between water vapour transport and electric circuits → in both cases the transport is due to specific gradients:
  - specific humidity for water
  - electric potential for electricity
- Environmental resistances - analogy with electric resistances → both = the ratio between potential difference and flux
- R_a - turbulence and wind speed
- R_b - turbulence, wind speed and surface properties
- Total surface resistance R_c - split up into canopy and ground related resistance
- Canopy resistance - surface properties, temperature, PAR, humidity, water content in soil
- HT deposition → ground resistance depends on the rates of diffusion and oxidation in soil;
  - much lower than the canopy resistance

Boundary layer

Turbulent eddies - responsible for transporting material through the surface boundary layer

Transport processes:

- transfer of heat
- mass
- momentum

} modify the atmosphere's properties

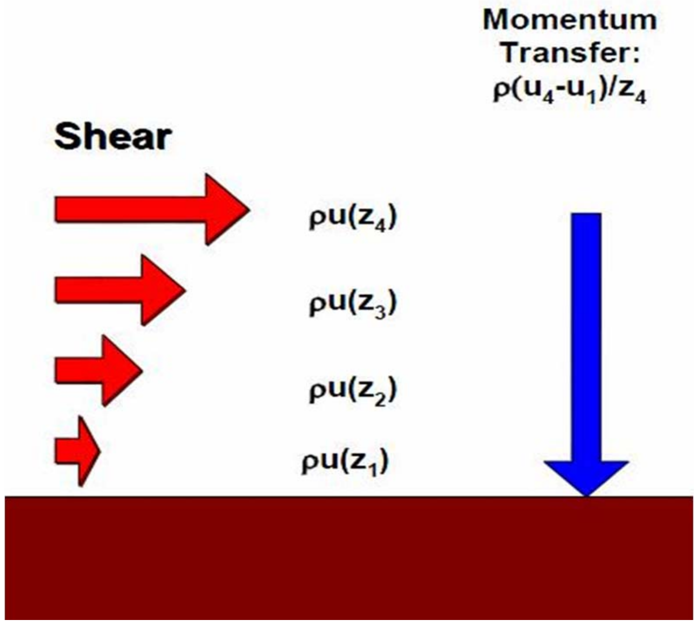
Distinct aspect of the boundary layer → turbulent nature

A **force** is needed to change momentum transfer from one level to another. This **drag force** or shear stress is also equivalent to the **momentum flux density**
Momentum must be transferred downward.

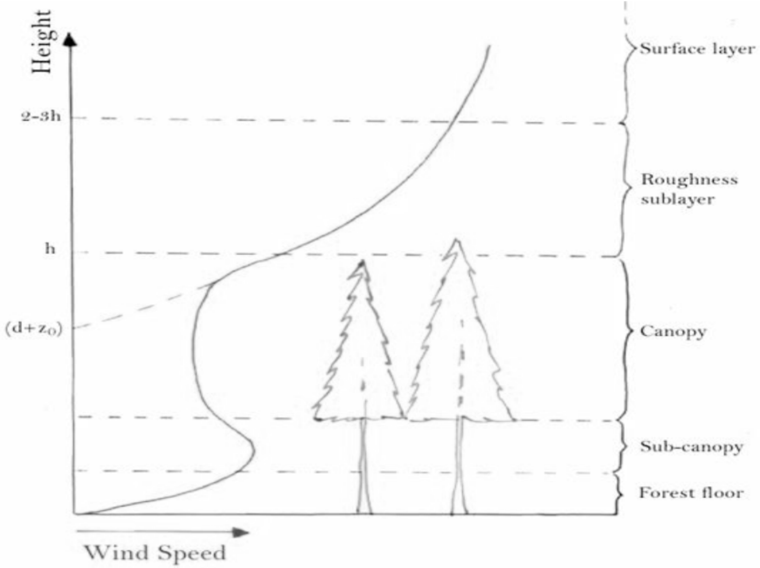
Logarithmic wind profile:

$$u(z) = \frac{u_*}{k} ln(\frac{z}{z_0})$$

u* - friction velocity
K – von Karmann's constant (=0.40)
z - height above the ground
z_0 – **roughness parameter** = the effectiveness of a canopy to absorb momentum; valid only for very short vegetation and for a neutrally stratified atmosphere
d - **Zero-Plane Displacement Height** = the level at which surface drag acts on the roughness elements or level which would be obtained by flattening out all the roughness elements into a smooth surface.



Visualization of momentum transfer



Atmospheric resistance (R_a) and boundary layer resistance (R_b)

$$R_a = \frac{1}{ku^*} \ln \frac{z - d}{z_o} - \psi_c$$

Turbulent eddies - responsible for transporting material through the surface boundary layer;
R_a - determines the rate that momentum, and other scalars, are transported between a given level in the atmosphere and the vegetation's effective surface sink.

ψ_c - adiabatic correction function

Boundary layer = that thin skin of unperturbed air which surrounds the surface of soil or vegetation

$$R_b = \frac{1}{ku^*} \ln \frac{z_o}{z_c} = \frac{const}{ku^*} (Sc / Pr)^{2/3}$$

z_c - scalar roughness length;
S_c - Schmidt number;
P_r – Prandtl number;
const - often assumed to be 2 over closed canopies, but it can be much larger over rough incomplete canopies

- Heat and water vapor must be transferred through this layer through molecular diffusion (conduction).
- The long timescale involved can be represented by a large resistance - the *boundary layer resistance*.
- The magnitude of this resistance depends mainly on the depth of the boundary layer and is proportional to leaf size/wind speed.

CANOPY RESISTANCE IS PREDOMINANT

R_a, R_b - affected by wind speed, crop height, leaf size, and atmospheric stability;
- decrease with the increasing of wind speed and crop height

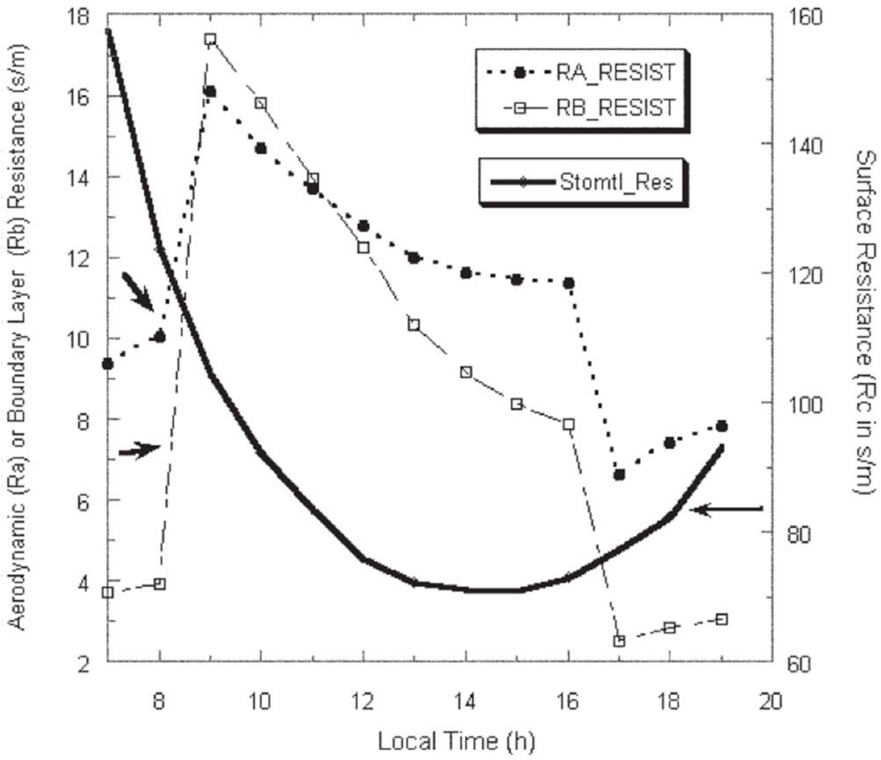
- Smaller resistances
  - over the tall forests than over short grass;
  - under unstable atmospheric thermal stratification, than under neutral and stable stratification
- For wind speed = 4 m s^{-1} →

$$R_b = \begin{cases} 60\ \mathrm{s\ m^{-1}}, \text{ for 0.1 m tall grass} \\ 20\ \mathrm{s\ m^{-1}}, \text{ for 1.0 m crop} \\ 10\ \mathrm{s\ m^{-1}}, \text{ for 10 m conifer forest} \end{cases}$$

- R_a, R_b < 20 s m^{-1} - during the daytime over a temperate deciduous forest (exp. results)
- $R_a \geq 150$ s m^{-1} – during the night time (turbulent mixing is reduced)

FOREST

Sample time history of simulated aerodynamic (Ra), boundary layer (Rb), (Rc) resistances using a photosynthesis-based biophysical model. Effects o changes and the dominance of the canopy resistance term is clearly seen



R_a , R_b ÷ 4 -18 s m^{-1}
R_c ÷ 70 – 160 s m^{-1}

Canopy resistance (R_C)

- R_c - function of:

  - canopy stomatal resistance (R_{stom})
  - canopy cuticle resistance ($R_{cuticle}$)
  - soil resistance (R_{soil})

  affected by:

  leaf area;
  stomatal physiology;
  soil pH;
  presence and chemistry of liquid drops and films

- R_{stom}, $R_{cuticle}$, R_{soil} act in parallel:

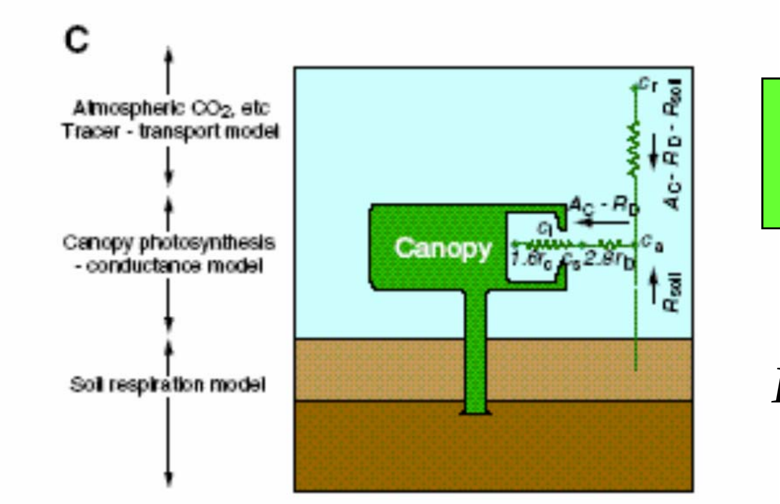
$$\frac{1}{R_c} = \frac{1}{R_{stom}} + \frac{1}{R_{soil}} + \frac{1}{R_{cuticle}}$$

- ***'Big-Leaf' resistance models*** - electrical analogy - current flow (mass or energy flux density) is equal to the ratio between a potential and the sum of the resistances to the flow:

$$F_c = \frac{C_a - C_0}{R_a + R_b + R_c}$$

C_a – concentration of a scalar in the atmosphere over the vegetation
C_0 – 'internal' concentration

Canopy resistance – physiological models



Stomatal cavity → common pathway for water and CO_2

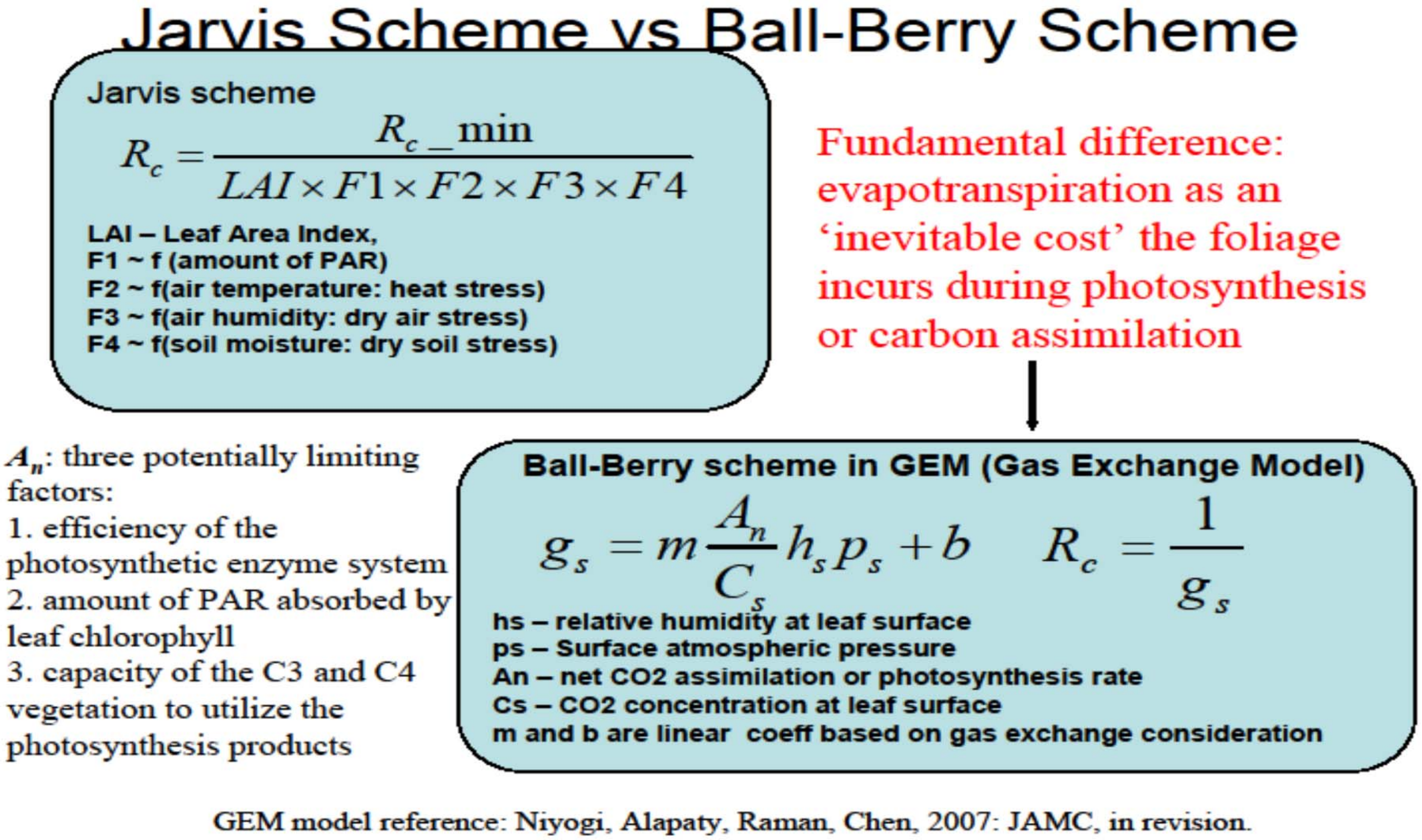
Leaf = Σ stomata

$$E = \rho_a \frac{q_{in} - q_{air}}{r_a + r_c}$$

E – evaporation
ρ_a – air density
q_{in} – saturated air vapour at leaf temp.
q_{air} – air vapour in atmosphere

Scalling from leaf to canopy:

- classic: $R_c = R_{leaf}/LAI$
- big leaf: integral over all canopy as a single leaf
- physiological approach



Jarvis Scheme vs Ball-Berry Scheme

Jarvis scheme

$$R_c = \frac{R_c\_\min}{LAI \times F1 \times F2 \times F3 \times F4}$$

LAI – Leaf Area Index,
F1 ~ f (amount of PAR)
F2 ~ f(air temperature: heat stress)
F3 ~ f(air humidity: dry air stress)
F4 ~ f(soil moisture: dry soil stress)

Fundamental difference: evapotranspiration as an 'inevitable cost' the foliage incurs during photosynthesis or carbon assimilation

A_n: three potentially limiting factors:
1. efficiency of the photosynthetic enzyme system
2. amount of PAR absorbed by leaf chlorophyll
3. capacity of the C3 and C4 vegetation to utilize the photosynthesis products

Ball-Berry scheme in GEM (Gas Exchange Model)

$$g_s = m\frac{A_n}{C_s}h_s p_s + b \qquad R_c = \frac{1}{g_s}$$

hs – relative humidity at leaf surface
ps – Surface atmospheric pressure
An – net CO2 assimilation or photosynthesis rate
Cs – CO2 concentration at leaf surface
m and b are linear coeff based on gas exchange consideration

GEM model reference: Niyogi, Alapaty, Raman, Chen, 2007: JAMC, in revision.

- Jarvis approach – light, temperature, water vapour deficit, and soil water deficit behave independently as modifying factors (0, 1)
  - minimal leaf resistance $R_{c\text{-}}$min is plant characteristic
- Ball-Berry scheme - uses m and b as semi-empirical coefficients → inconvenience
- Physiological approach – link between water and CO_2 pathway to photosynthesis (A_n), taking into account different diffusion coefficients

Physiological approach (preferred and tested)

- assumes that C conductance is determined by ratio between photosynthetic rate and the concentration difference of CO_2 for leaf surface and leaf interior

$$g_{l,c} = g_{\min,c} + \frac{a_1 A_g}{(C_s - \Gamma)\left(1 + \frac{D_s}{D_*}\right)},$$

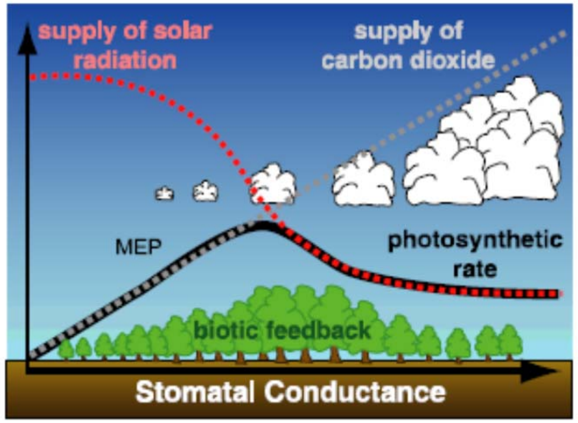
$$g_{l,c} = \frac{g_{l,w}}{1.6} \Rightarrow g_{c,c} = \frac{g_{c,w}}{1.6}.$$

$g_{l,c}$ – leaf C conductance;
$g_{l,w}$ – leaf water conductance;
$g_{c,c}$ – C canopy conductance;
$g_{c,w}$ - water canopy conductance

$g_{\min,c}$ - the cuticular conductance
A_g - the gross assimilation rate of leaf
D_s - the vapour pressure deficit at plant level
C_s - the CO_2 concentration at the leaf surface
C_i - the CO_2 concentration in the plant interior
f_0 - the maximum value of $(C_i - \Gamma)/(C_s - \Gamma)$
$f_{\min}$ - the minimum value of $(Ci - \Gamma)/(Cs - \Gamma)$
D_0 - the value of Ds at which the stomata are closed
Γ – CO_2 compensation point

$$\frac{C_i - \Gamma}{C_s - \Gamma} = f_0\left(1 - \frac{D_s}{D_0}\right) + f_{\min}\frac{D_s}{D_0},$$

(Jacobs - Calvet)



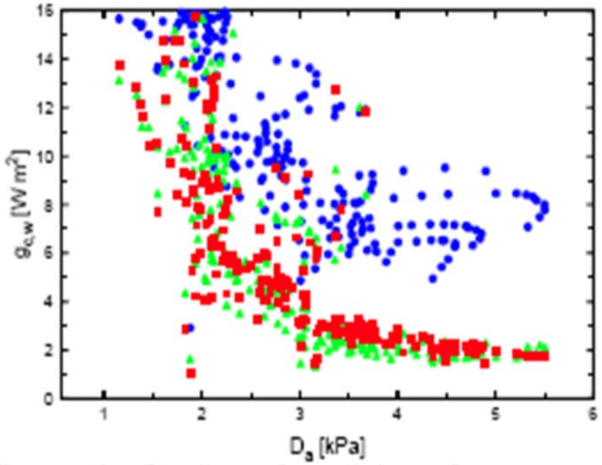


Figure 2: Scatter plot giving the canopy conductance as function of D_a; measurements (red), physiologically based model (green) and JS-model (blue).

- **For canopy - integrate on LAI**
- **We use gross canopy photosynthesis rate from WOFOST**
- **Data base exist → advantage**

Ronda approach

- simplifies Jacobs – Calvet approach:

$$\frac{C_i - \Gamma}{C_s - \Gamma} = f_0 - a_d D_s,$$

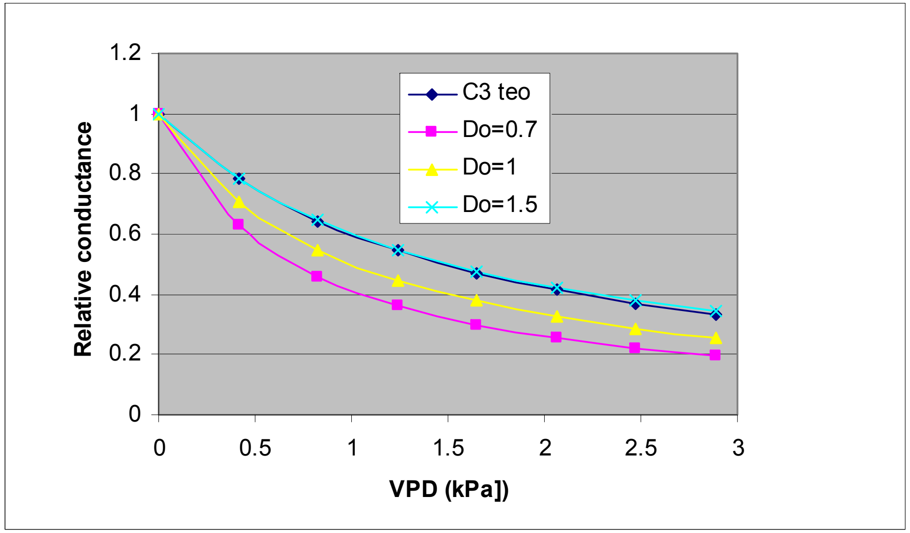
$$D_0 = \frac{f_0 - f_{\min}}{a_d}.$$

f_0, a_d – empirically found as regression coefficients
D_0 – vapour pressure deficit for which stomata are closed

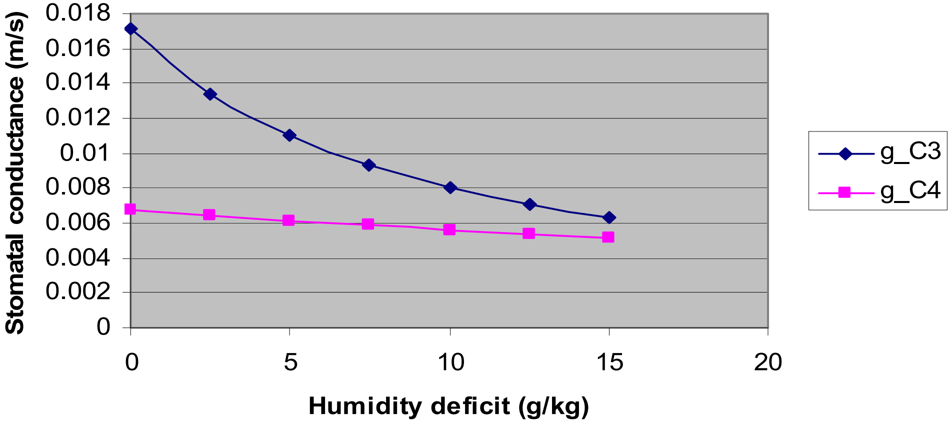
Vegetation type	f_o	a_d (kPa^{-1})
Low vegetation C3	0.89	0.07
Low vegetation C4	0.85	0.015
Lobos	0.093	0.12
Rice and phalaris grass	0.89	0.18
Forest temperate	0.875	0.06
Boreal forest	0.4	0.12

Water vapour deficit

- light, temperature, VPD, soil water deficit - environmental factors influencing the canopy resistance



Stomatal conductance and humidity deficit - C3 and C4 plants



Soil water deficit

- CO_2 assimilation rate - seriously affected by soil water stress, especially during the summer time → the water supply is low

$$A_g = A_g^*[2\beta(\overline{\theta}) - \beta^2(\overline{\theta})].$$

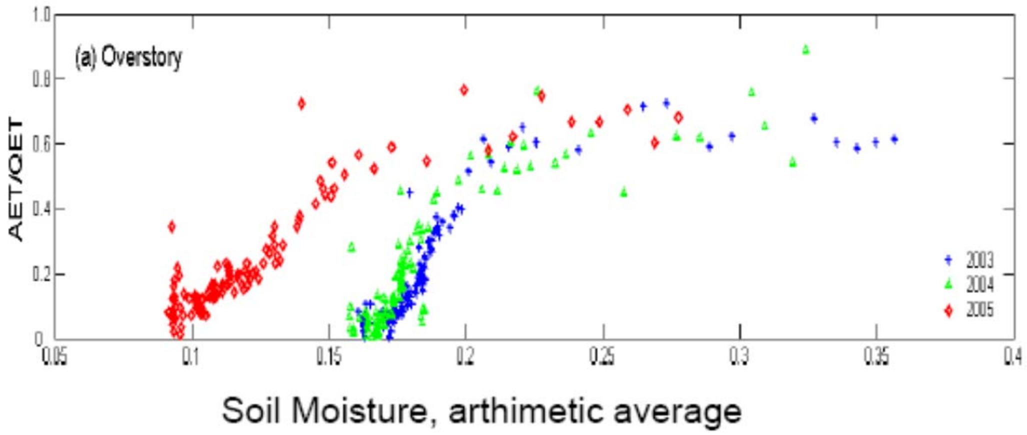
$$\beta(\overline{\theta}) = \max\left[0, \min\left(1, \frac{\overline{\theta} - \mathrm{WP}}{\mathrm{FC} - \mathrm{WP}}\right)\right].$$

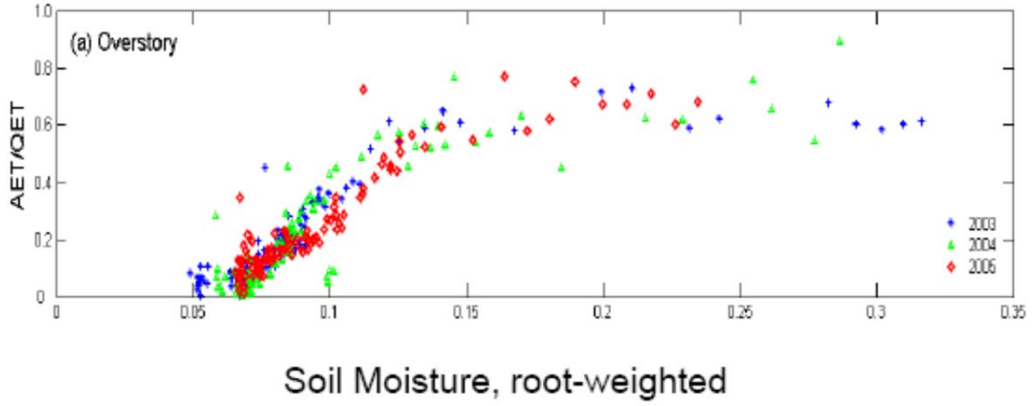
↓

correction factor for water stress

$$\overline{\theta} = R_1\theta_1 + R_2\theta_2 + R_3\theta_3 + R_4\theta_4.$$

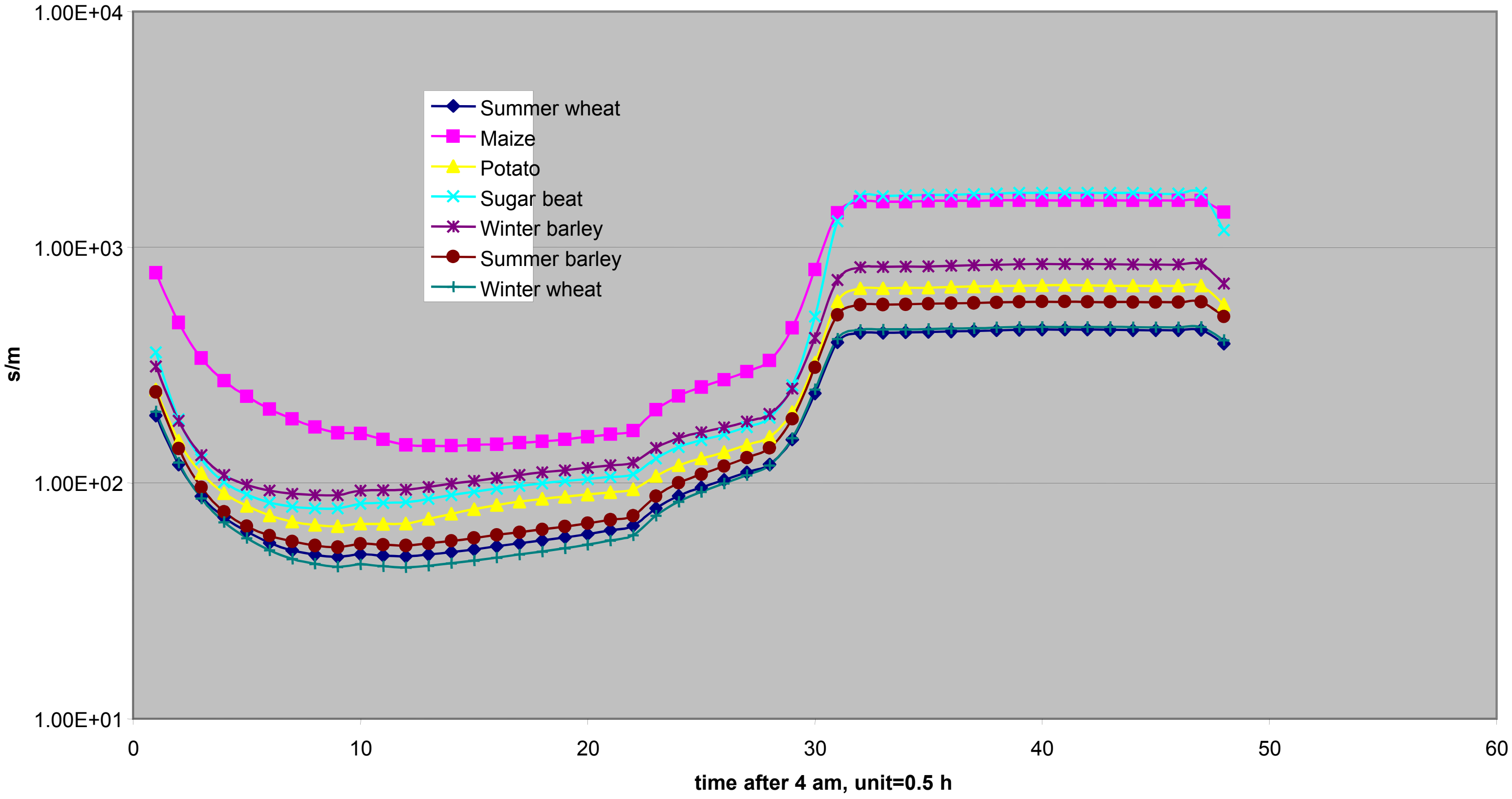
A_g - the gross assimilation rate of leaf
A_g^* - the unstressed assimilation (mol $m^{-2}s^{-1}$) rate
$\overline{\theta}$ - the average soil water content in root zone
WP - the wilting point
FC - the field capacity
Θ_i - mean soil moisture in "i" layer
R_i - root fraction in "i" layer





Canopy resistance controls the HTO transfer from air to plant – Our model results

$$g_{c,w} = \int_0^{LAI} \left[\frac{g_{\min,w}}{1.6} + \frac{a_l A_g}{(C_s - \Gamma)(1 + \frac{D_s}{D_*})}\right] dL = \frac{g_{\min,w}}{1.6} LAI + \frac{a_l \int_0^{LAI} A_g \, dL}{(C_s - \Gamma)(\Gamma + \frac{D_s}{D_*})}$$

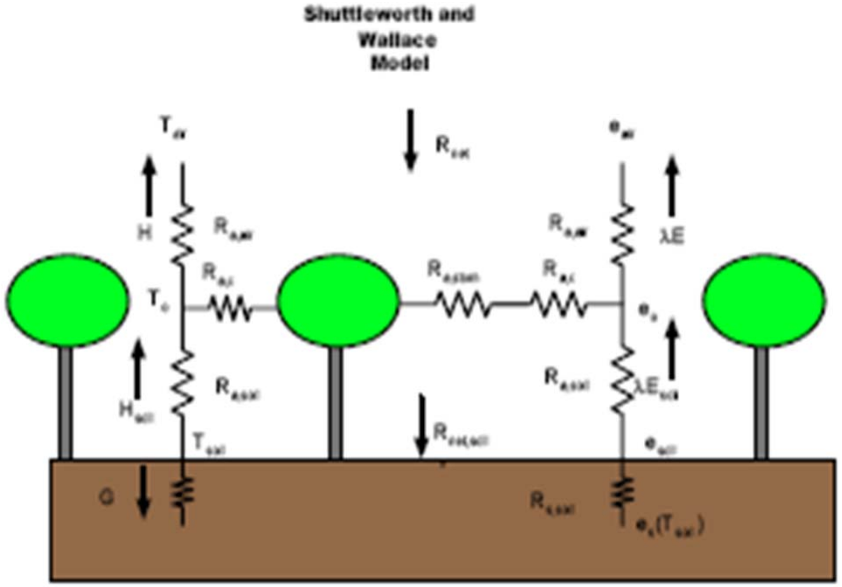


Canopy resistence

Comparison between experimental and theoretical data for maximum stomatal resistance

Plant type	Experimental val. (s/m)	Model val. (s/m)	References
Wheat, vegetative stage	41 – 52	56	Baldocchi, 1994
Wheat, anthesys	62 - 100	60	Baldocchi, 1994
Maize, vegetative	121 - 131	111	Baldocchi, 1994
Wheat	17 - 20	18	Choudhury, 1998
Potato	100 - 130	130	Vos, 1987
Alpha-alpha	100 - 120	110 – 130 (dep. VPD)	Saugier, 1991
Soya	66	70	Oliosa, 1996
Grass C3	74	74 – 120 (dep. VPD)	Knap, 1993
Grass C4	151	156 – 178 (dep. VPD)	Knap, 1993

Soil – vegetation coupling and tritium transfer



The Shuttleworth-Wallace model defines fluxes from the vegetative and soil components with a resistance network.
With the Shuttleworth-Wallace model, there is need to define values of the humidity deficit, temperature and vapour pressure at the canopy source height, D_0, T_0, e_0.

By analogy, for HTO:

$$F_c(R_{aa}+R_{ab}+R_{ac})+F_sR_a=C_a-C_c$$

$$F_cR_a+F_s(R_{aa}+R_{as}+R_{ss})=C_a-C_s$$

C_a – HTO concentration in air;
C_c – HTO concentration in vegetation;
C_s – HTO concentration in soil;
R_{aa}– atmospheric resistance between reference level and canopy source height;
R_{ac} – boundary layer resistance;
R_{sc} – canopy resistance;
R_{as} – atmospheric resistance between canopy source height and soil surface;
R_{ss} - soil resistance;
F_c - flux atmosphere – vegetation;
F_s - flux atmosphere – soil.

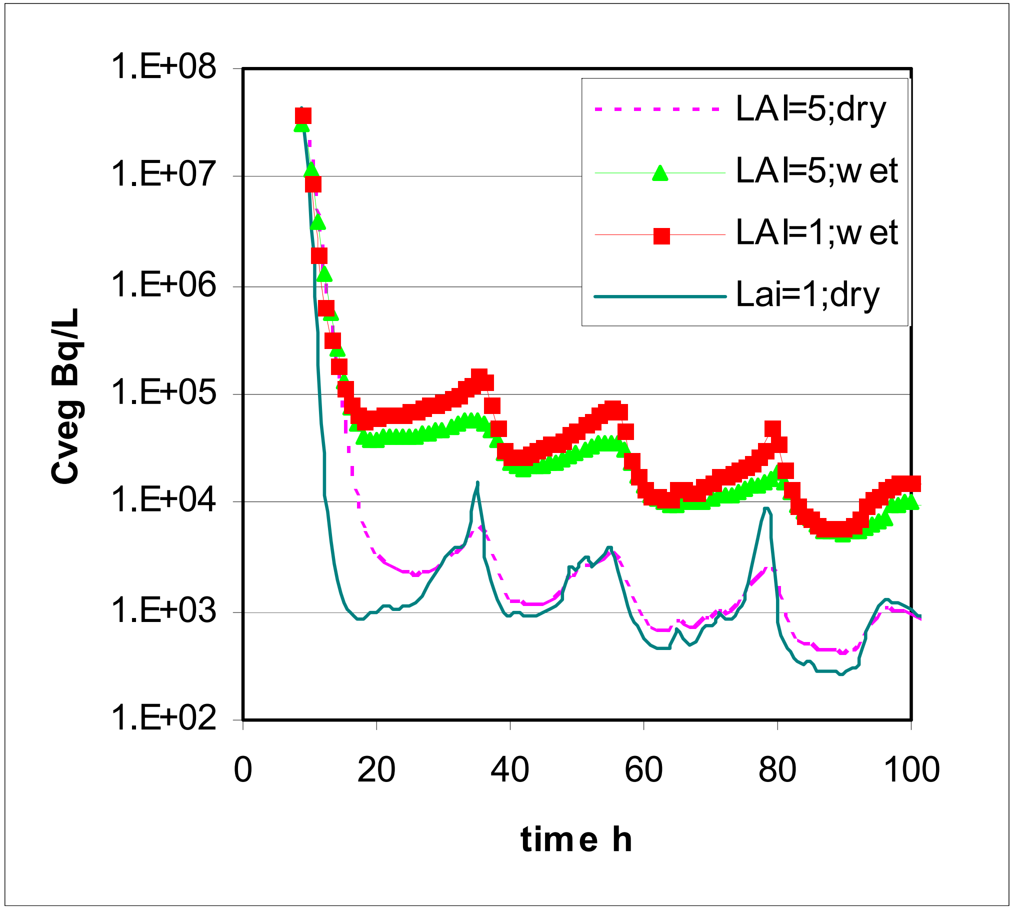
$$F_c=V_{ex}(C_a-C_{va})-V_{ex2}(C_a-C_{sa})$$

$$F_s=V_{ex1}(C_a-C_{sa})-V_{ex2}(C_a-C_{va})$$

Details are given elsewhere

(A. Melintescu, D. Galeriu, “A versatile model for tritium transfer from atmosphere to plant and soil”, *Radioprotection*, Suppl. 1, Vol. 40 (2005), S437-S442, May 2005)

HTO concentration in vegetation in the sparse canopy approach



Coupling between soil surface and vegetation layer has a significant influence on canopy HTO concentration at both low and high Leaf Area Index → more studies are justified.

Photosynthesis

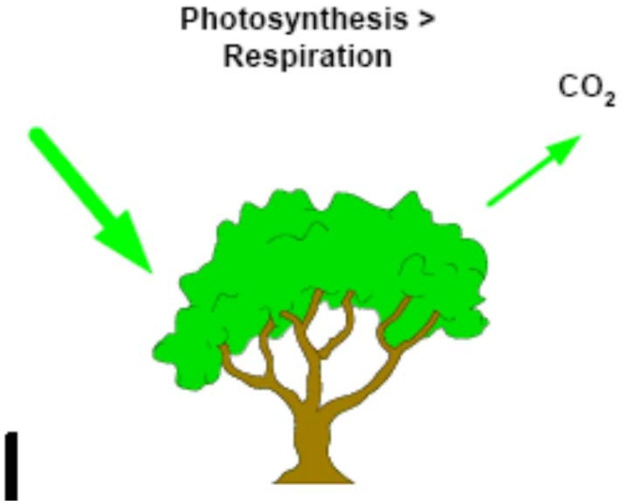
Biochemical reactions in the presence of light:

- **Diffusion of CO_2 to chloroplasts -** passing through the leaf stomata
- **Photochemical reaction** - light usage to split water producing O_2, NADPH and ATP
- **Dark reaction** - NADPH and ATP produced in the light are used to reduce CO_2 to carbohydrate and other organic compounds in a chain of reactions mediated by specific enzymes.
- Two biochemical processes important - **C3 and C4 pathways**

  - **C3 pathway (Calvin cycle) -** CO_2 is first incorporated into compounds with 3 carbon atoms; most temperate plants are based on the C3 process.

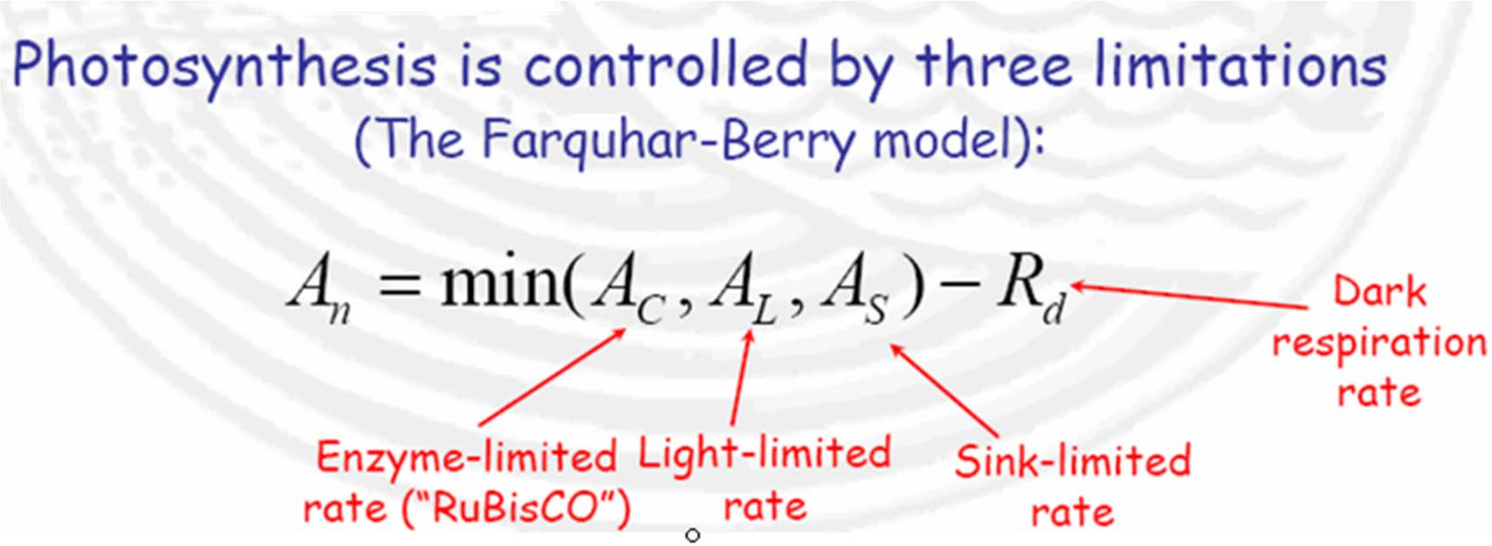
  - **C4 pathway -** CO_2 is first fixed in molecules with 4 carbon atoms; C-4 plants (maize, alfalfa, sugarcane) are well adapted to a climate with high temperatures, high light intensities and limited water supply.

Photosynthesis is accompanied by respiration, a process of dry matter oxidation needed to produce energy for the plant growth and maintenance of metabolic processes.



NADPH - reduced nicotinamide adenine dinucleotide phosphate;
ATP - adenosin triphosphate

Photosynthesis approaches



Photosynthesis is controlled by three limitations (The Farquhar-Berry model):

$$A_n = \min(A_C, A_L, A_S) - R_d$$

Enzyme-limited rate ("RuBisCO")

Light-limited rate

Sink-limited rate

Dark respiration rate

- the most complex biochemical model;
- used in land-atmosphere interaction;
- needs too many parameters for site-specific applications, covering genotype of various species, effect of fertilization and temperature adaptation → **great disadvantage**

The Romanian photosynthesis approach

- We use the canopy photosynthesis model from the WOFOST;
- Leaf gross photosynthesis rate:

$$A_{Lg} = A_{gm}(1 - \exp(-\frac{\varepsilon \times I_{aL}}{A_{gm}}))$$

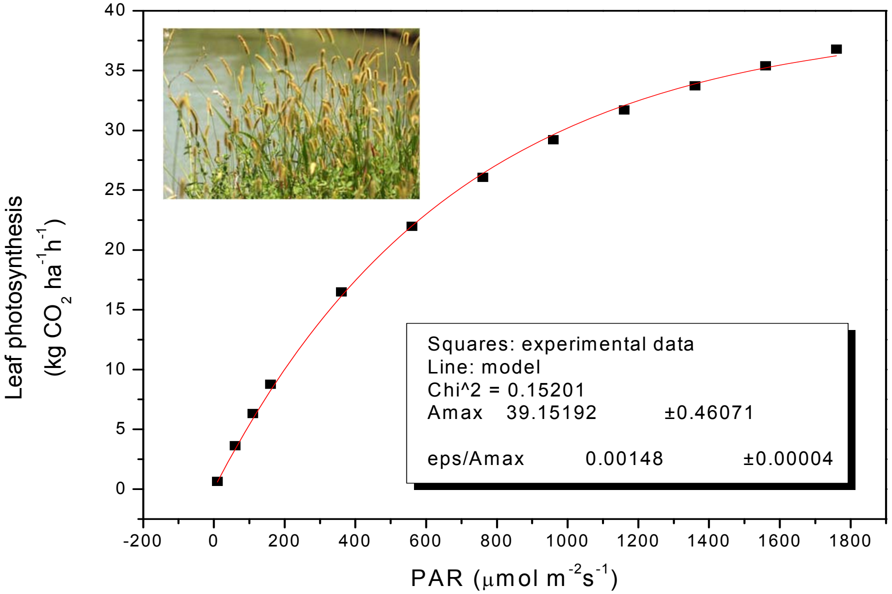
A_{gm} - gross assimilation rate at light saturation (kg m^{-2} d^{-1})
ε - initial slope or light use efficiency (kg J^{-1})
I_{aL} - the absorbed PAR (μmol $m^{-2}s^{-1}$)

Many plant specific results given by the biochemical models can be reproduced using the simplified WOFOST model

↓

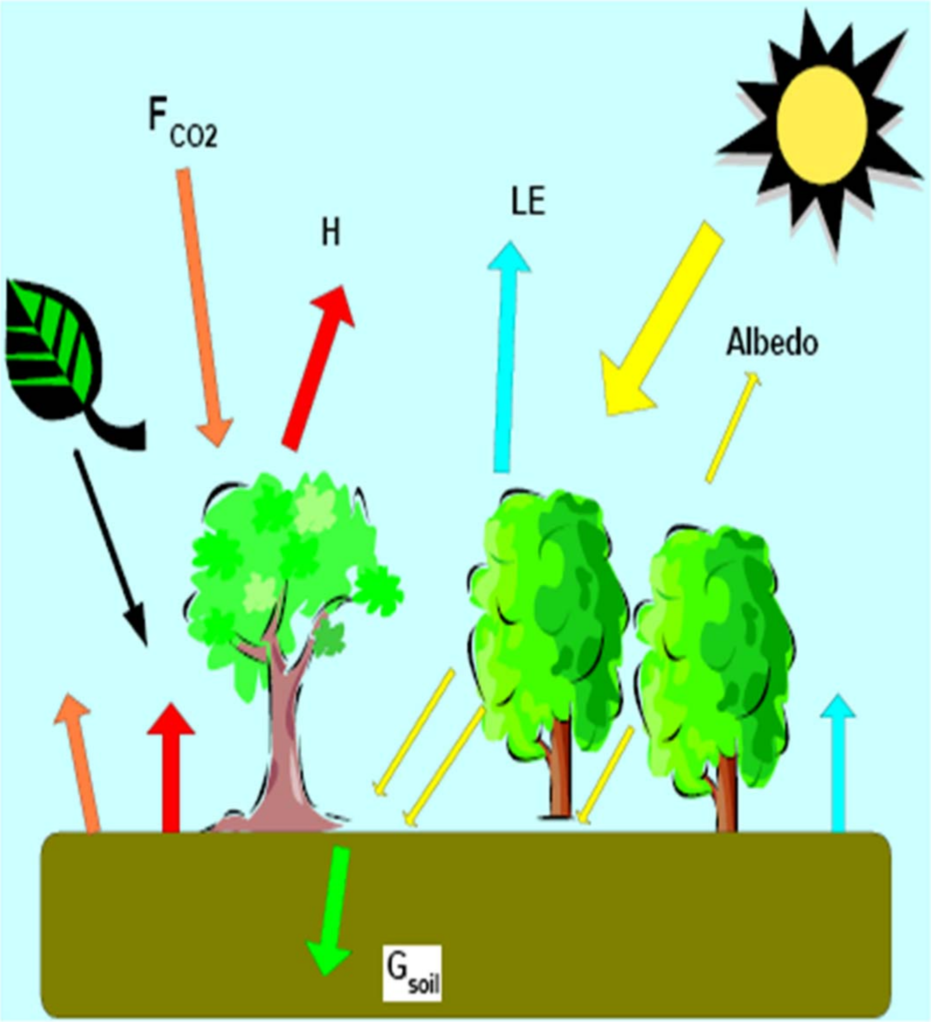
T (°C)	A_{max} (kg CO_2 $m^{-2}h^{-1}$)	ε (kg CO_2 J^{-1})
15	**19.0**	**0.33**
20	**36.5**	**0.33**
25	**55.5**	**0.32**
30	**74.0**	**0.32**
35	**70.7**	**0.32**

Comparison between WOFOST model and experimental data for Kansas grass at ambient temperature of 40 °C



Scaling from leaf to canopy using WOFOST approach

- We distinguish between sunlit and shaded leaves;
- We take into account the difference between air temperature (above the crop) and canopy temperature;
- To explain the experimental data, we recommend to consider the crop development stage effect on photosynthesis and canopy resistance (aging effect);
- We ignore the difference between temperature and stomatal resistance for shaded and sunlit leaves in field conditions.



OBT production in the daytime

- In the simplest approach, we ignore details on respiration and focus on net photosynthesis rate (net of respiration).
- Assume that we know the net assimilation rate of CO_2 as kg CO_2 per unit time and unit surface of crop, Pc.
- One mol of CO_2 and one mol of H_2O gives one mol of photosinthate (the initial organic matter produced), with a generic formula CH_2O.
- The rate of water assimilation in non-exchangeable matter (bound with C) can be obtained using stoichiometric relations (molar mass of CO_2 is 44, molar mass of H_2O is 18) and is 0.41 P_C.
- Consider tritium, as tritiated water → due to higher mass, all reactions rates will be slower.
- Energy of radioactive disintegration (average 5.8 keV) will be used partially for the activation energy of many biochemical reactions.
- Plant varies in their molecular constituent → the balance of slow down and acceleration of biochemical reaction is reflected in a variable fractionation (discrimination) ratio, FD (formation of OBT/formation of OBH), with an average of 0.5 and range between 0.45 and 0.55.

With a known C_{HTO} in leaves, we can assess the formation rate of OBT in light conditions:

$P_{OBT} = FD*0.41*P_c* C_{HTO}$ ($Bq/h/m^2$) → we must use the HTO in leaves, because leaves are the site of photosynthesis

In the same conditions of time and space, the net dry matter production is:

$$P_D = \frac{30}{44} P_C$$

Total organic tritium is higher, because about 22 % is non-exchangeable:

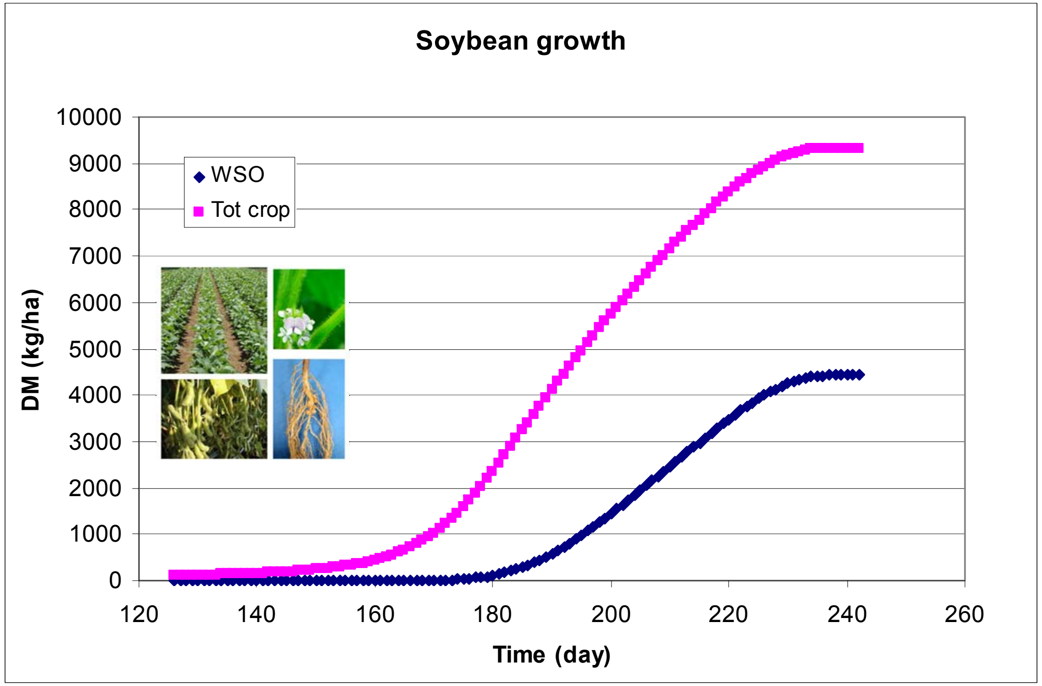
$$P_{OBT} = 0.88*P_{OT}$$

In practice, the leaf HTO concentration varies in time → Pc varies, also (with zero during the night time)

Consider the start of air contamination with HTO, t_0, and a subsequent moment, t, later in time; at start, the net dry matter of the crop is Y_0 and at time t is:

$$Y=Y_0+\int_{t0}^{t} 30/44 P_c(\tau)d\tau$$

P_c- net assimilation rate (net of respiration) (kg dm/m^2)



- If we ignore OBT production during the night time, we can derive a similar equation of OBT production for the whole crop.
- The evolution of OBT concentration C_{OBT} (Bq/kg dm) is of interest in food chain modelling.
- First, we consider the concentration in whole crop (including roots); we have:

$$\frac{dC_{OBT}}{dt} = (\frac{1}{Y}) * P_{OBT} - (\frac{C_{OBT}}{Y}) * P_{D}$$

where: $A_{OBT} = C_{OBT} * Y$ $\qquad \frac{dA}{dt} = Y * \frac{dC}{dt} + C * \frac{dY}{dt}$

$$P_{OBT} = Y * \frac{dC}{dt} + C * \frac{dY}{dt}$$

$$\frac{dC_{OBT}}{dt} = (\frac{1}{Y}) * 0.41 * FD * P_{c} * C_{HTO} - (\frac{C_{OBT}}{Y}) * 0.68 * P_{c}$$

$$\frac{dC_{OBT}}{dt} = (\frac{1}{Y}) * 0.6 * FD * P_D * C_{HTO} - (\frac{C_{OBT}}{Y}) * P_D$$

Y and C_{HTO} are function of time

We demonstrate the close relationship between OBT and C

PD/Y is Relative Growth Rate (RGR) - time dependent

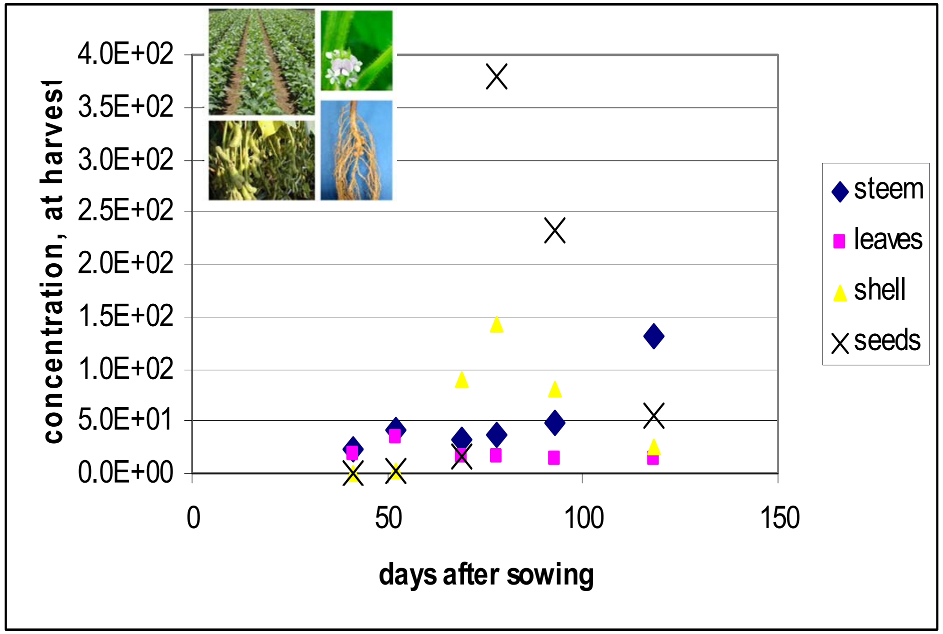
Dynamic equation for OBT production in plants:

$$\frac{dC_{OBT}}{dt} = (\frac{P_D}{Y}) * [0.6 * FD * C_{HTO} - C_{OBT}]$$

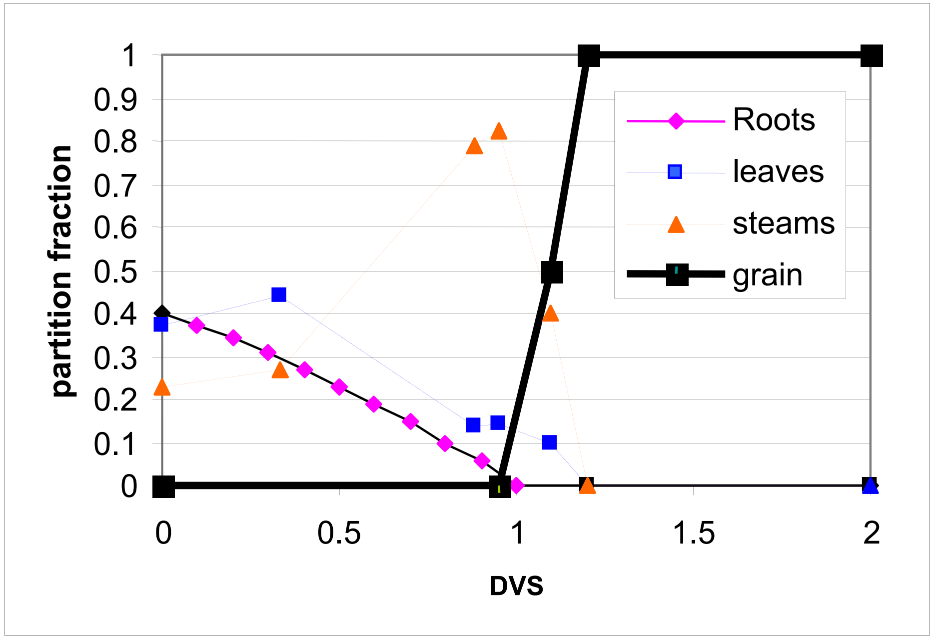
C_{HTO} dynamics depends on air concentration AND canopy resistance and this last one depends on Pc

OBT concentration in edible plant parts (net of respiration)

- At each stage of plant development, the new formed net dry matter will be differently distributed to various plant parts → initial uptake and time evolution depends on plant part.
- We must know these partition factors in order to assess OBT in the edible plant part.
- Even for leafy vegetables and pasture, we must know the partition to root.



OBT concentration for soybean at harvest for 1 hour air contamination at various plant DVS



Partition fraction of new produced dry matter to roots, leaves, stems and edible grains as function of DVS (0=emergence; 1= flowering; 2= full maturity) for maize cultivar F320 (South Romania)

- PARTITION FACTORS DEPEND ON CULTIVAR (GENOTYPE), not only on PLANT

- P_c depends on:
    - crop type;
    - development stage (DVS);
    - leaf area index (LAI);
    - temperature;
    - light;
    - water stress (air vapour deficit and soil water)

- We must understand the plant growth

- Development stages:

  0 -1 - emergence to anthesis (flowering) → generative stage
  1 -2 - anthesis to maturity → reproductive stage
  } both can be finer divided

- Evolution of plant development depends on Thermal time = sum of air temperature over a basis

OBT concentration in different plant parts

- At least, we must know crop specific accumulated thermal time until anthesis and maturity → we can define the increasing of DVS each day → partition factors → increase in leaf mass → green leaves → LAI

- Knowing the ambient data on temperature, light, vapour pressure and soil water, we can determine P_C, P_D, P_{OBT}

OBT concentration in plant part i

Partition fraction PF_i (DVS) → $PF_i(t)$

$P_{D,i}=P_D*PF_i$
$P_{OBT,i}= P_{OBT}* PF_i$

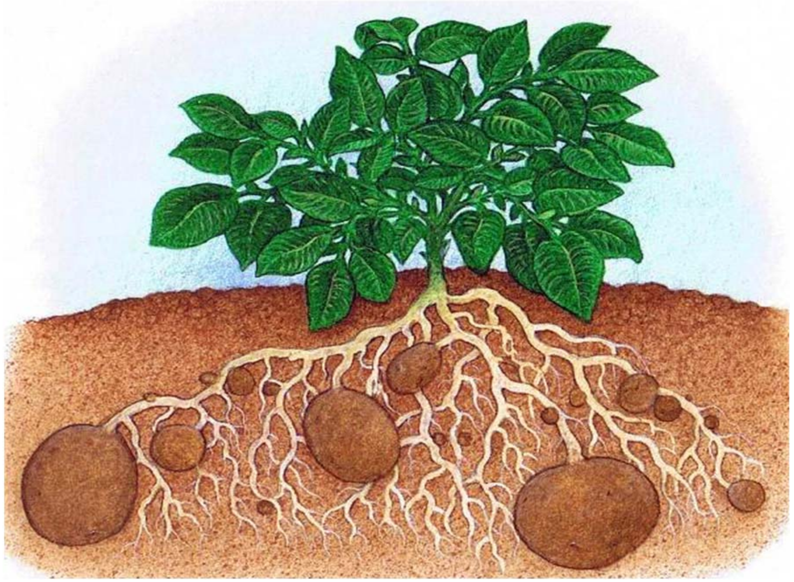
$$\frac{dC_{OBT,i}}{dt} = (\frac{1}{Y_i}) * P_{OBT,i} - (\frac{C_{OBT,i}}{Y_{i_i}}) * P_{D,i}$$

Comparison between experimental data and model predictions for relative OBT concentration in wheat at harvest

Time	Rel. OBT conc. at harvest (%)		Exposure conditions	
	Exp.	Model	Solar radiat. (W m^{-2})	Temp. (°C)
Dawn	0.18	0.29	90-170	11-26
Day	0.25	0.34	400-800	26-36
Dusk	0.20	0.34	26-38	15-24
Night	0.15	0.31	0	12-17

Model predictions for relative HTO uptake, HTO half-time and relative OBT concentration in potato at harvest

Day of year	DVS	LAI	Canopy resistance (s/m)	Rel. HTO uptake (%)	HTO Half time (min)	Rel. OBT (%)
162	1.02	2	75	43	44	3.6e-3; 0.03
177	1.16	3.5	60	51	32	0.026; 0.21
193	1.31	4	60	49	52	0.051; 0.42
202	1.4	4	45	50	68	0.075; 0.6
219	1.55	3.4	95	44	62	0.03; 0.25
236	1.71	1.9	125	37	90	0.039; 0.33
177 (night)	1.16	3.5	690	14	600	0.022; 0.23

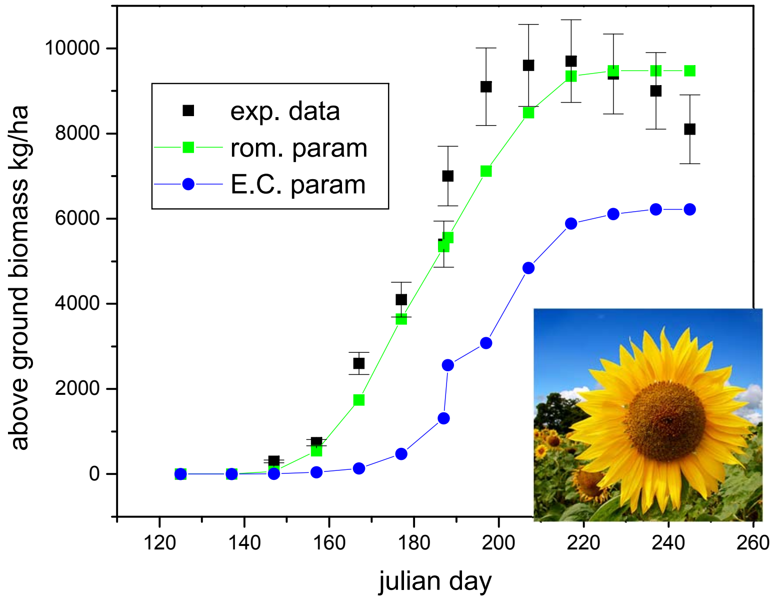


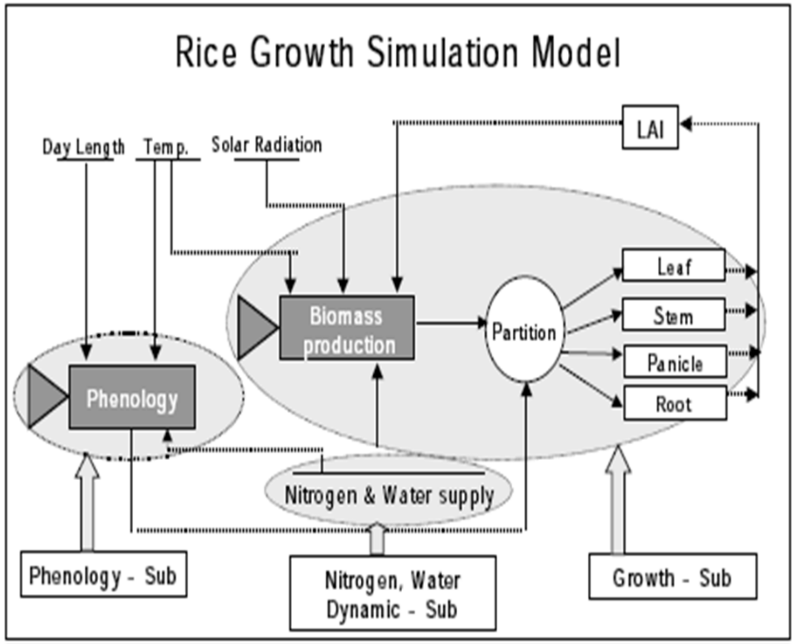
- DVS is 0 at emergence, 1 at anthesis and 2 at harvest;
- Relative uptake is the concentration of HTO in leaf water at the end of exposure relative to HTO conc. in air moisture;
- Relative OBT is OBT concentration at harvest (per kg fw or per L of combustion water, assuming 0.2 g dm in tuber) relative to HTO conc. in leaf water at the end of exposure.

Basic plant growth model – site adaptation

Having at least one year of data on biomass production (plant part and, total, daily meteo data, soil type), we started with default parameters in the physiological crop growth and adapted them for local conditions

Full description is given elsewhere
(A. Melintescu, D. Galeriu, E. Marica, “Using WOFOST Crop Model for Data Base Derivation of Tritium and Terrestrial Food Chain Modules in RODOS”, *Radioprotection*, 37 (C1): 1242-1246, February 2002)





Sunflower above ground biomass, experimental data (exp), WOFOST result for default cultivar (EC param.) and parameters adapted to Romanian cultivars (rom param)

Role of respiration in OBT formation

- Respiration is often subdivided into:
  - Growth;
  - Maintenance;
  - Transport costs.

  Growth respiration (a.k.a. "construction respiration") – a "fixed cost" that depends on the tissues or biochemical's that are synthesized → Often described in terms of "glucose equivalents"

- The conversion of assimilate into dry matter (growth respiration) can be counted first converting the CO_2 assimilation to assimilate production (30/44) and further considering the conversion from assimilate top dry matter depending also on plant stage
- In vegetative period (only leaves, roots and stems) a value of 0.69 is OK (coefficient of variance less than 5%).
- In reproductive stage the same value can be used, but with a larger variance.
- Storage organs for different plants have:
  - soybean - 0.48;
  - field bean - 0.59;
  - sugar beat - 0.82;
  - potato - 0.85

It seems that growth respiration ends the next morning!

Maintenance respiration - The cost of maintaining existing tissues and functions (Protein turnover is the largest cost of maintenance respiration)

- is subtracted from the assimilate production and depends on dry mass of plant organs

$$W_r=RML*WL+RMS*WS+RMR*WR+RMO*WO$$

where: L - leaf, S - stem, R - root, O - storage organ; RM – maintenance respiration.

RMX in kg photosinthate per kg dry matter and day (data from Wageningen school)

RML=0.026

0.03	wheat sugar soy potato maize barley
0.02	rice
0.027	bean

RMS=0.015

RMR=0.012

0.015	maize sugar beat wheat
0.01	barley bean potato rice soybean

RMO=0.003-0.01

0.01	barley maize wheat
0.003	sugar beet rice
0.0045	potato
0.005	bean

Sunflower swap

RML = 0.0050 ! Rel. maintenance respiration rate of leaves, [0..1 kg CH_2O/kg/d, R]
RMO = 0.0230 ! Rel. maintenance respiration rate of st. org.,[0..1 kg CH_2O/kg/d, R]
RMR = 0.0100 ! Rel. maintenance respiration rate of roots, [0..1 kg CH_2O/kg/d, R]
RMS = 0.0080 ! Rel. maintenance respiration rate of stems, [0..1 kg CH_2O/kg/d, R]

It seems that maintenance respiration is a long time process (λ~0.2 d^{-1})

OBT formation during the night time
Maintenance respiration dynamics
To re-write the dynamic equation for OBT production taking into account the respiration dynamics

} OPEN QUESTIONS

CONCLUSIONS

- Various approaches describing the stomatal (canopy) conductance and photosynthesis rate;
- The goal is to select the best formalism in order to be applied for operational cases in field conditions;
- We developed a research grade model for plants based on process level, pointing out that model inputs can be obtained using Life Science research in connection with National Research on plant physiology and growth, soil physics, and plant atmosphere interaction → **Interdisciplinary Research**;
- The aim of this work in progress is to develop a robust model for the HTO transfer from atmosphere to plants and the subsequent conversion to OBT.

THANK YOU!