Evapotranspiration, ET, & Root water uptake

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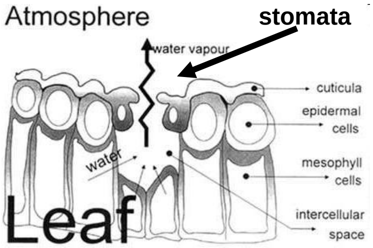
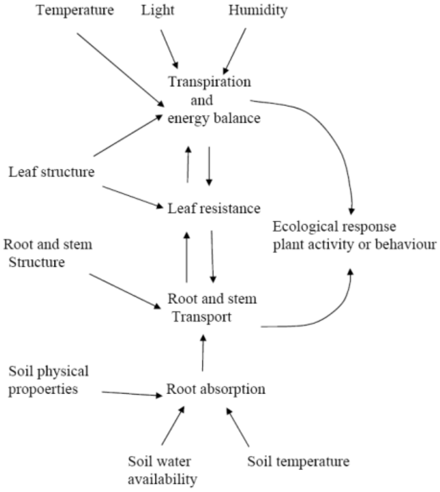
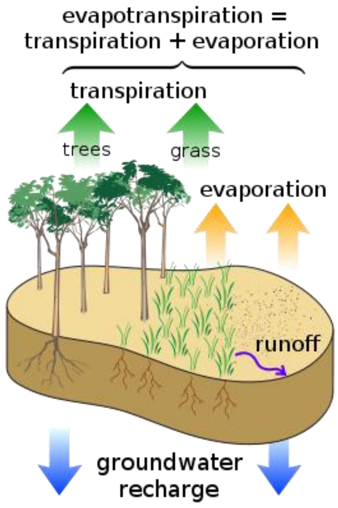
Hopmans, Skaggs, Snyder



Soil-Plant-Air Continuum (SPAC)


Temperature
Light
Humidity
Transpiration and energy balance
Leaf structure
Leaf resistance
Ecological response plant activity or behaviour
Root and stem Structure
Root and stem Transport
Soil physical propoerties
Root absorption
Soil water availability
Soil temperature

1. Evapo-transpiration, ET



- Evaporation: process whereby liquid water is converted to water vapor and removed from the evaporating surface;

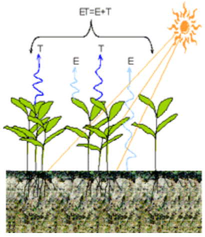
- It takes energy to evaporate water: 540 cal/g or 2,260 J/g of water;

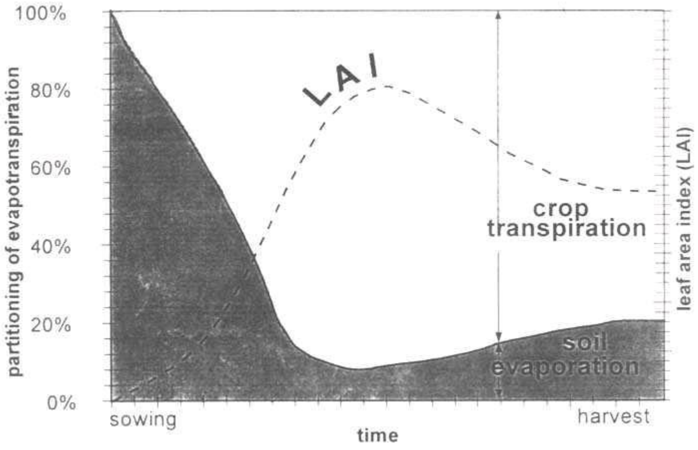
- Evaporation rate is controlled by evaporative demand – atmospheric conditions;

- Evaporative demand: wind velocity, temperature, net radiation, air humidity;

- Further controlled by plant and soil factors.

Plant transpiration versus Soil evaporation





Units of ET

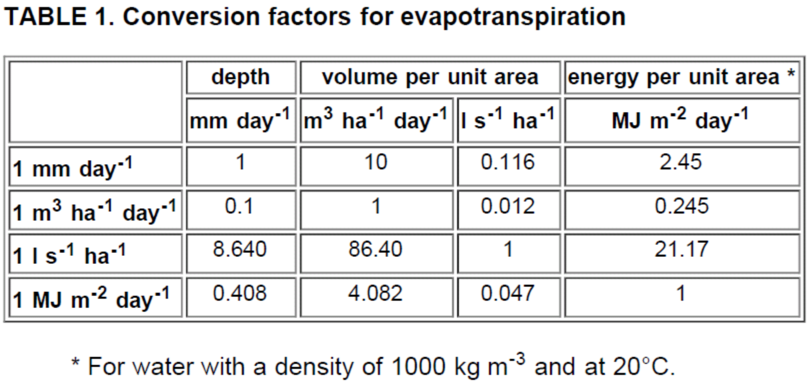
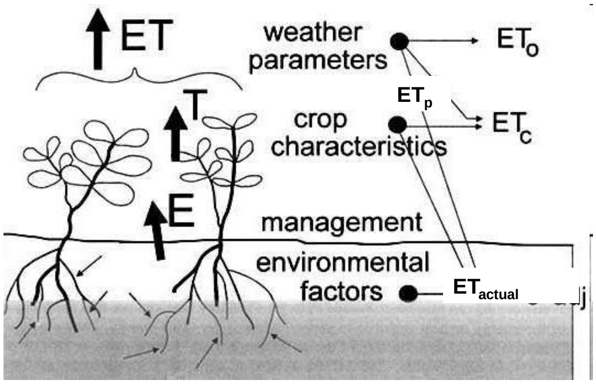


TABLE 1. Conversion factors for evapotranspiration

	depth	volume per unit area		energy per unit area *
	mm day^{-1}	m^3 ha^{-1} day^{-1}	l s^{-1} ha^{-1}	MJ m^{-2} day^{-1}
1 mm day^{-1}	1	10	0.116	2.45
1 m^3 ha^{-1} day^{-1}	0.1	1	0.012	0.245
1 l s^{-1} ha^{-1}	8.640	86.40	1	21.17
1 MJ m^{-2} day^{-1}	0.408	4.082	0.047	1

* For water with a density of 1000 kg m^{-3} and at 20°C.

Factors affecting evapotranspiration: FAO report



Reference Evapotranspiration ET_o , determined by weather parameters

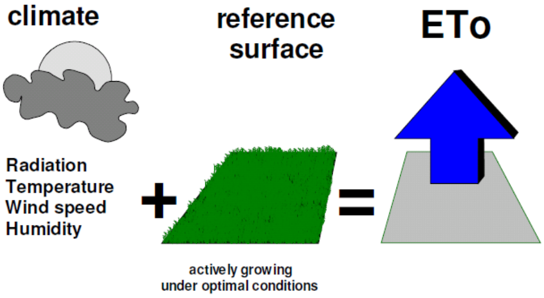
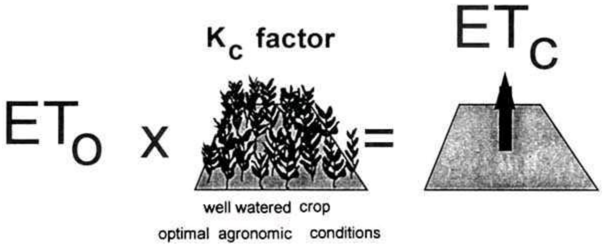


Figure 1.
Reference evapotranspiration (ETo)

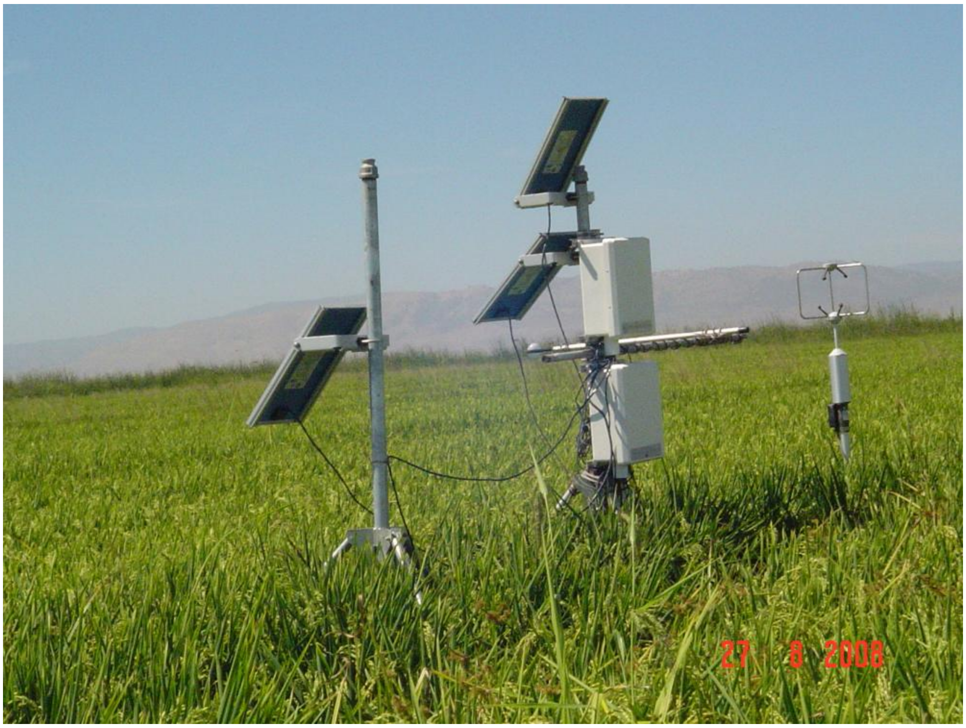
http://wwwcimis.water.ca.gov/cimis/welcome.jsp

Map of ET_o in California

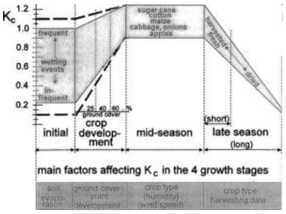
Potential crop ET from Reference ET (ET_c)



Well-watered; no soil water or salinity stress



Crop growth stages to compute ETp



Crop evapotranspiration

Guidelines for computing crop water requirements

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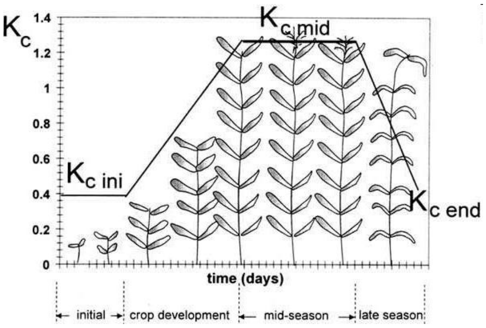
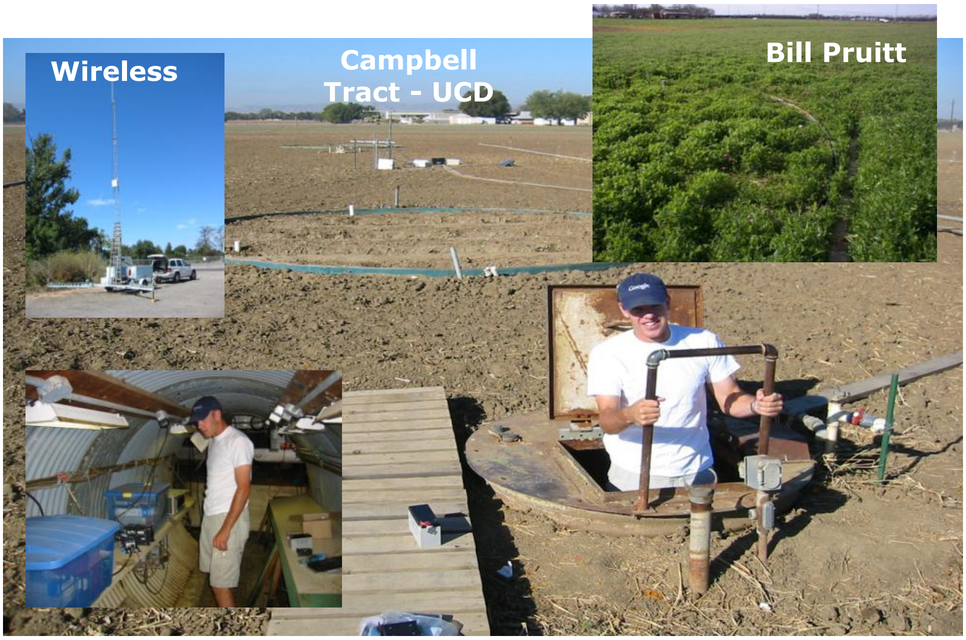


http://www.fao.org/docrep/X0490E/x0490e00.htm#Contents

Lysimeter

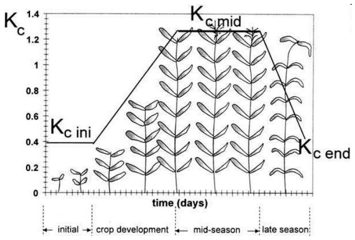


Potential crop ET - ET_c

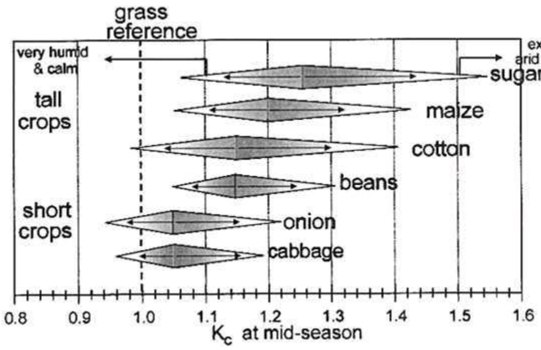
- Reference evapotranspiration, ET_0
  http://wwwcimis.water.ca.gov/cimis/welcome.jsp
- Potential ET, Crop Coefficient
  $ET_c(t) = K_c(t)\ ET_0(t)$

“Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56” by Allen et al.

http://www.fao.org/docrep/X0490E/x0490e00.htm



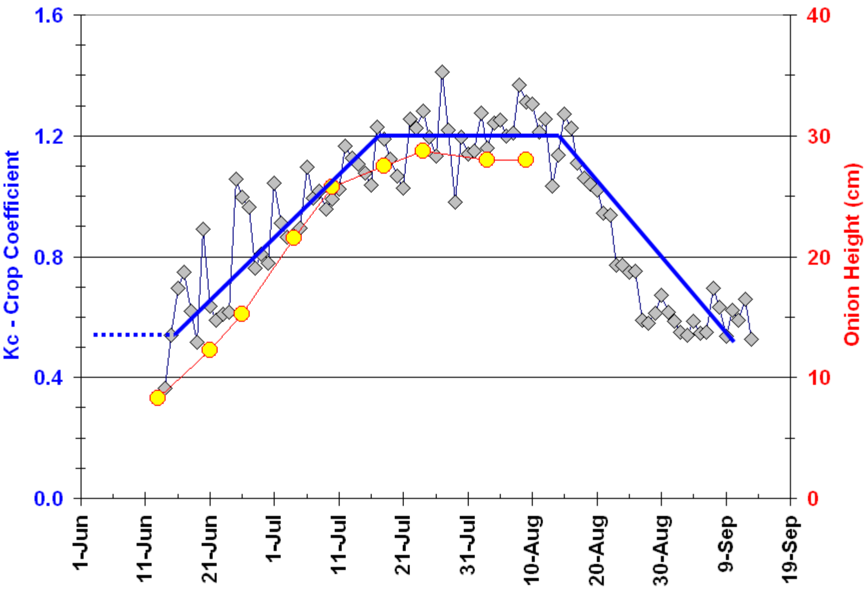
Crop ET - ET$_c$



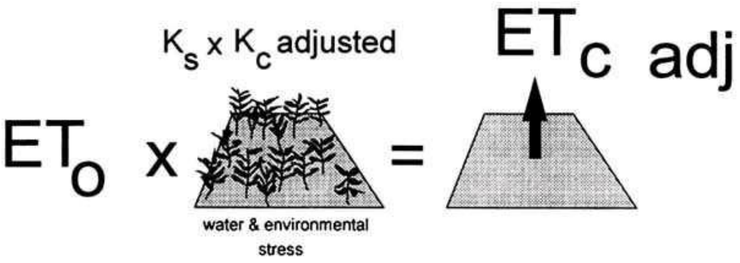
The crop coefficient, K_c, is basically the ratio of the crop ET_c to the reference ET_o, and it represents an integration of the effects of four primary characteristics that distinguish the crop from reference grass. These characteristics are:

·1. Crop height, affecting magnitude of aerodynamic resistance, r_a
·2. Albedo (reflectance) of the crop-soil surface. The albedo is affected by the fraction of ground covered by vegetation and by the soil surface wetness.
·3. Canopy resistance. The resistance of the crop to vapor transfer is affected by leaf area (number of stomata), leaf age and condition, and the degree of stomatal control. The canopy resistance influences the surface resistance, r_s.
·4. Evaporation from soil, especially exposed soil.

Tulelake K$_c$: from rick snyder



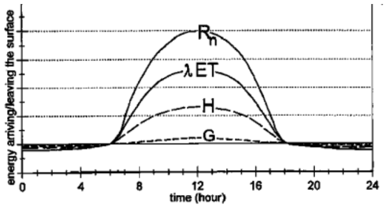
ET, adjusted by soil factors
ET_a – actual ET
Soil water/salinity stress



How to estimate ET_c

1. Energy Balance

$R_n – G – \lambda ET – H = 0$



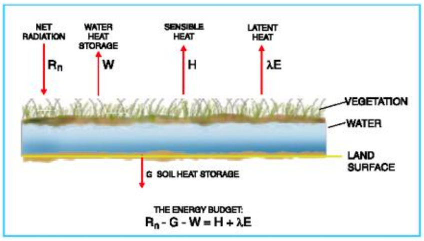


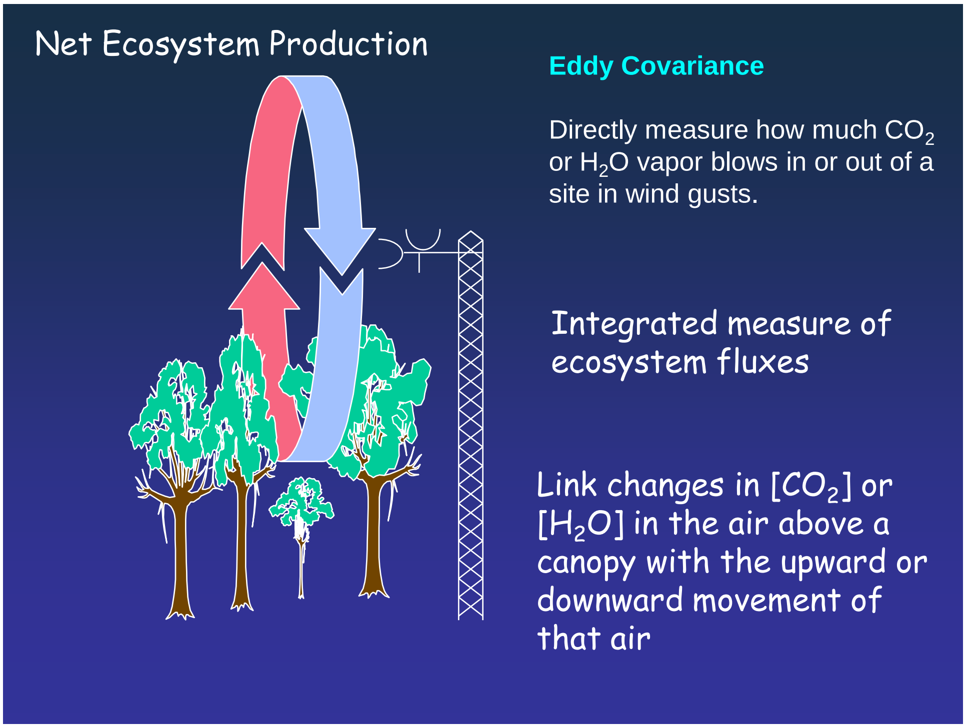
Figure 4. Energy budget during daytime heating.

2. Mass transfer method

Considers vertical movement of small parcels of air (eddies) above a land surface. The eddies transport mass and energy across the evaporating surface. Typically, includes wind speed, water vapor and air temperature measurements:

a. Bowen ratio : gradients of air temperature and water vapor

b. Eddy covariance method: gradients of vapor pressure, air temperature and wind speed.



Net Ecosystem Production

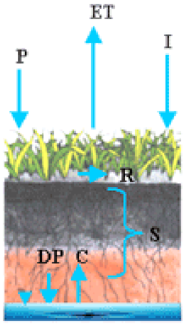
Eddy Covariance

Directly measure how much CO_2 or H_2O vapor blows in or out of a site in wind gusts.

Integrated measure of ecosystem fluxes

Link changes in $[CO_2]$ or $[H_2O]$ in the air above a canopy with the upward or downward movement of that air

3. Soil water balance



I = Irrigation
R = Runoff
S = Storage
C = Capillary Rise
P = Precipitation
ET = Evapotranspiration
DP = Deep Percolation

$$S = I + P + C - ET - DP - R$$

Lysimeter

4. From Meteorological Data

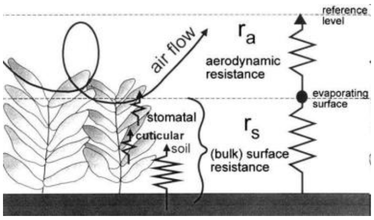
Penman-Monteith equation

In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. This so-called combination method was further developed by many researchers and extended to cropped surfaces by introducing resistance factors.

It is now the official accepted FAO equation that is widely used.

$$ET_0 = ET_{rad} + ET_{aero} = \frac{1}{\lambda}\left[\frac{\Delta(R_n - G)}{\Delta + \gamma(1 + r_c / r_a)} + \frac{\rho c_p (e_a - e_d) / r_a}{\Delta + \gamma(1 + r_c / r_a)}\right]$$

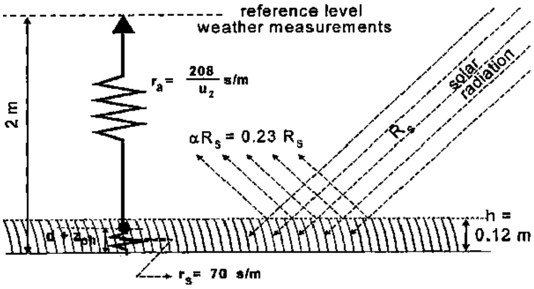
Simplified representation of the (bulk) surface and aerodynamic resistances for water vapour flow



$$ET_0 = ET_{rad} + ET_{aero} = \frac{1}{\lambda}\left[\frac{\Delta(R_n - G)}{\Delta + \gamma(1 + r_c / r_a)} + \frac{\rho c_p (e_a - e_d) / r_a}{\Delta + \gamma(1 + r_c / r_a)}\right]$$

FAO Penman Monteith - 1990

ET_o for reference crop (grass, **Daily values**)



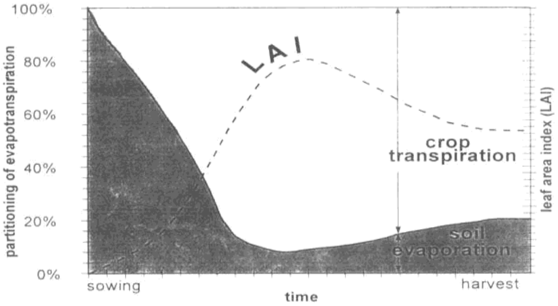
$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} U_2 \left(e^o - e_a\right)}{\Delta + \gamma(1 + 0.34 U_2)}$$

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
e_s - e_a saturation vapour pressure deficit [kPa],
Δ slope vapor pressure curve [kPa $°C^{-1}$],
γ psychrometric constant [kPa $°C^{-1}$].

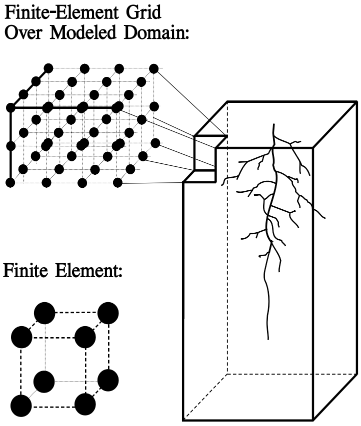
$$ET_c = E + T_c \quad \text{or} \quad ET_p = E_p + T_p$$

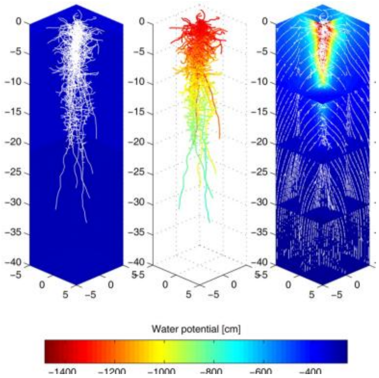
$$T_p = ET_p\left(1 - e^{-k\cdot \mathrm{LAI}}\right) = ET_p SCF$$
$$E_p = ET_p e^{-k\cdot \mathrm{LAI}} = ET_p(1 - SCF) \qquad (2.75)$$

where ET_p, T_p, and E_p are potential evapotranspiration, transpiration and evaporation fluxes [LT^{-1}], respectively, LAI is the leaf area index [-], SCF is the soil cover fraction [-], and k is a constant

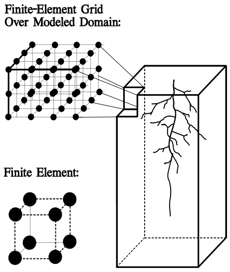


2. Plant Root Water Uptake





Variably Saturated Flow Equation



$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}[K(h)\frac{\partial h}{\partial z} - K(h)] - S$$

θ = volumetric water content ($L^3\ L^{-3}$)
h = pressure head (L),
K = hydraulic conductivity (LT^{-1})
S = sink term ($L^3\ L^{-3}\ T^{-1}$)

The sink term is introduced into the flow equation to account for the root water uptake. Many possibilities exist for specifying the particular form of S. We define as actual root water uptake or **$S = S_a$, hereafter**

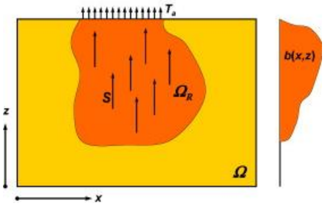
Macroscopic root water uptake

Soil sink term, one-dimensional root domain:

Potential Uptake: $S_p(x) = b(x)T_p$

Actual water uptake: $S_a(h,x) = \alpha(h)S_p = \alpha(h)b(x)T_p$

$$\int_\Omega S_a(h,x) = \alpha(h)S_p = \int_\Omega \alpha(h)b(x)T_p\,d\Omega = T_a$$



Simunek and Hopmans (2009)

S(z) as a function of potential plant transpiration, T_p (T_c previously)

$$S(z) = b(z)\alpha(h)T_P$$

Normalized root length density function (L^{-1})

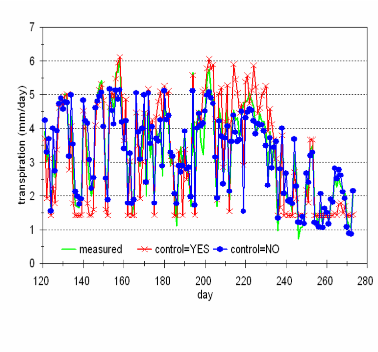
Dimensionless ‘water stress function’ ($0 \leq \alpha \leq 1$) (aka ‘uptake reduction function’)

Potential transpiration rate, with units of volume of water per area of soil per unit of time ($L^3\ L^{-2}\ T^{-1}$)

$$T_{act} = \int_{RZ} S dz = \sum_{i=1}^{Nl} S_i \Delta z_i$$

Potential Plant Transpiration

$$S(z) = b(z)\alpha(h)T_P$$

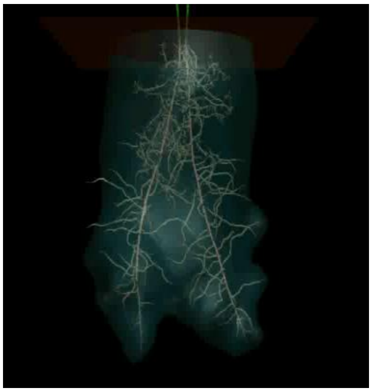


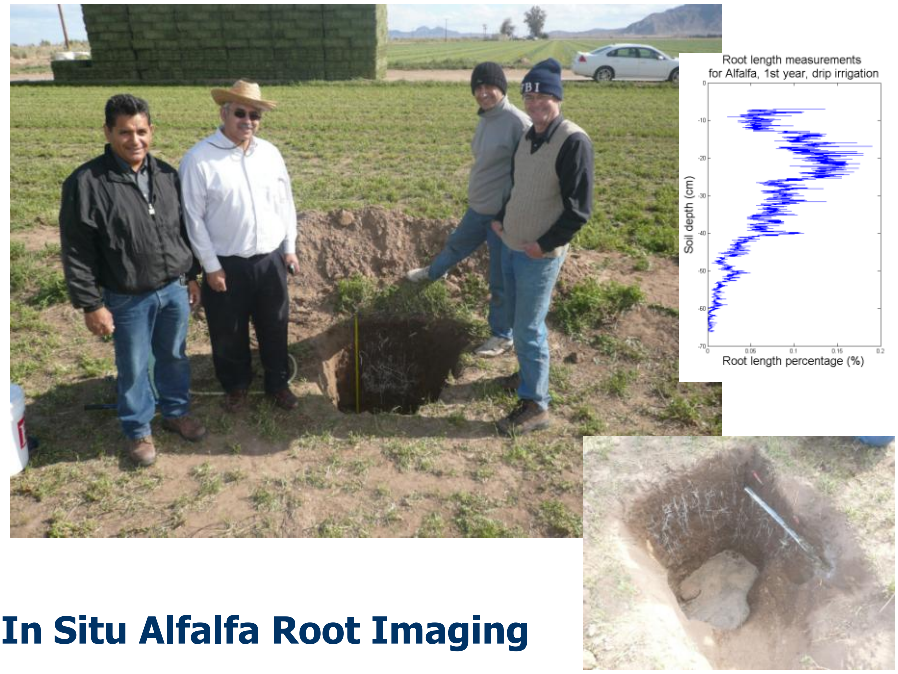
Potential transpiration rate, with units of volume of water per area of soil per unit of time ($L^3\ L^{-2}\ T^{-1}$)

Root Density Distribution

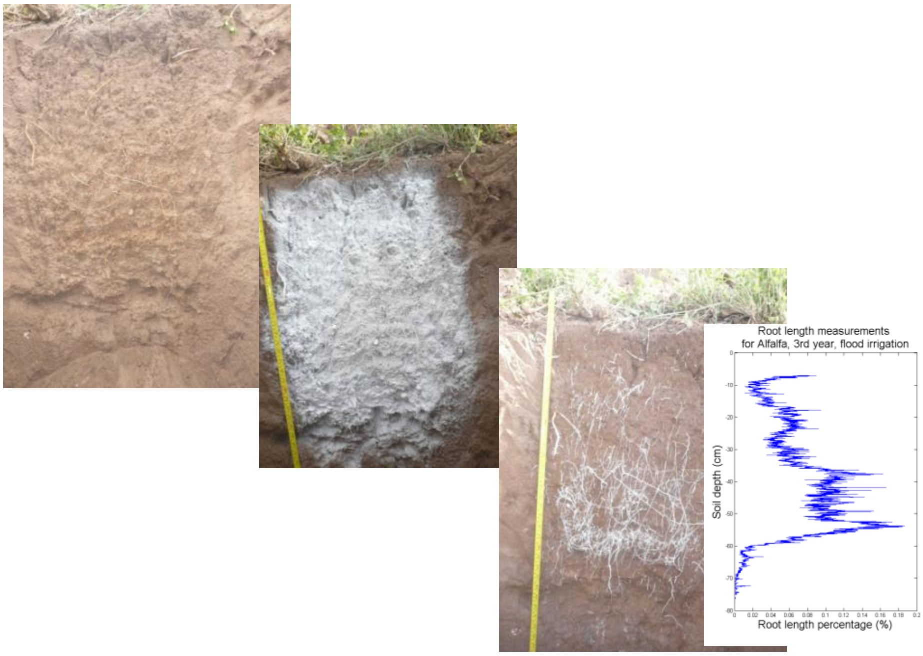
$$S(z) = b(z)\alpha(h)T_P$$

Normalized root length density function (L^{-1})



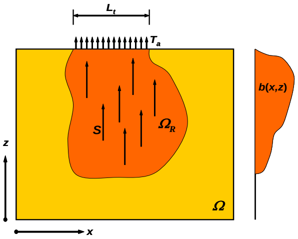


In Situ Alfalfa Root Imaging



Normalized Root density distribution function, b(x)

(Can be 1, 2, or 3 dimensional)



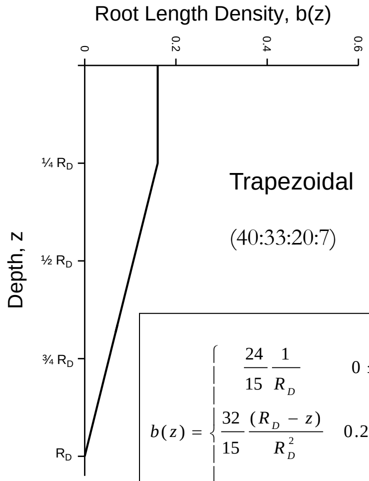
$$S_p = b(x)T_p$$

where $b(x)$ is the normalized water uptake distribution [L^{-1}]. This function describes the spatial variation of the potential extraction term, S_p, over the root zone (Fig. 2.2), and is obtained by normalizing any arbitrarily measured or prescribed root distribution function, bN(x), as follows

$$b(x) = \frac{b'(x)}{\int_{L_R} b'(x)\,dx} \qquad (2.14)$$

In reality, b(x) is effectively the root distribution function.

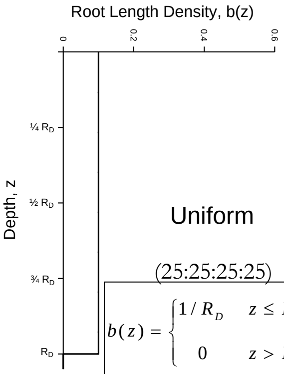
Model root length density functions (one-dimensional only)



Trapezoidal

(40:33:20:7)

$$b(z) = \begin{cases} \frac{24}{15}\frac{1}{R_D} & 0 \le z \le 0.25 R_D \\ \frac{32}{15}\frac{(R_D - z)}{R_D^2} & 0.25 R_D < z \le R_D \\ 0 & z > R_D \end{cases}$$



Uniform

(25:25:25:25)

$$b(z) = \begin{cases} 1/R_D & z \le R_D \\ 0 & z > R_D \end{cases}$$

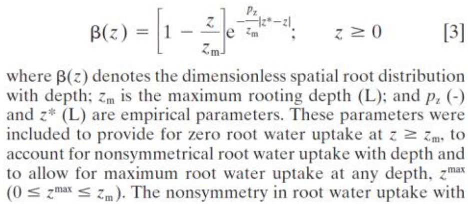
Root Growth

- Specify R_D as a function of time

e.g.

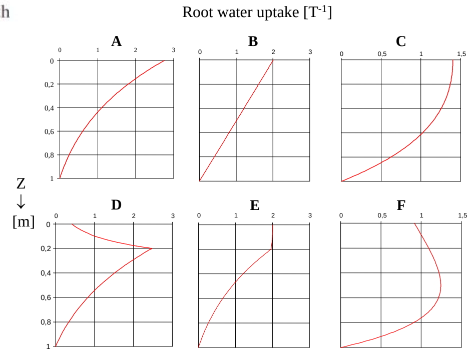
$$R_D(t) = \frac{R_{\max} R_{\min}}{R_{\min} + (R_{\max} - R_{\min})\exp(-rt)}$$

Exponential root water uptake model (HYDRUS) – Vrugt and Hopmans,



$$\beta(z) = \left[1 - \frac{z}{z_m}\right] e^{-\frac{p_z}{z_m}|z^* - z|}; \qquad z \geq 0 \qquad [3]$$

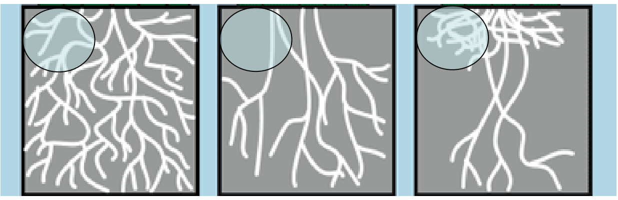
where $\beta(z)$ denotes the dimensionless spatial root distribution with depth; z_m is the maximum rooting depth (L); and p_z (-) and z^* (L) are empirical parameters. These parameters were included to provide for zero root water uptake at $z \geq z_m$, to account for nonsymmetrical root water uptake with depth and to allow for maximum root water uptake at any depth, z^{max} $(0 \leq z^{max} \leq z_m)$. The nonsymmetry in root water uptake with



Stress and Compensation

- But not only root distribution varies!
- Water and Nutrients availability also vary in space and time.

  How does the uptake change?

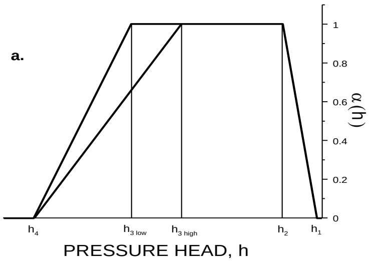


Stress Functions
(Water and/or Salinity)

$$S(z) = b(z)\alpha(h)T_P$$

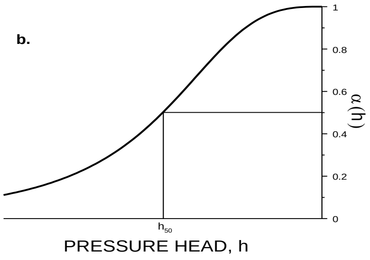
Dimensionless ‘water stress function’ ($0 \le \alpha \le 1$) (aka ‘uptake reduction function’)

Water Stress Reduction Functions (Skaggs, Salinity Lab, Riverside)



a. Piecewise Linear (Feddes et al., 1978)

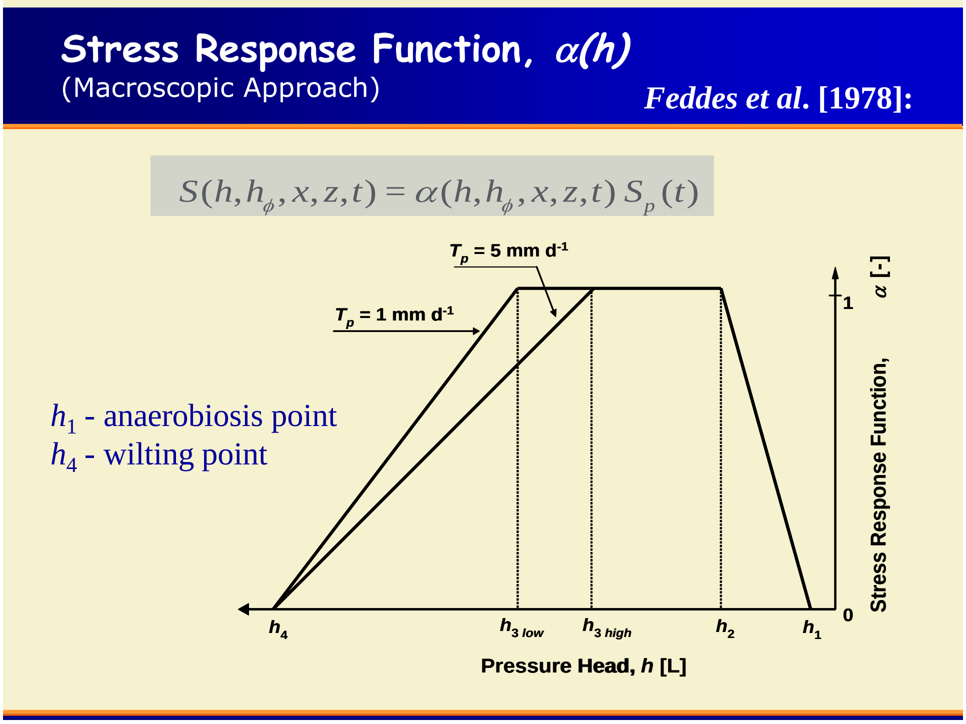
$$\alpha(h) = \begin{cases} \dfrac{h - h_4}{h_3 - h_4} & h_3 > h > h_4 \\ 1 & h_2 \ge h \ge h_3 \\ \dfrac{h - h_1}{h_2 - h_1} & h_1 > h > h_2 \\ 0 & h \le h_4 \text{ or } h \ge h_1 \end{cases}$$



b. S-shaped Function

(van Genuchten, 1987)

$$\boldsymbol{\alpha(h) = \frac{1}{1 + (h/h_{50})^{p}}}$$



Stress Response Function, $\alpha(h)$

(Macroscopic Approach)

***Feddes et al.* [1978]:**

$$S(h,h_\phi,x,z,t) = \alpha(h,h_\phi,x,z,t)\, S_p(t)$$

h_1 - anaerobiosis point

h_4 - wilting point

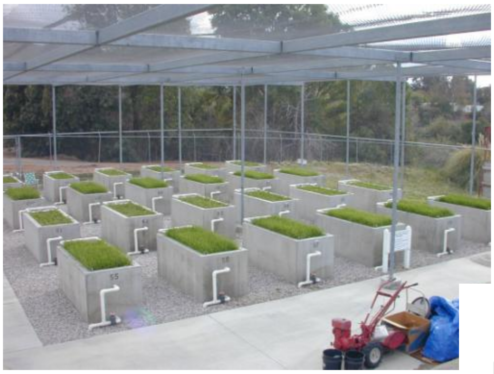
Combined Stress Response Function, $\alpha(h,\pi)$

Additive:

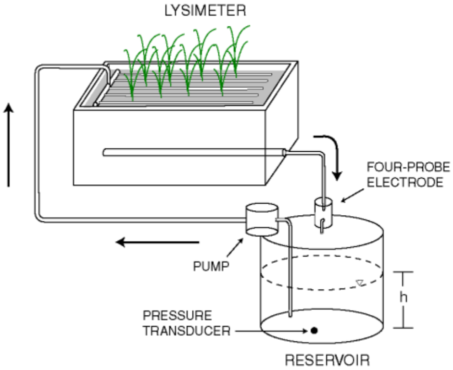
$$\alpha(h,\pi) = \alpha\left(a_1 h + a_2 \pi\right) = \frac{1}{1+\left(\dfrac{a_1 h + a_2 \pi}{h_{50}}\right)}$$

Multiplicative:

$$\alpha(h,\pi) = \alpha_1(h)\alpha_2(\pi) = \frac{1}{1+\left(\dfrac{h}{h_{50}}\right)^{p_1}} \times \frac{1}{1+\left(\dfrac{\pi}{\pi_{50}}\right)^{p_2}}$$



Case Study: Effects of water and salinity stress on root water uptake by forage crops (Skaggs, Salinity Lab, Riverside)

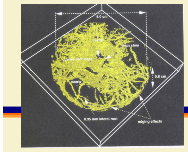


Lysimeter dimensions:
82 x 203 cm surface
85 cm deep

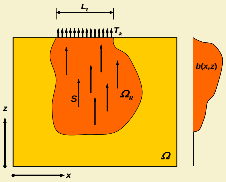
Soil is 96% sand

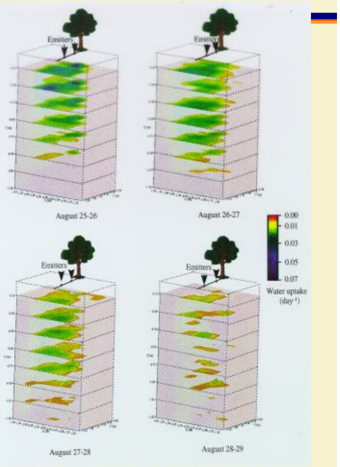
Modeling of Soil - Plant Root Interactions

(HYD210-Spring'09)



Jan W. Hopmans
University of California,
Davis, CA



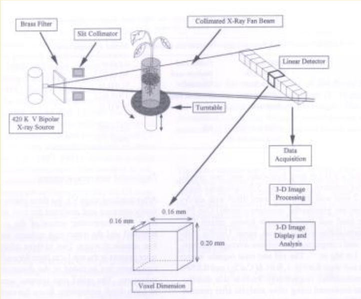


Contributors: L. Andreu, K. Bristow, V. Clausnitzer, D. Heeraman, T. Kamai, K. Koumanov, F. Somma, J. Simunek, L. Tumlinson, J. Vrugt, and others

Root functioning of water and nutrient uptake

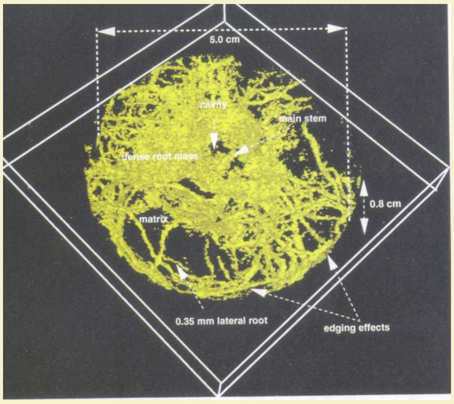
- Root-Soil interactions is a largely underexplored study area;
- How to integrate local uptake variations to total plant uptake as a function of soil environmental stresses (water, nutrient, salinity, temperature, density);
- Understanding of plant's response to spatially-distributed soil water and plant-available nutrients;
- Ecological & Agricultural Implications: Biodiversity - Climate Change – Invasive Species – World Crop Production – Irrigated Agriculture;

Example of X-ray Computed Micro Tomography for nondestructive 3D plant root measurements



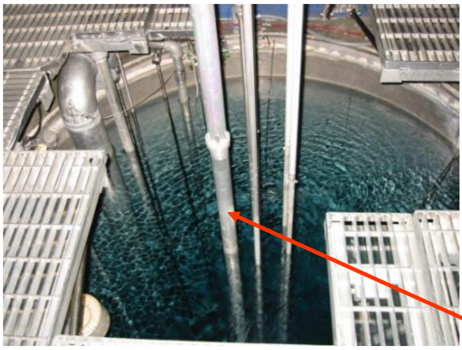
Experimental Setup

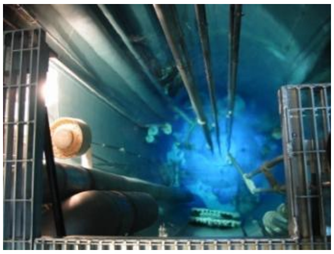
3D Root Image, showing isolines of attenuation



Heeraman, Hopmans and Clausnitzer
Plant &Soil, 1997

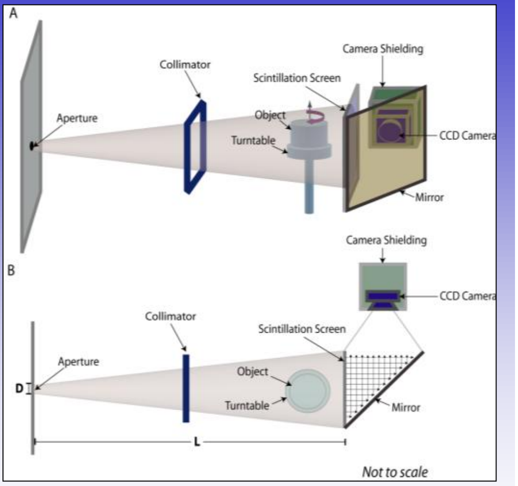
Thermal Neutron Computed Tomography - MNRC

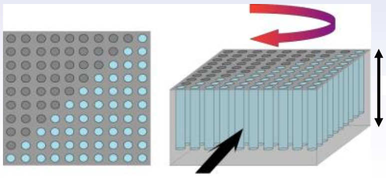




Gadolinium control rods

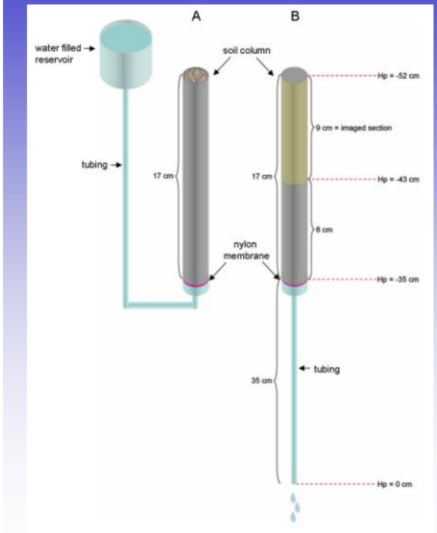
Thermal Neutron Tomography

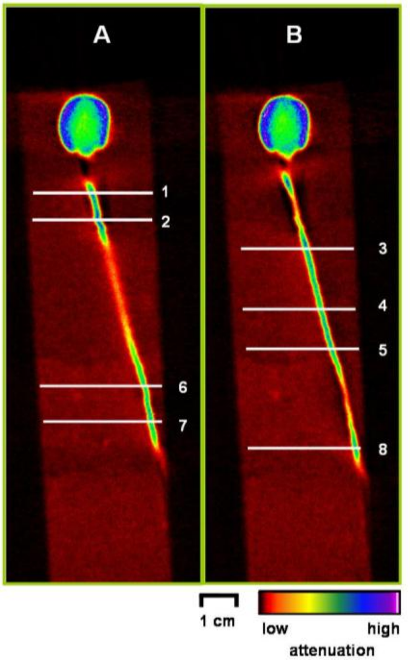




BAY 3

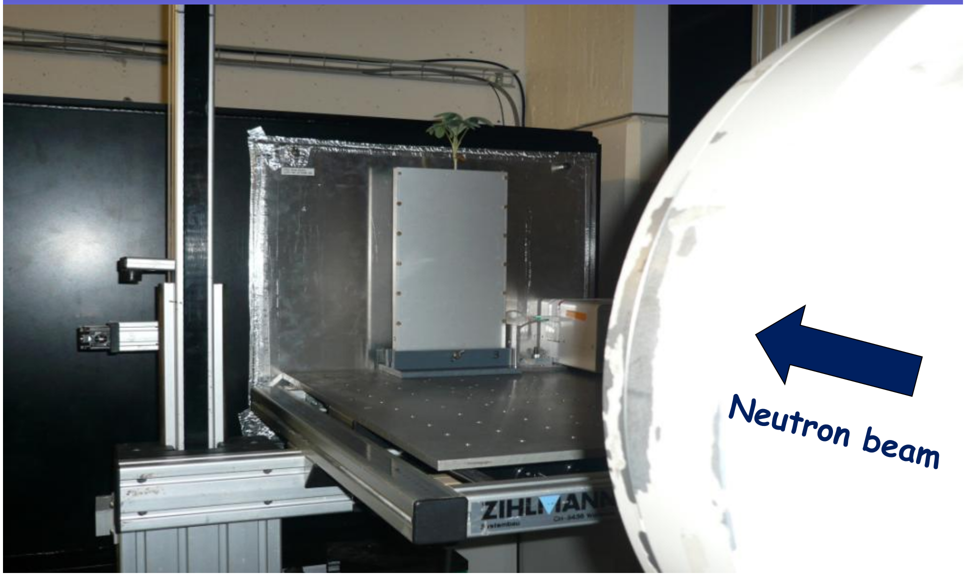
Root Cylinder



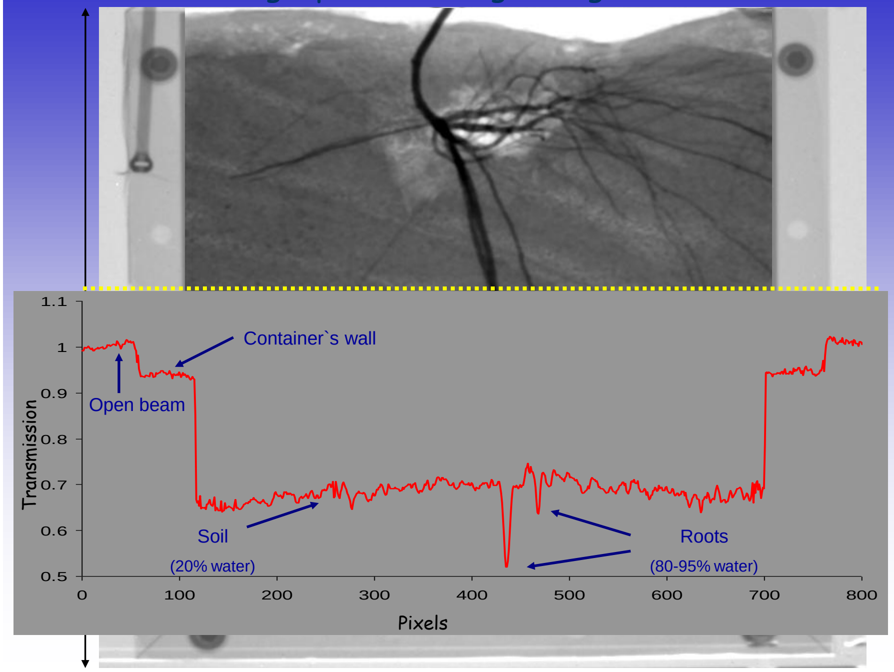


Neutron Imaging Setup - RADIOGRAPHY

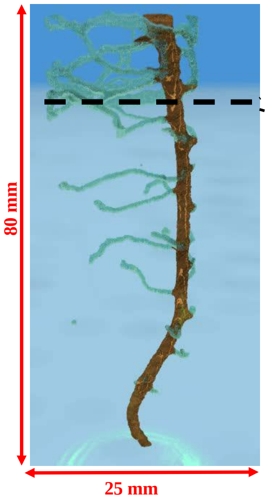
Paul Scherrer Institute (PSI), Villigen, Switzerland

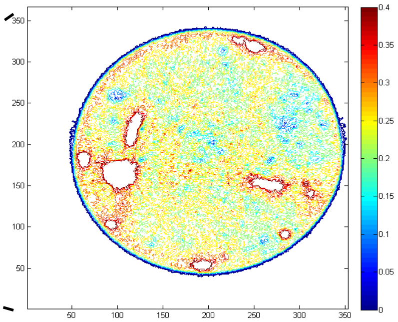


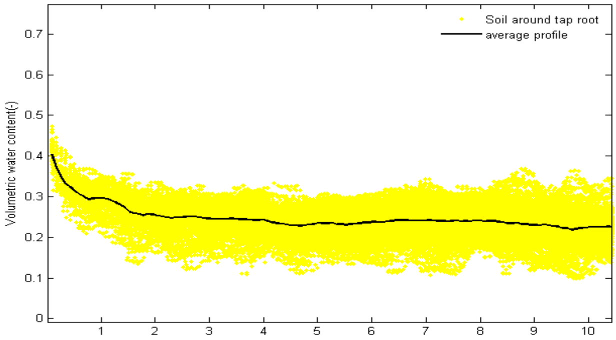
Neutron radiograph of roots growing in soil



Neutron tomography data (Chick pea)

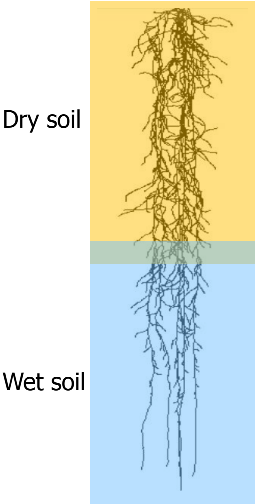


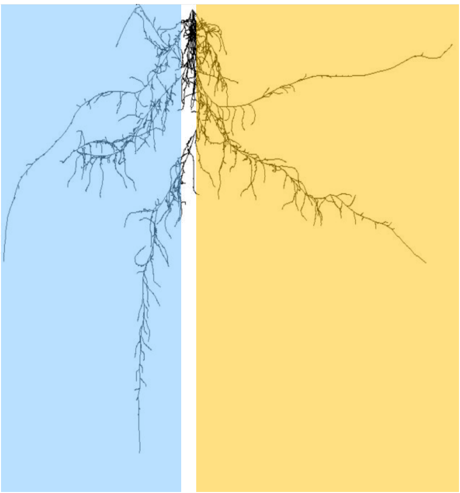




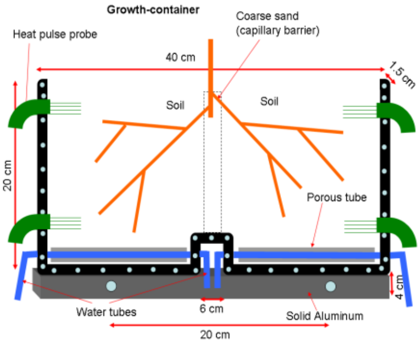
Moradi et al. 2010, sub. New Phytologist

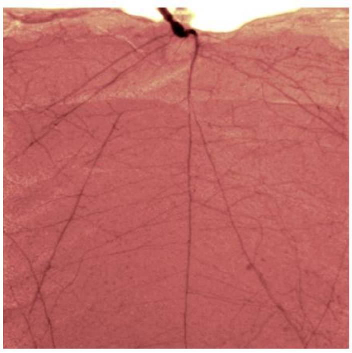
Next step:
Root water-uptake under differential soil water contents (Compensation mechanism)



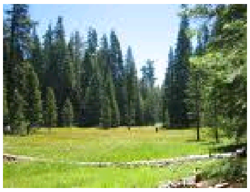


Bay 4 MNRC – Root imaging
Study soil water stress on root development – Chick pea





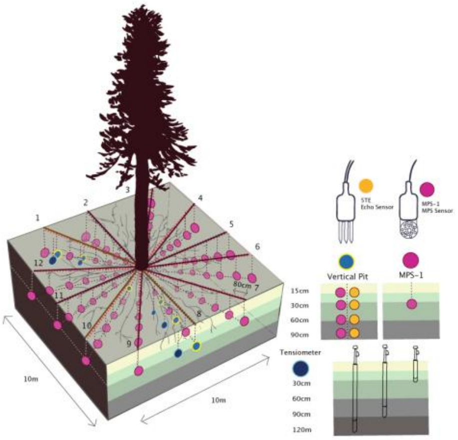
Chick pea in Aluminum growth box – April, 2011



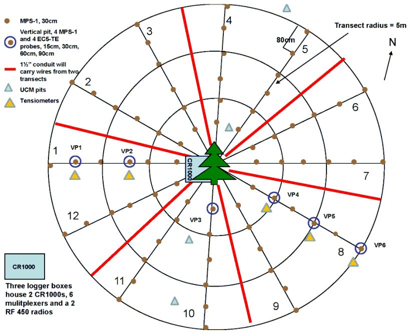
The California Critical Zone Observatory (CZO)

Snowline processes in the southern Sierra Nevada Ecosystem

Jan Hopmans, Roger Bales, Pete Hartsough, Toby O'Geen, and many others



CZO- TREE 1
P301




0-60 cm

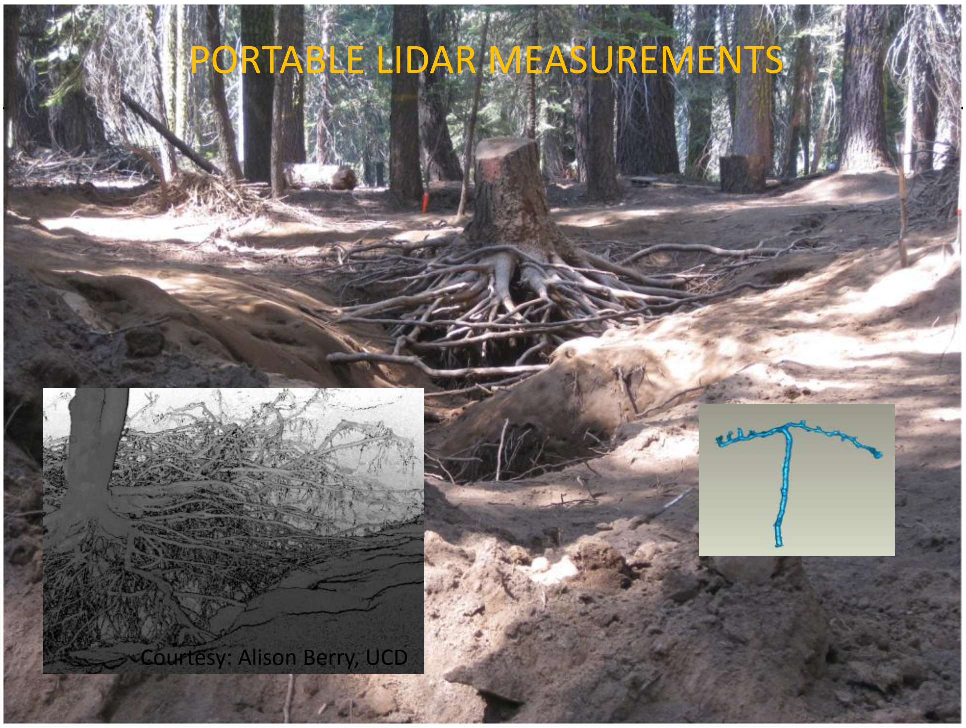

0-100 cm


0-150 cm


200 cm

Saprolite-saprock interface

PORTABLE LIDAR MEASUREMENTS



Courtesy: Alison Berry, UCD