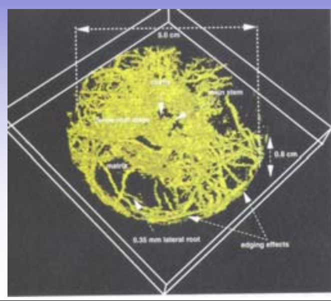
Estimation of Multi-Dimensional Root Water and Nutrient Uptake Rates under Time-Varying Soil Moisture Conditions

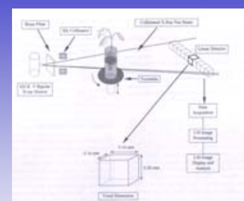
(2002, Advances Agronomy, Vol 77)

Jan W. Hopmans and colleagues

University of California, Davis



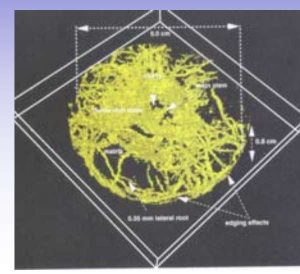
Example of CMT for nondestructive 3D plant root measurements



Experimental Setup

Heeraman, Hopmans and Clausnitzer
Plant &Soil, 1997

3D Root Image



ROOT FUNCTIONING OF WATER & NUTRIENT UPTAKE:

HISTORICAL POINT-OF-VIEW

OUT-OF-SIGHT = OUT-OF-MIND

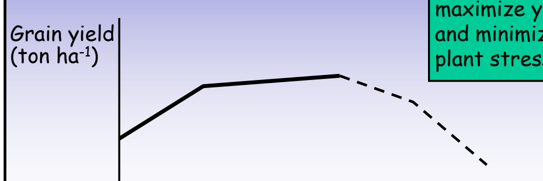
(Clothier and Green, 1997)

RESULT:

MOSTLY EMPIRICAL RELATIONSHIPS BETWEEN CROP YIELD AND RESOURCE AVAILABILITY

GOAL:

maximize yield and minimize plant stress



KNOWLEDGE GAP ON PLANT RESPONSE OF WATER AND NUTRIENT LIMITATIONS TO CROP PRODUCTION

THIS IS IMPORTANT

INCREASINGLY, CONTRAINTS BECAUSE OF :

- WATER LIMITATIONS
- ENVIRONMENTAL CONCERNS

EXAMPLES:

- Micro-irrigation and Fertigation
- Deficit Irrigation and Partial root zone drying
- Agroforestry
- Bioremediation and Phytoremediation

CURRENT NEED:

COMBINE SOIL WITH PLANT EXPERTISE,

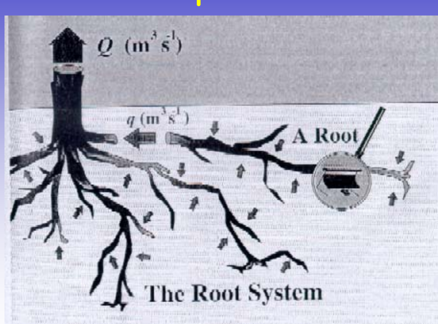
TO BETTER UNDERSTAND CONCEPTS AND PROCESSES OF WATER AND NUTRIENT STRESSES ON CROP GROWTH

SINCE THE REALITY IS THAT BOTH SOILS AND ROOTS ARE HETEROGENEOUS

AND

BOTH WATER AND NUTRIENT DISTRIBUTION ARE VARIABLE IN BOTH SPACE AND TIME

Overall root transport is controlled by local variations in root water and nutrient uptake

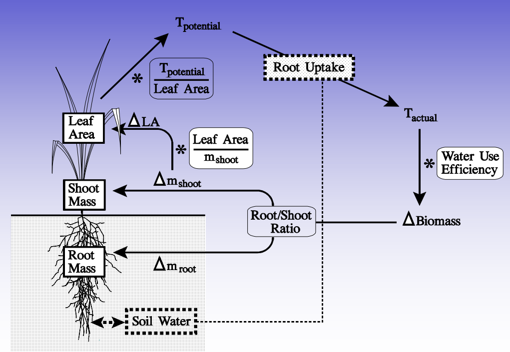


Clothier and Green, 1997

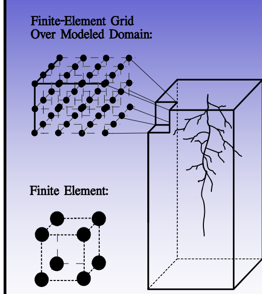
Progress requires:

- **Multi-dimensional modeling approach,**
- **Understanding of plant's response to spatially-distributed soil water and plant-available nutrients, ? ? ?**
- **Additional experimental data**

Comprehensive multi-dimensional SPAC approach
(Clausnitzer and Hopmans, 1994)



DYNAMICS IN SOIL WATER FLOW AND TRANSPORT



WATER:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial \psi_m}{\partial x_j} + K_{i3}^{A}\right)\right] - S(x_j, \psi_m, \psi_o)$$

NUTRIENT:

$$(\theta + \rho k)\frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right) - J_{w,i}\frac{\partial c}{\partial x_i} - S'$$

COUPLED WATER AND NUTRIENT UPTAKE

(microscopic approach, using two-compartment model, with membrane separating apoplast from symplast)

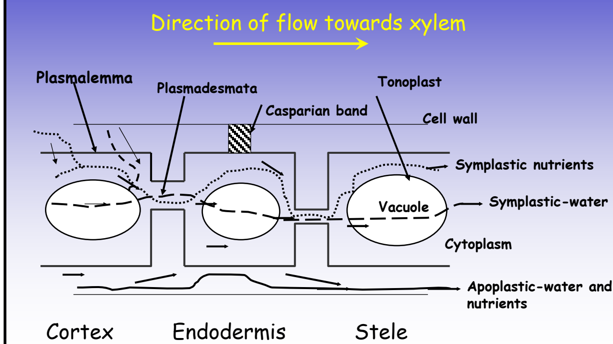
$$J_{water} = L(\Delta P - \sigma \Delta \Pi)$$

$$J_{solute} = \omega \Delta \Pi + (1 - \sigma) C_{soil} J_{water} + J^*$$

σ: reflection coefficient
ω: effective permeability of membrane

If $\sigma = 1$, then $\omega = 0$ (semi-permeable membrane)
If $\sigma = 0$, then $\omega = 1$ (diffusion across membrane)
J*: Active nutrient uptake

PATHWAYS FOR WATER AND NUTRIENT THROUGH PLANT ROOT



ACTIVE NUTRIENT UPTAKE (J*)

(or transport against driving forces: chemical water potential)

Passive nutrient transport – apoplastic pathway

plasmalemma......................

Active nutrient transport – symplastic pathway

I. ROOT WATER UPTAKE

Microscopic: $J_{water} = \dfrac{\psi_m - \psi_x}{R_s + R_r}$

From single root to root zone domain

Macroscopic: $$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi_m)\frac{\partial \psi_t}{\partial z}\right] - S(z,t)$$

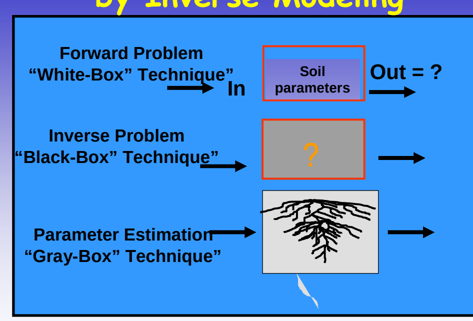
$$T_{act} = \int_{RZ} S dz = \sum_{i=1}^{Nl} S_i \Delta z_i$$

HOW TO FIND MULTI-DIMENSIONAL ROOT WATER UPTAKE PARAMETERS?

- Conduct multi-dimensional experiment
- Construct a multi-dimensional root water uptake model
- Integrate root uptake into multi-dimensional water flow model
- Compare experimental with numerical data
- Minimize their residuals

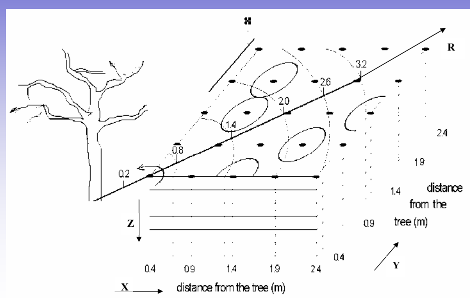
PARAMETER OPTIMIZATION BY INVERSE MODELING

PARAMETER ESTIMATION by Inverse Modeling



Effectively: Model Calibration

EXPERIMENTAL LAYOUT OF THREE-DIMENSIONAL SOIL MOISTURE MEASUREMENTS (ALMOND TREE)



Multi-dimensional root water uptake & soil hydraulic parameters

(Vrugt, Hopmans and Simunek, SSSAJ and Water Resources Research)

Solve unsaturated water flow equation for three-dimensional soil domain, with root water uptake term (S)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial \psi_m}{\partial x_j} + K_{ij}^{A}\right)\right] - S(x,y,z)$$

SIMULATION MODEL: HYDRUS-3D

MULTI-DIMENSIONAL ROOT WATER UPTAKE MODEL

$$\mathbf{RDF}(x,y,z) = \left(1 - \frac{x}{X_m}\right)\left(1 - \frac{y}{Y_m}\right)\left(1 - \frac{z}{Z_m}\right) e^{-\left(\frac{p_x}{X_m}|x^* - x| + \frac{p_y}{Y_m}|y^* - y| + \frac{p_z}{Z_m}|z^* - z|\right)}$$

$$S_{max}(x,y,z) = \frac{X_m Y_m RDF(x,y,z) T_{pot}}{\int_0^{X_m}\int_0^{Y_m}\int_0^{Z_m} RDF(x,y,z)\,dxdydz}$$

Unstressed Normalized Root Water Uptake, at a point

Water Uptake under Water-Stressed Conditions

Water Stress Response Function

$$\alpha(\psi_m) = \frac{1}{\left[1 + \left(\frac{\psi_m(x,y,z,t)}{\psi_{m,50}}\right)^{p}\right]}$$

Actual Water Uptake:

$$S(\psi_m, x, y, z) = \alpha(\psi_m) S_{max}(x,y,z)$$

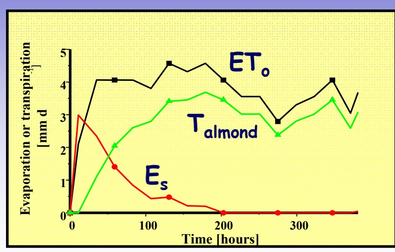
Actual Plant Transpiration:

$$T_{a,alm} = \frac{1}{X_m Y_m}\int_0^{X_m}\int_0^{Y_m}\int_0^{Z_m} S(\psi, x, y, z)\,dxdydz$$

Computation of T_{pot}

$$T_{pot,almond} = ET_{almond} - E_s$$

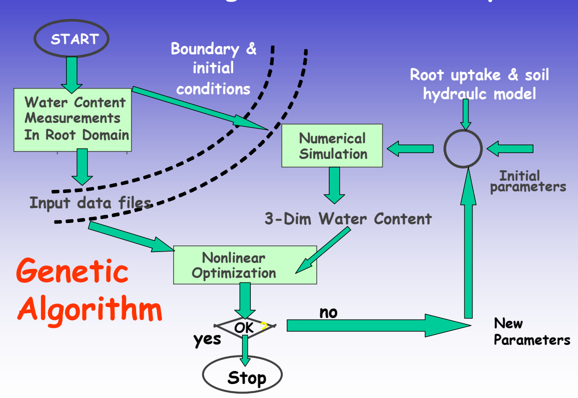
$$ET_{almond} = K_c ET_0$$



PARAMETER OPTIMIZATON OF THREE-DIMENSIONAL ROOT WATER UPTAKE MODEL

- Obtain field measurements of multi-dimensional soil moisture during a 2-week monitoring period;
- Simulate multi-dimensional soil moisture distribution, using transient HYDRUS-3D model;
- Optimize root water uptake & soil hydraulic parameters using inverse modeling, minimizing residuals of measured and simulated water contents

Inverse Modeling of Root Water Uptake



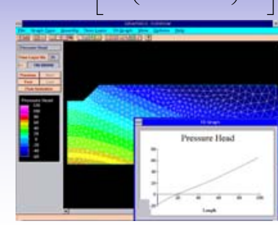
Genetic Algorithm

MODELING

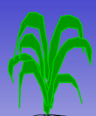
Van Genuchten-Mualem & HYDRUS

$$S_e = \left[\frac{1}{1+(\alpha h)^n}\right]^m \qquad K_r = S_e^l\left[1-\left(1-S_e^{1/m}\right)^m\right]^2$$

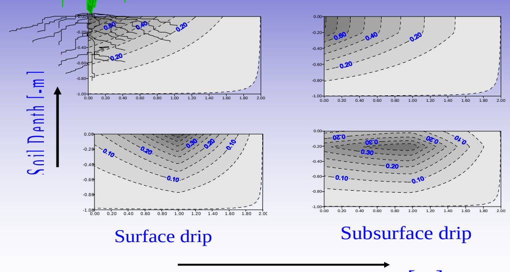
SIMULATION MODEL: HYDRUS-3D



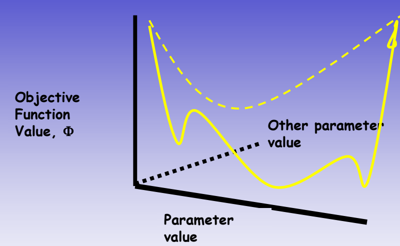
Flexibility of two-dimensional root water uptake model



$$\beta(r,z) = \left[\left(1 - \frac{z}{z_m}\right)\right]\left[\left(1 - \frac{r}{r_m}\right)\right] e^{-\left(\frac{p_z}{z_m}|z^* - z| + \frac{p_r}{r_m}|r^* - r|\right)}$$



Optimization – Minimize Objective Function

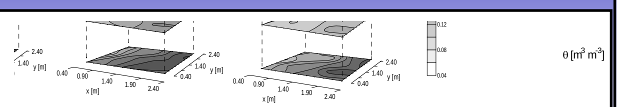


$$\Phi(\mathbf{p},\theta) = w_1 \sum_{i=1}^{n} \left[\theta^*(\mathbf{x},t_i) - \theta(\mathbf{x},t_i,\mathbf{p})\right]^2$$

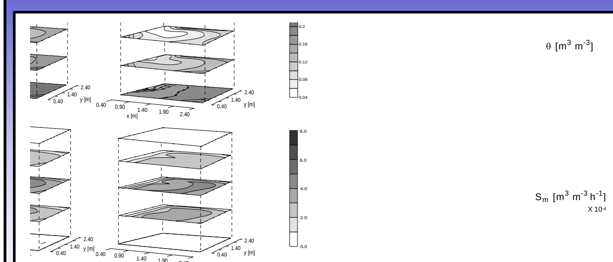
p: vector with optimized parameters

THREE-DIMENSIONAL SOIL MOISTURE OBSERVATIONS

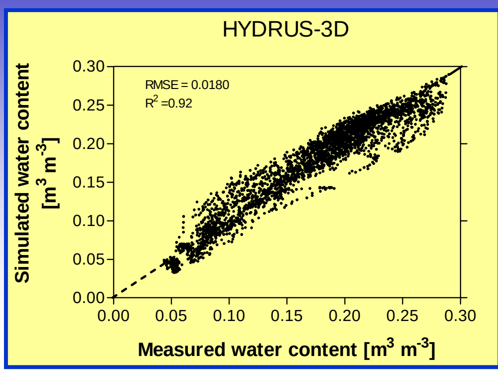
(Vrugt et al., 2001)



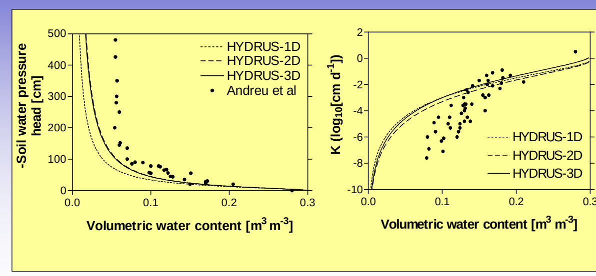
SIMULATED THREE-DIMENSIONAL SOIL MOISTURE AND ROOT WATER UPTAKE DISTRIBUTION



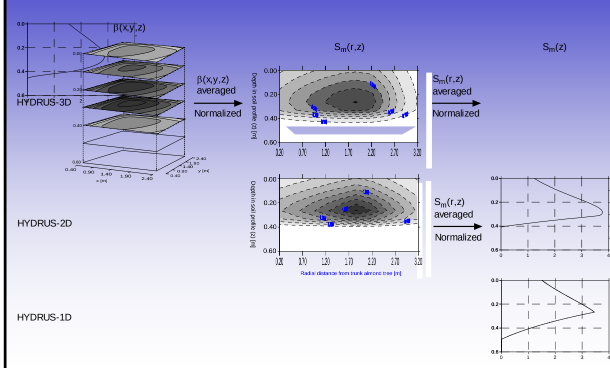
Simulated (after optimization) verses Measured Water Content



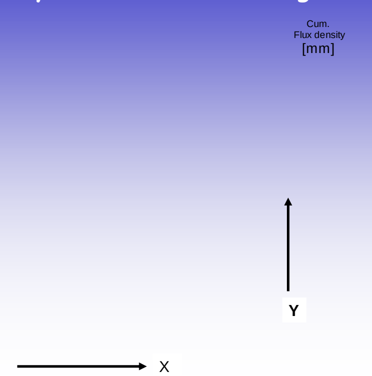
Soil hydraulic functions, for instrumented field plot



Comparison of one-, two, and three-dimensional uptake distributions



Multi-dimensional root water uptake may have enormous influence on spatial and temporal variability of root zone leaching



II. ROOT NUTRIENT UPTAKE

Microscopic: $J^* = \frac{J^*_{max}.(c - c_{min})}{K_m + (c - c_{min})}$

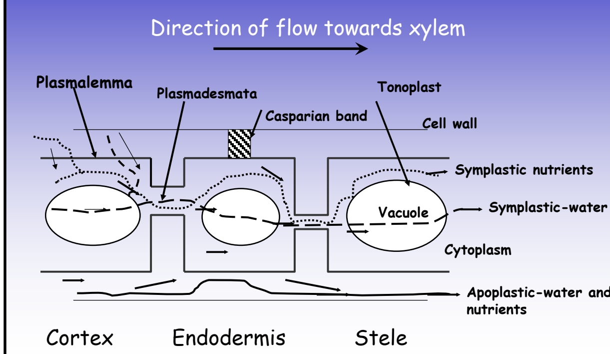
From single root to root zone domain

Active nutrient uptake: $N_i = RDFN_i J_i^*$

Macroscopic: $\theta \frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij} \frac{\partial c}{\partial x_j}\right) - J_{w,i} \frac{\partial c}{\partial x_i} - S'$

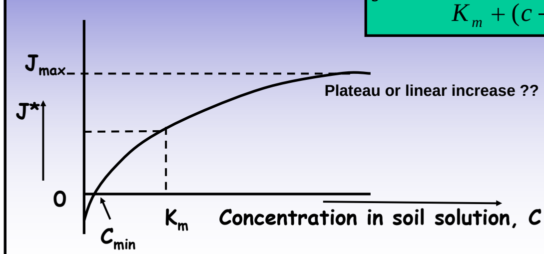
For each compartment i, partition between passive and active uptake:
$S_i' = f_1 S_i c_i + f_2 N_i$

PATHWAYS FOR WATER AND NUTRIENT THROUGH PLANT ROOT

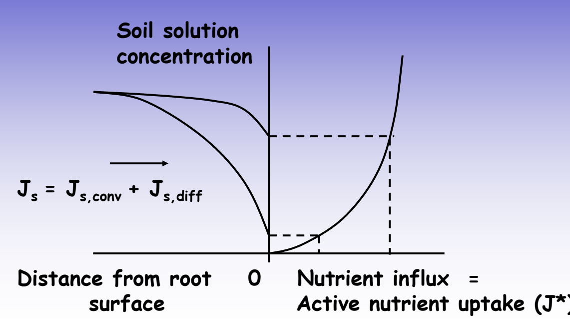


ACTIVE TRANSPORT IS CONSIDERED EQUIVALENT TO ENZYME KINETICS (MICHAELIS-MENTEN)

$J^* = \frac{J^*_{max}.(c - c_{min})}{K_m + (c - c_{min})}$



SUPPLY-CONTROLLED ACTIVE NUTRIENT UPTAKE



PARTITION NUTRIENT UPTAKE BETWEEN PASSIVE AND ACTIVE UPTAKE

$$S' = f_1 Sc + f_2 N$$

S' – Total nutrient uptake

Sc – Passive nutrient uptake (with water uptake – apoplastic pathway)

N – active nutrient uptake (symplastic pathway)

f_1 and f_2 - may be a function of nutrient availability and plant nutrient demand or deficit

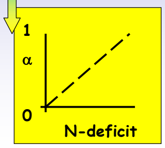
Define active nutrient uptake (N) using RDFN (as water uptake), to characterize distribution of active uptake sites

$(S' = f_1 Sc + f_2 N)$

$$N_{pot} = \int_{RZ} J^* \qquad N_{max,i} = RDFN_i \times N_{pot}$$

$$N_i = \alpha(\text{plant N deficit}) \times N_{max,i}$$

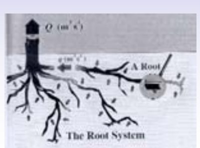
$$N_{act} = \int_{RZ} N_i$$



RECOMMENDATION 1

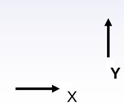
The overall functioning of the plant is controlled by local variations in uptake rates.

Research is needed to integrate local uptake variations to total plant uptake as a function of soil environmental factors (water and nutrient stresses),



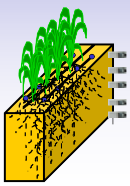
RECOMMENDATION 2

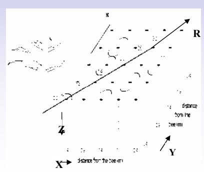
A multi-dimensional approach is essential to improve model predictions of plant response to water and nutrient stresses and nutrient loads to the groundwater



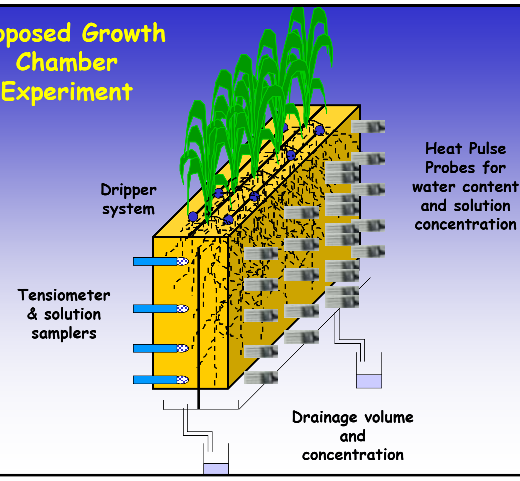
RECOMMENDATION 3

Dedicated experiments are needed to test and calibrate multi-dimensional root water and nutrient uptake models, and to better understand the partitioning between passive and active nutrient uptake





Proposed Growth Chamber Experiment



NEW Heat Pulse Probe DESIGN

To measure:
- Soil thermal properties
- Soil water content
- Bulk soil and solution EC
- Darcy water flux
- Solute dispersivity