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Water Use Efficiency

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Water Use Efficiency Workshop Prague

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Key processes to biomass accumulation

$$\text{Yield} = \int_i^f \text{PPFD} * \epsilon_a \times \epsilon_b \times \text{HI}$$

Light ($\text{mol m}^{-2} \text{s}^{-1}$),

ϵ_a % = PPFD intercepted by leaves

ϵ_b (kg mol^{-1}) = conversion ratio of intercepted light into biomass

$$\text{Yield} = \int_i^f \text{ET} \times \text{WUE} \times \text{HI}$$

EvapoTranspiration (kg m^{-2})

WUE/Transpiration Efficiency (kg kg^{-1}) = biomass/transp. Water

Harvest Index (kg kg^{-1}) = harvested biomass/total biomass.

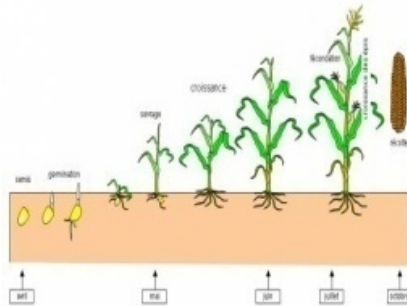
... a multiscalar definition:

Seconds



Photosynthesis
Stomatal conductance

Days to weeks



Yield
Input water

Crop cycle



Biomass
Transpiration

Escaping water deficit through ..

... changing plant phenology

$$\text{Yield} = \int_i^f \text{PPFD} * \epsilon_a * \epsilon_b * \text{HI}$$

Sowing

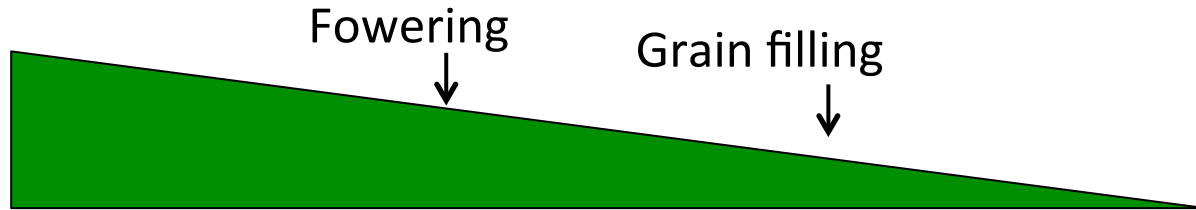
Fowering

Grain filling

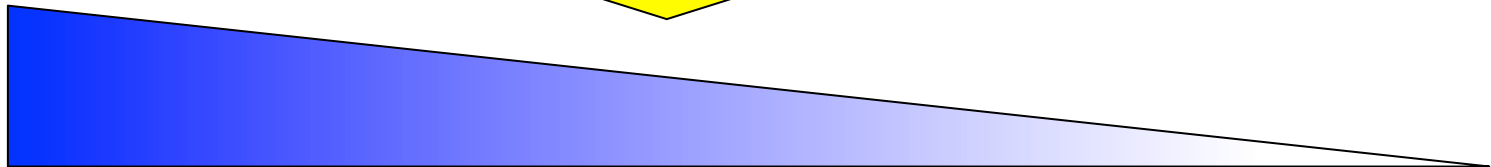
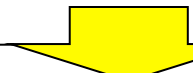
Crop cycle length...



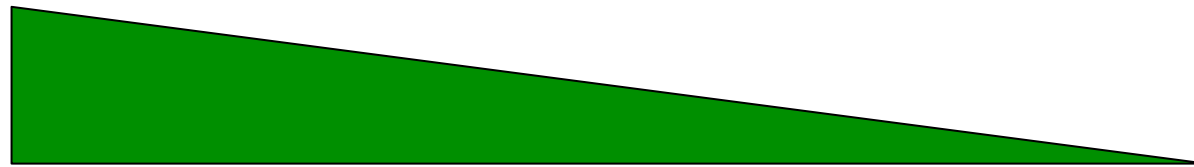
...reduced



Reduces amount of light intercepted



Reduce total soil water depletion



Decreased biomass

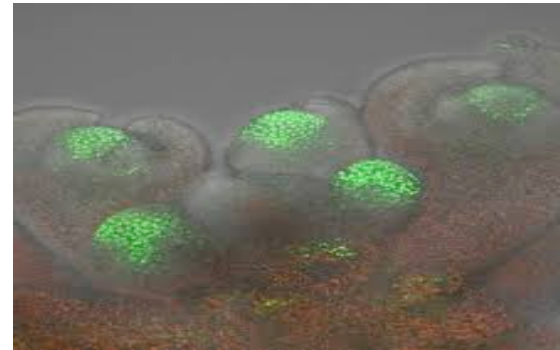
Severe drought



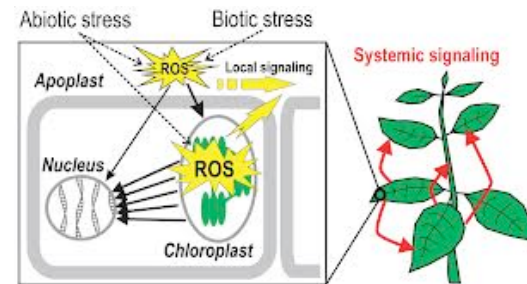
Cell protection mechanisms

Tolerance conferred by

Plant survival



Accumulation of molecules (stabilise proteins, membranes, structures)



Avoids accumulation of toxic species

Resisting severe deficit through survival mechanisms

Severe drought



Water deficits in agriculture

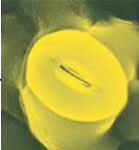
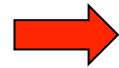
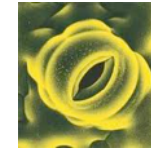


Tolerance conferred by

Cell protection mechanisms



Stomatal closure



$$\text{Yield} = \int_i^f \text{ET} \times \text{WUE} \times \text{HI}$$

$$\text{Yield} = \int_i^f \text{PPFD} * \epsilon_a \times \epsilon_b \times \text{HI}$$

Reduce plant demand for water
 Decreases the %intercepted light
 Reduces efficiency of transformation

Severe drought

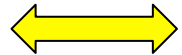
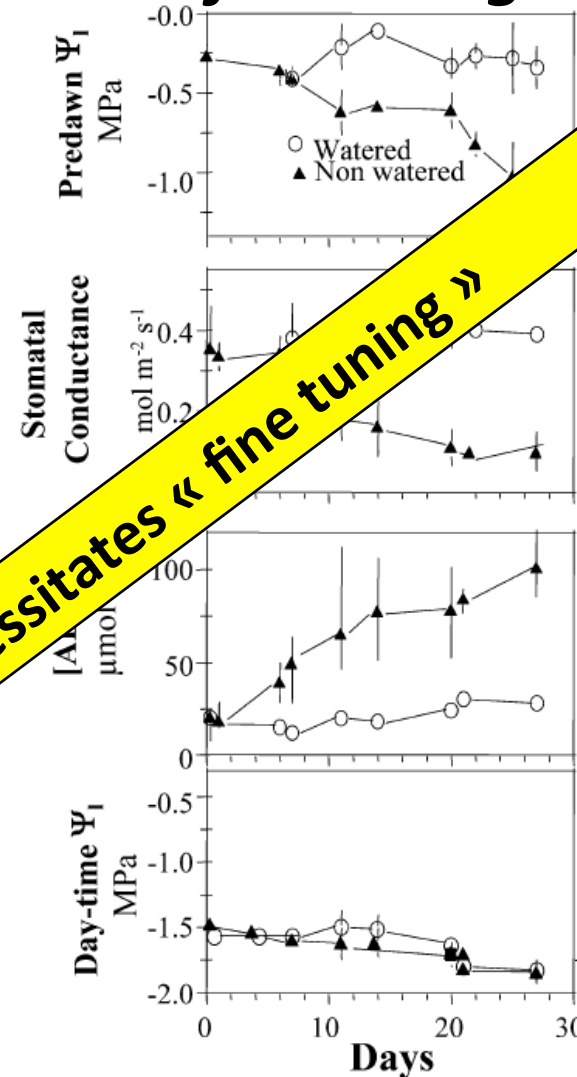


Tolerance conferred by

Cell protection mechanisms

Water deficits in agriculture

Necessitates « fine tuning »

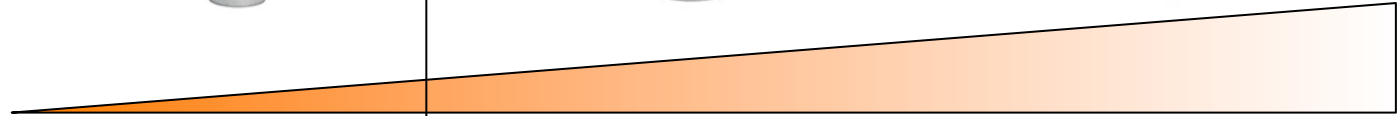


Avoidance mechanisms

Severe drought



Water deficits in agriculture



Tolerance conferred by

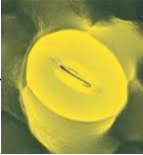
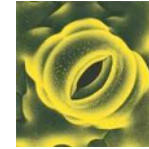
Cell protection mechanisms

$$\text{Yield} = \int_i^f \text{ET} \times \text{WUE} \times \text{HI}$$

$$\text{Yield} = \int_i^f \text{PPFD} * \epsilon a \times \epsilon b \times \text{HI}$$



Stomatal closure



Changes plant architecture, leaf growth etc (senescence)



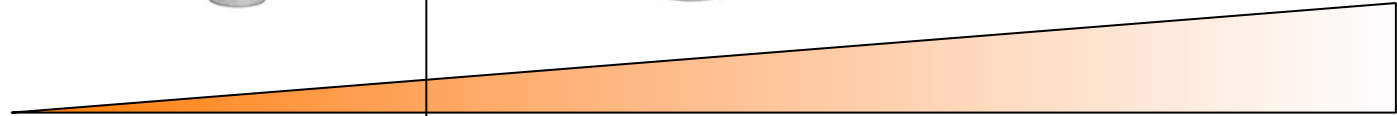
Reduce plant demand for water
Decreases the %intercepted light
Reduces leaf size, LAI

Avoidance mechanisms

Severe drought



Water deficits in agriculture

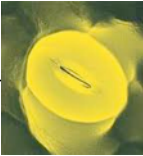
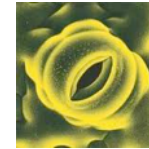


Tolerance conferred by

Cell protection mechanisms



Stomatal closure



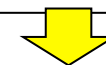
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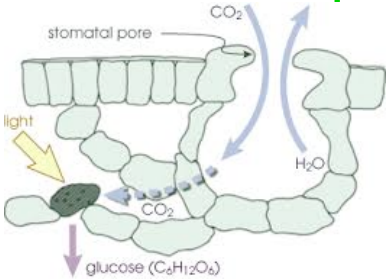
Cropping systems (length/position of the crop cycle vs drought)

Ok in most circumstances of water deficits compatible with agriculture...

Production



Stomata conductance/leaf growth: determinants of plant transpiration and carbon accumulation



Similar advantages and drawback

Leaf area, stomatal

conductance



...but negative in severe terminal droughts



Slower soil water depletion
Sense longer wet soil
« Stay »



Increased leaf temperature



Decreased biomass



Early experience of a dry soil.



Decreased biomass

Stress symptoms therefore appear later

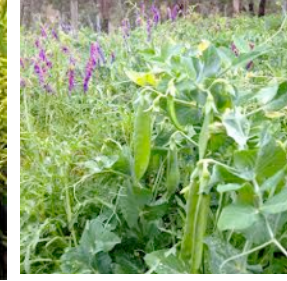
$$\text{Yield} = \int_i \text{PPFD} * \epsilon a * \epsilon b * HI$$

Large part of genetic progress of several species

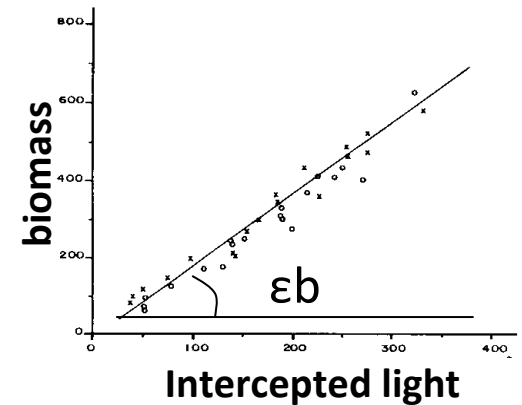
ϵa = f(leaves orientation)



ϵb = f(species).



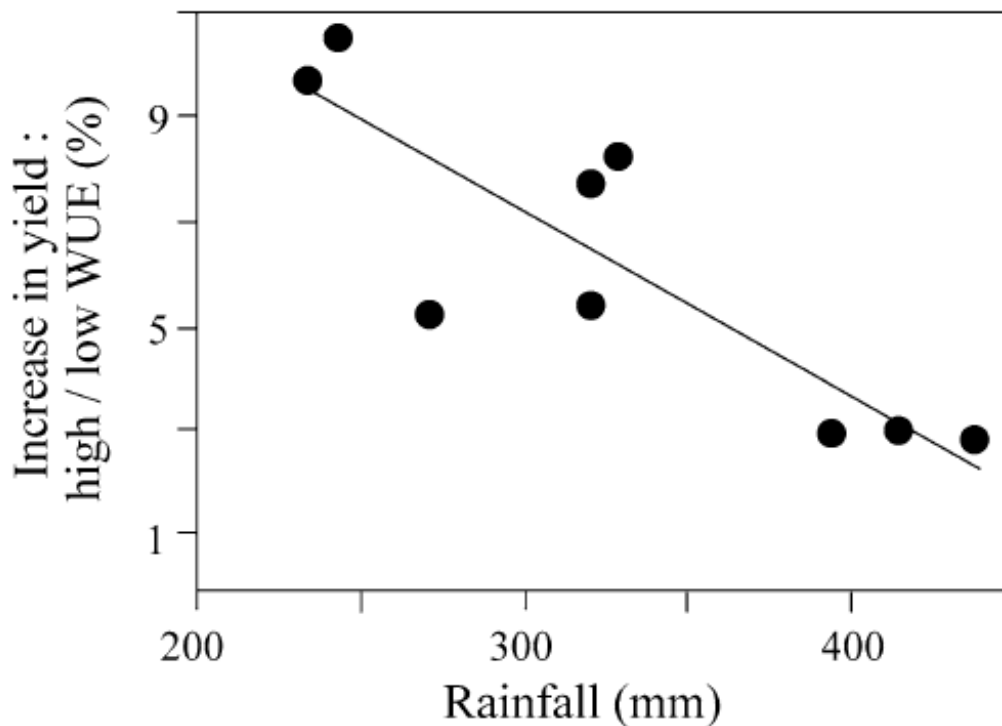
ϵb less variable within a given species.



... increased in wheat = a positive trait in driest environments

Select wheat lines 1) on stomatal conductance, then 2) for WUE.

introgressed into elite material genomic regions that confer high water-use efficiency but maintained photosynthesis.



Rebetzke et al., 2002

Positive effect in very dry environments only (avoidance)

No yield advantage at rainfalls such as in wheat growing regions

Transpiration rate = (VPD) for sorghum

High yielding genotypes under water limited conditions
Field screen : 26 selected over 297 genotypes

Table 1

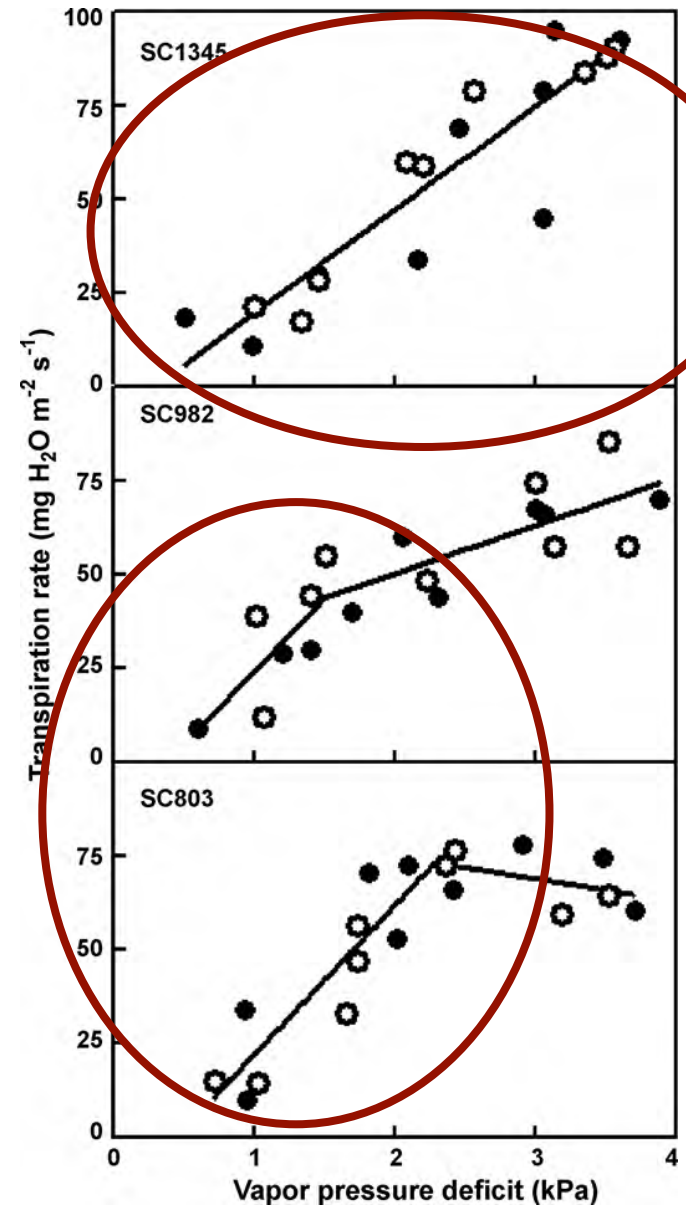
Field observations on selected genotypes. Genotypes were selected under the rainfed conditions of 2006 based on high yield or on stay-green characteristics. Genotypes were selected under the irrigation conditions of 2007 based on measurements of leaf temperature. Air temperature during the canopy measurements was approximately 33 °C.

Genotype	Characteristic	Leaf temperature (°C)	Grain yield (kg ha ⁻¹)
2006 (rainfed)			
SC532	High yield	34.9	2741
SC489	High yield	34.9	2916
SC630	High yield	34.5	3675
SC299	High yield	34.0	3836
SC982	High yield	35.6	3903
BTXARG1	High yield	34.7	4221
SC1345	High yield	36.5	5189
RTX430	High yield	35.2	5656
SC599	Stay green rating	36.7	4447
B35	Stay green rating		
TX3042	Non-stay green		
TX7078	Non-stay green		
2007 (irrigated)			
BTX378	Low leaf temperature	32.8	5487
BTX623	Low leaf temperature	32.8	5993
BTX2752	Low leaf temperature	32.9	5545
Macia	Low leaf temperature	33.3	5516
BTX3197	Low leaf temperature	33.4	5516
SN149	High leaf temperature	35.0	6393
SC1047	High leaf temperature	36.8	5496
SC1019	High leaf temperature	36.8	9065
SC1074	High leaf temperature	36.9	5301
SC979	High leaf temperature	37.1	5189
SC803	High leaf temperature	37.1	5354
DK28	Hybrid	32.9	7040
DK54	Hybrid	33.8	7960

Transpiration rate = (VPD)

**Linear response of
TR vs VPD**

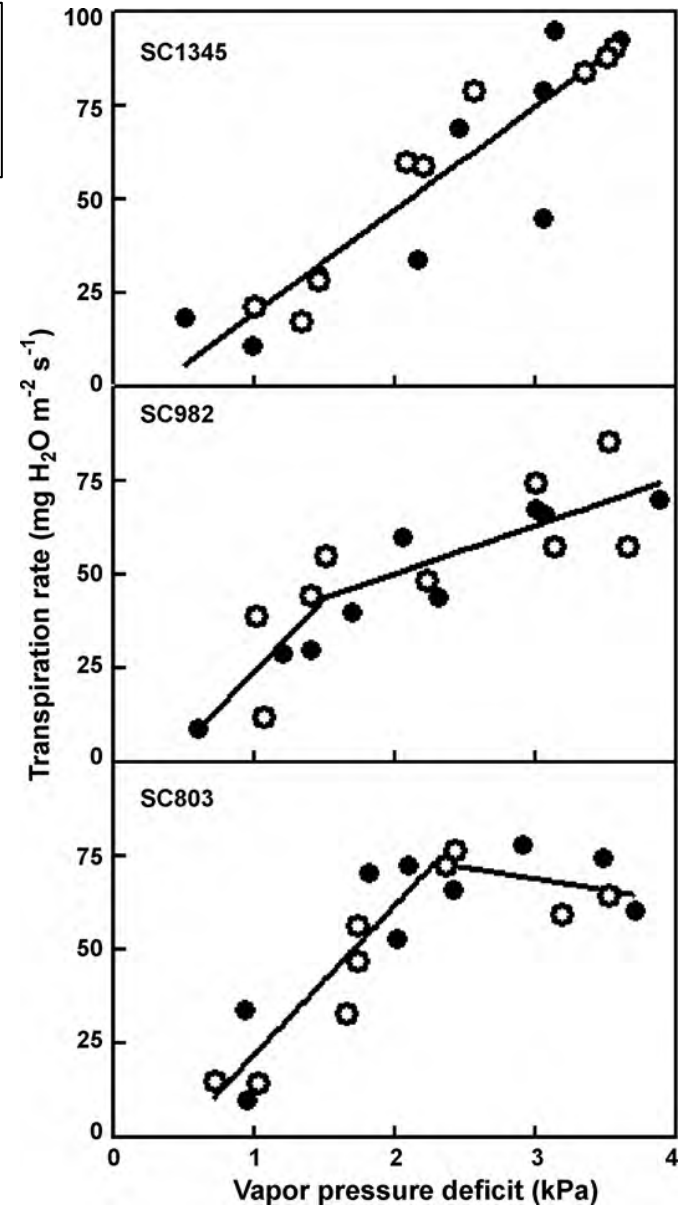
**A Break Point in TR
response to VPD**



Yield is not the only criterion to select limited TR with increasing VPD

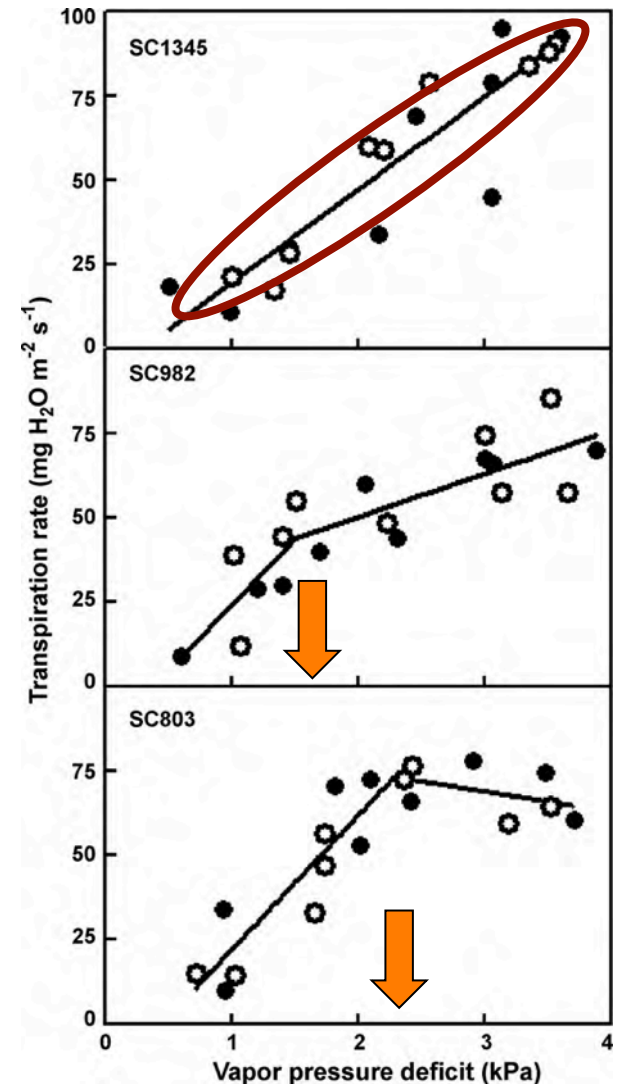
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Selection of BP matching the likelihood of water-deficit conditions.

- Without BP + low TR/VPD = **dry conditions**
 ... But restricted A, slow growing, low yielding under well-watered conditions!
- With a high initial slope and a low BP: good strategy for **terminal drought conditions**.
 ... maximize A at low VPD, water conservation at high VPD,
- A low BP : **greatest water conservation** when soil water is still available
- A high BP imposes **less-restrictive water conservation**.



... via improving size, architecture of the root system

$$\text{Yield} = \int_i^f \text{PPFD} * \epsilon_a \times \epsilon_b \times \text{HI} \quad \text{Yield} = \int_i^f \text{ET} \times \text{WUE} \times \text{HI}$$



Improve soil tillage or select genotypes with increased root growth/branching



Useful when a soil water reserve is root free

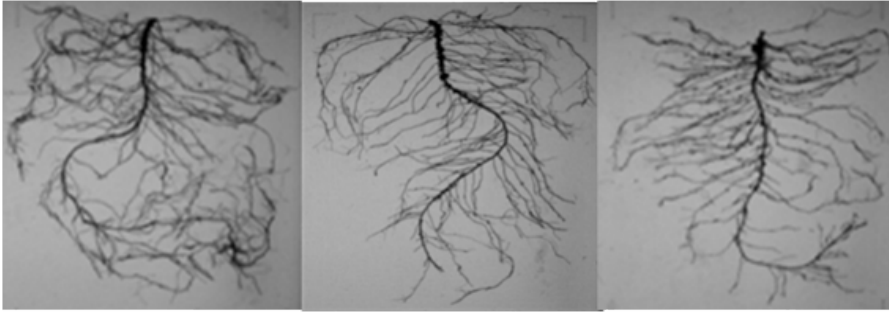
When limited amount of water (e.g., shallow soil) of little interest or even counter-productive!



Take care of optimal carbon investment in roots in case of HI increase

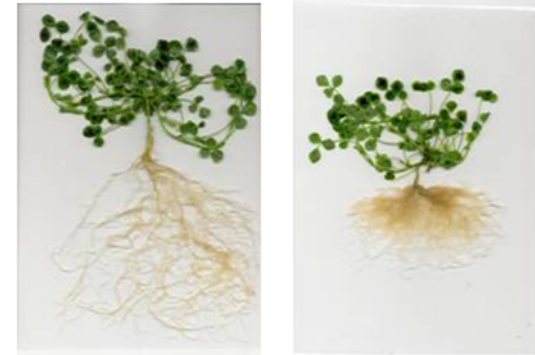
... a large genetic variability for genetic progress

Natural (pea)



Bourion et al. *Annals Bot.* 2007

Natural (Medicago)



Mutants (MSE Pea)



Control

Ramified

Nod++

Nod++ x
Ramified

Coll. KK Sidorova

Mutants (Tnt1 *Medicago*)



Control

Long root

Ramified

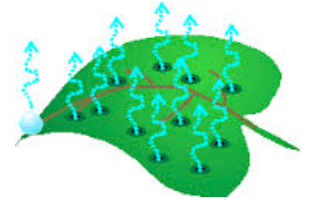
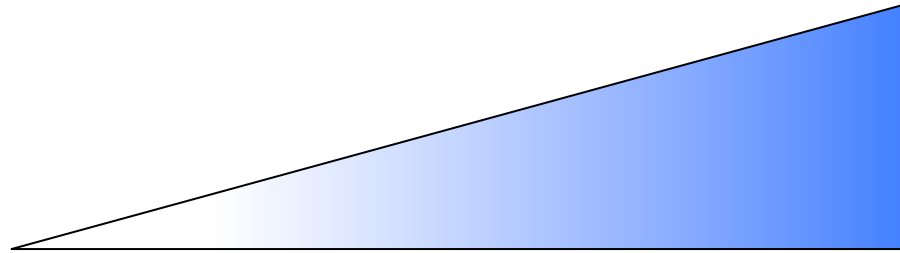
Nod++

Porceddu et al. *BioMed* 2008

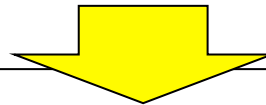
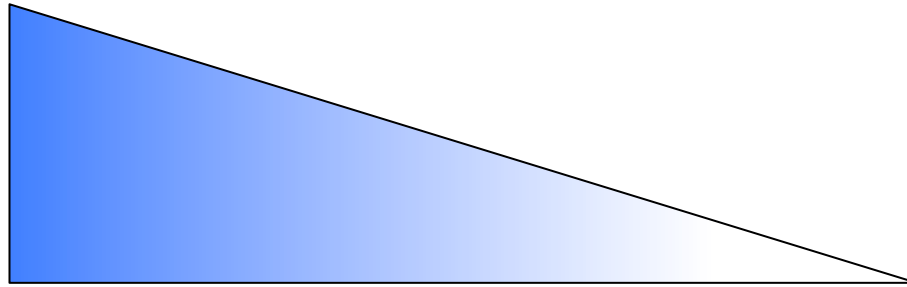
Maintain transpiration..

... a large genetic variability for genetic progress= RLD

Evaporative Demand

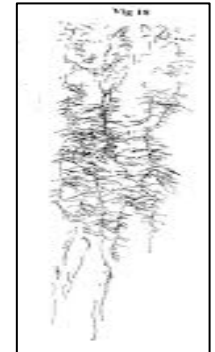
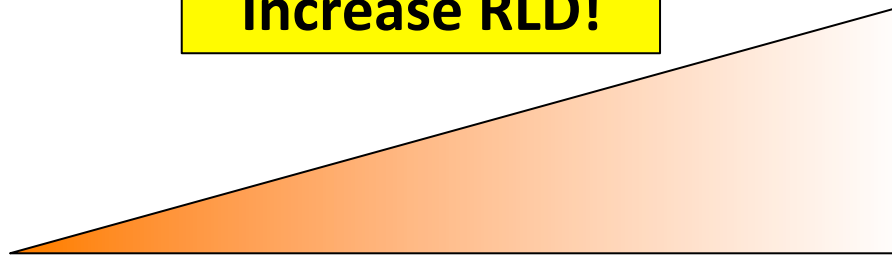


Soil water



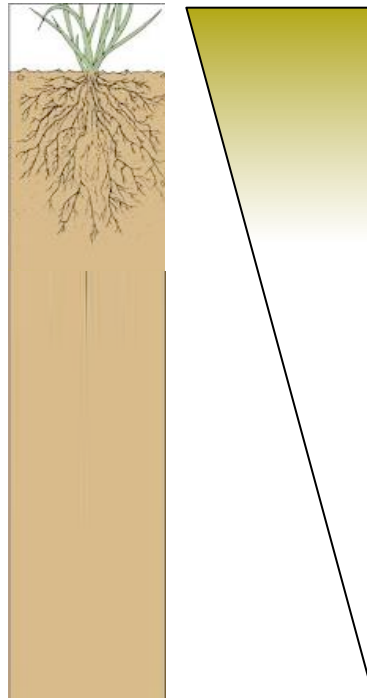
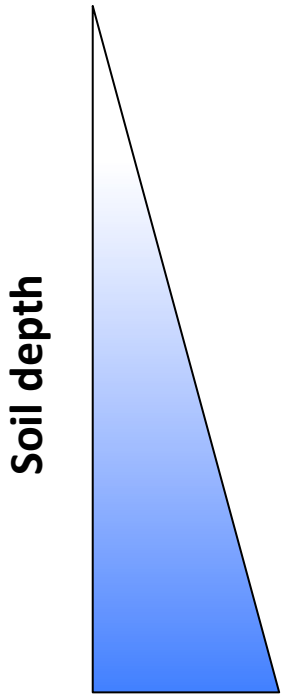
Increase RLD!

Root length density

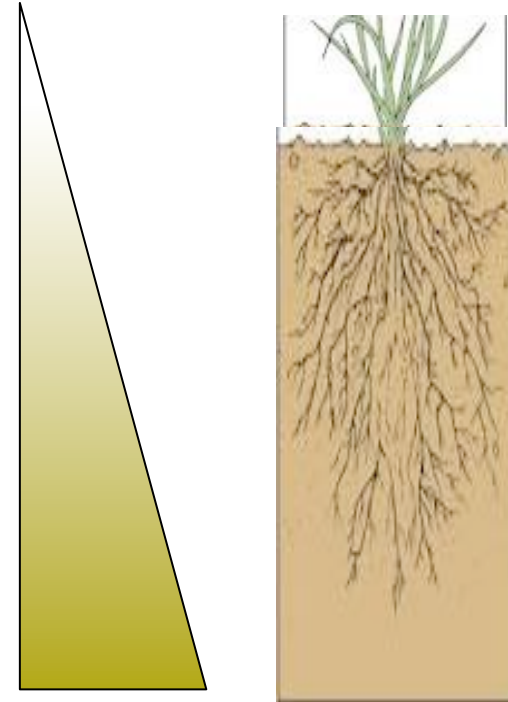
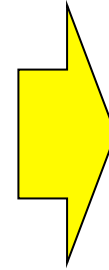


Always increase soil exploration by roots in case of drought ?

Soil water



Root Length Density



**Carbon waste for no
water benefit.**

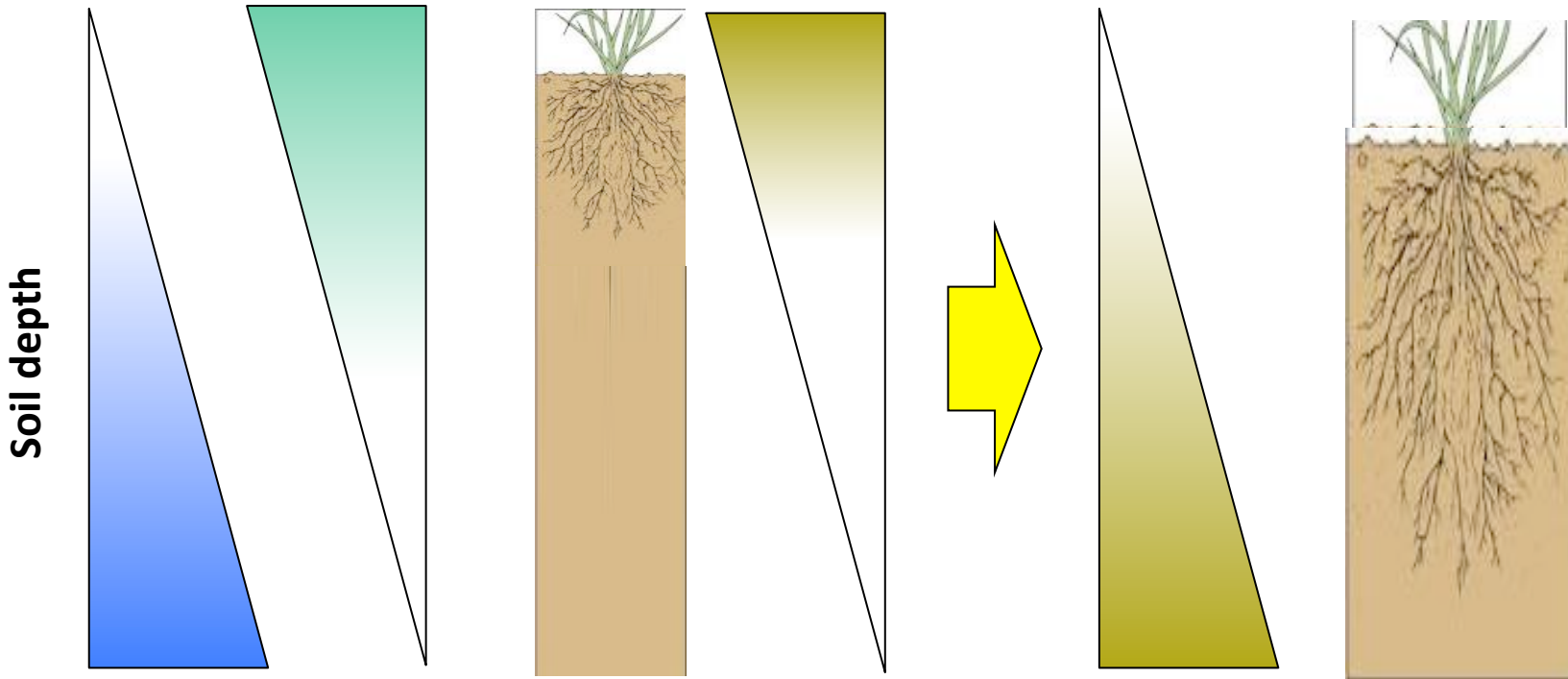
**Increase RLD in deeper
layers!**

Always increase soil exploration by roots in case of drought ?

Soil water

NO₃

Root Length Density

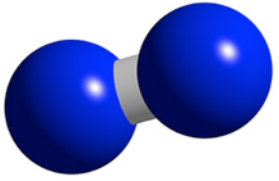


... detrimental for
nutrient uptake

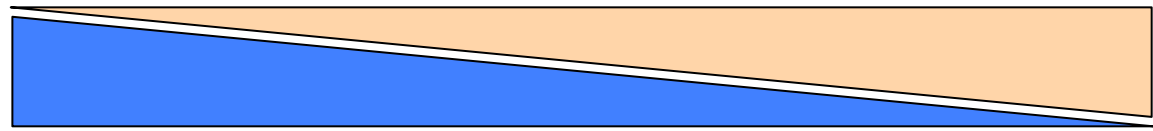
Always increase RLD in
deeper layers?

Improving Root Systems Efficiency, rather than root biomass.

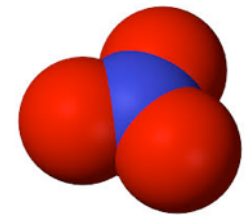
Resource



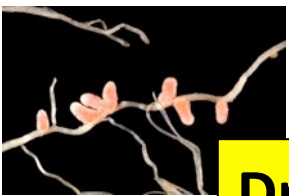
N_2



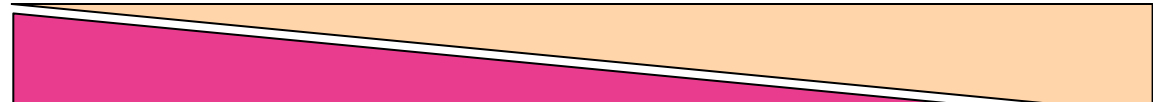
Nitrate



Function

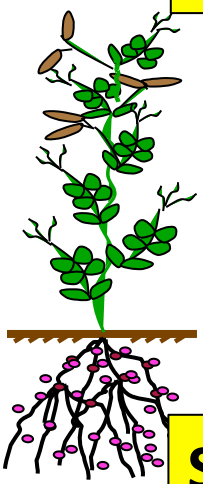


Nitrate Assimilation



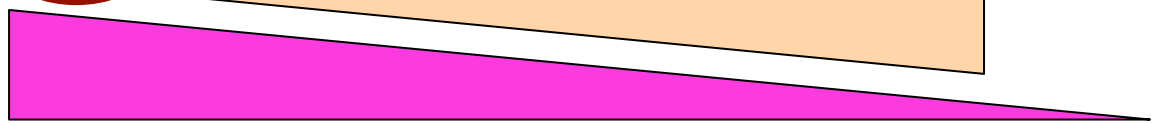
Drought modifies nodule/root biomass

Structure

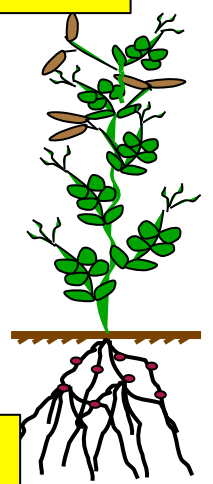


Nodules, a strong C sink

Roots



Nodules



Spatio temporal conflict of nodule root biomass

Which root traits ?

Description »level 1" :

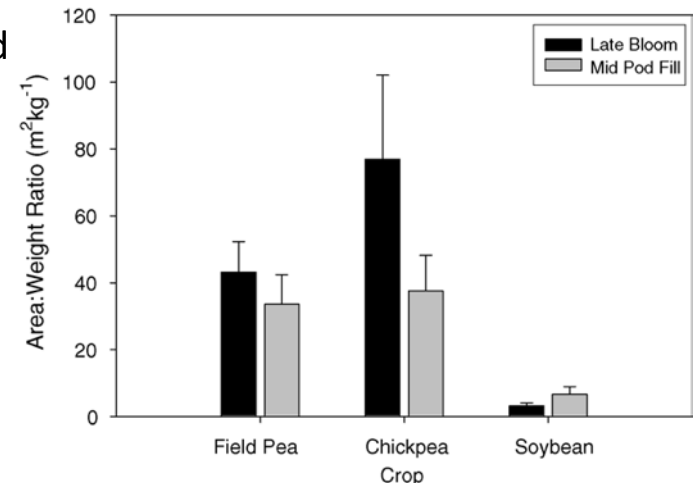
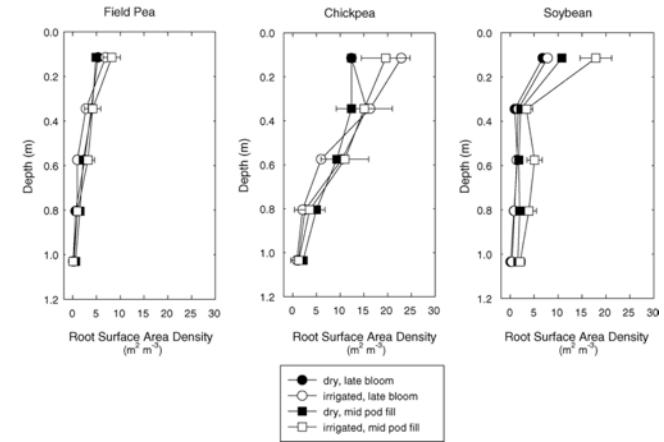
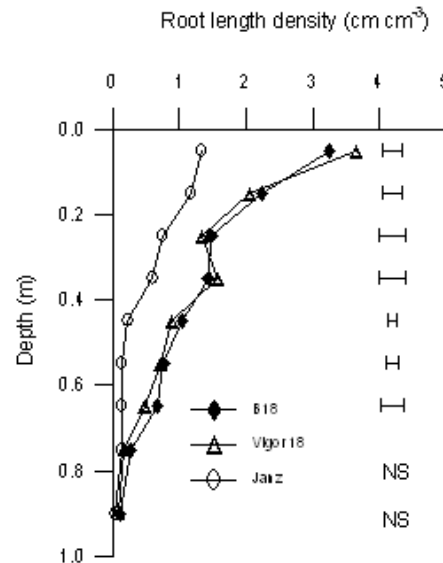
- Root projected area
- Nodule projected area
- Nodule number
- Total root length
- Root prospection
- Root Length Density
- Root surface area to weight ratio
- Root surface area to weight ratio

Description »level2" :

- Main root length
- Longest lateral root length
- Number of lateral roots
- Number of nodules on each root
- Nodule positions (individual and by class) on all of the roots and
- Apical diameter of roots

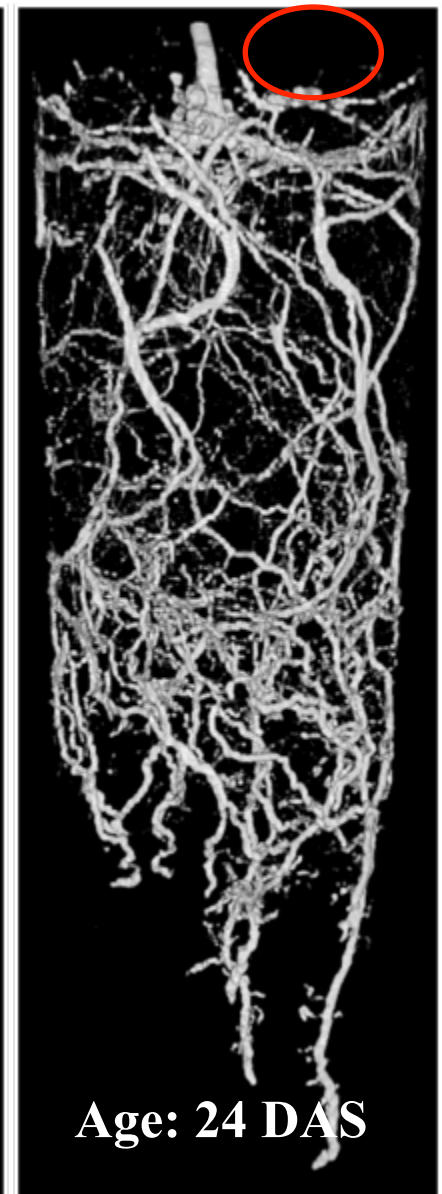
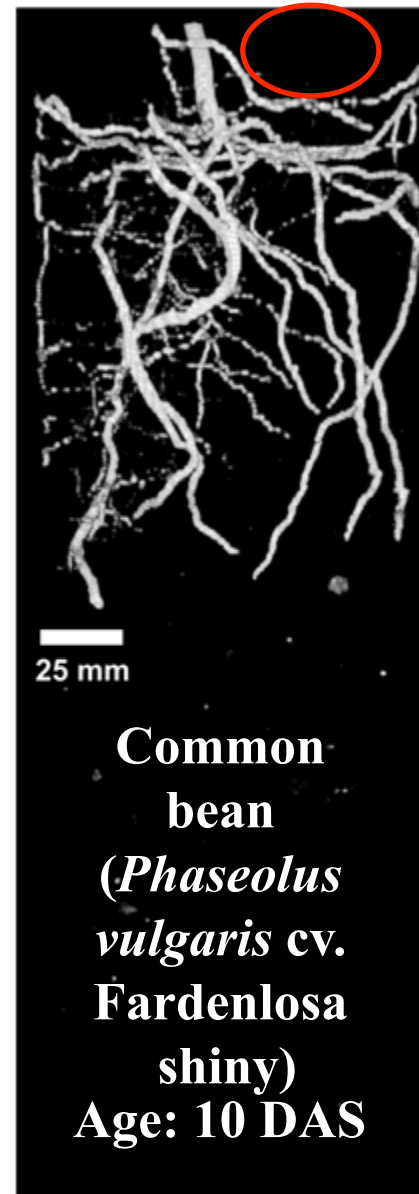
« Convention » :

- Number: total and by segment-segment length
- Projected area : individual and by class
- Position: : individual and by class
- Nodule efficiency : individual and by class
- Estimated biovolume : a root = cylinder
- Biomass estimation by calibration



Magnetic Resonance Imaging

- Non-invasive
- Soil-potted plants
- High contrast between roots/ nodules and soil
- Monitoring root and nodule development in 3D
- Measuring water and solid content development in pods
- Combines well with Positron Emission Tomography (PET) for monitoring Photoassimilate allocation



Which tools ?

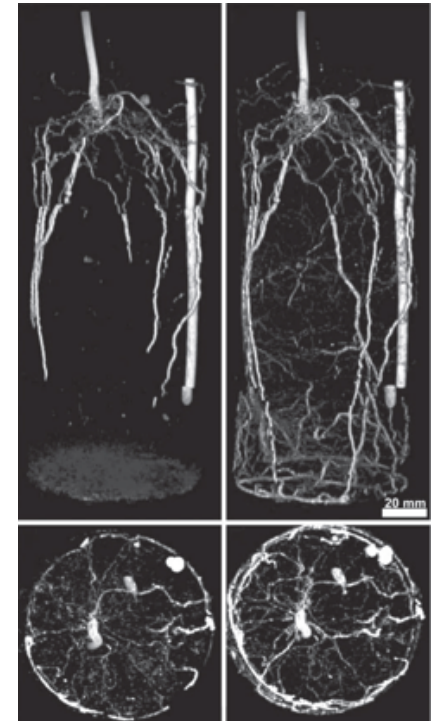
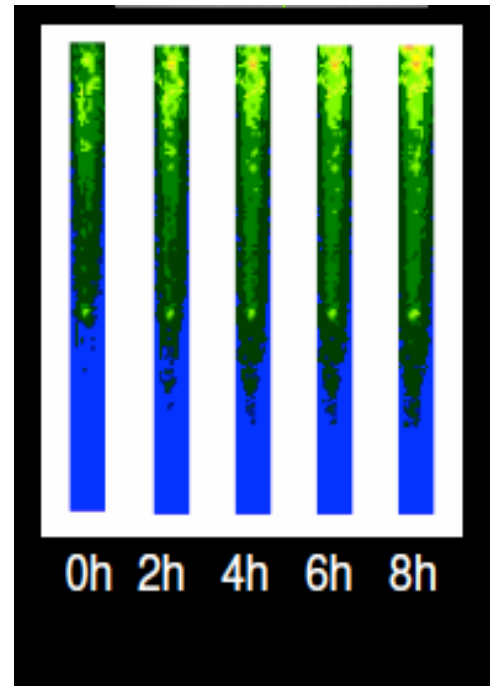
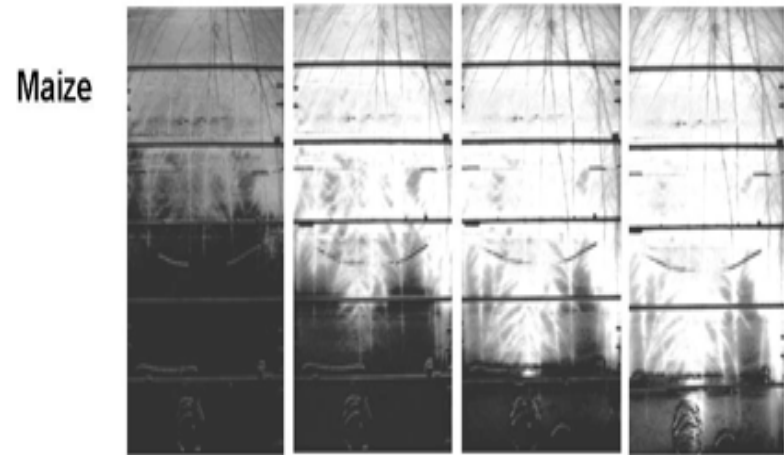
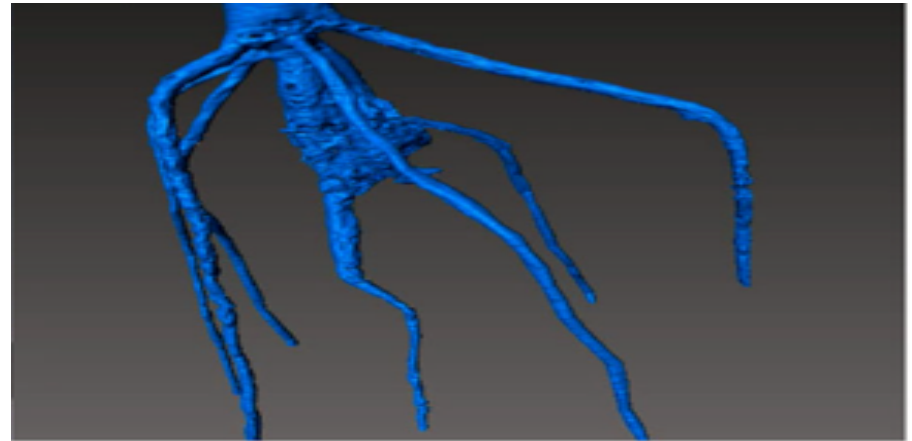
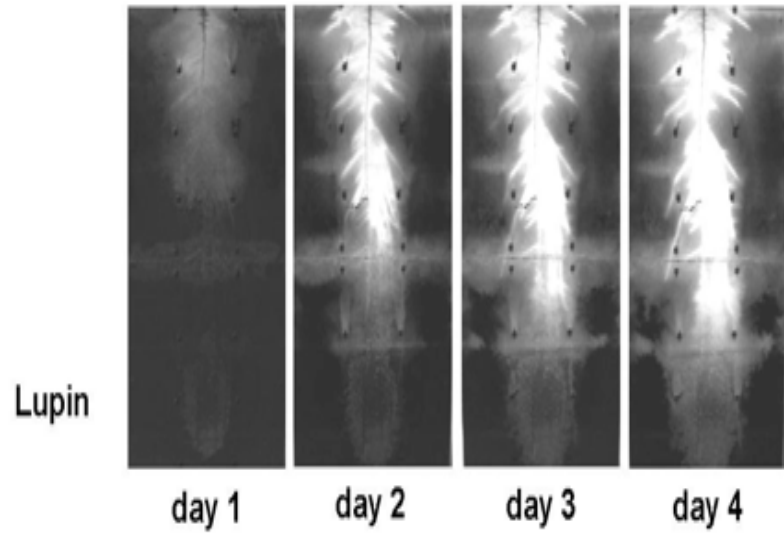


Figure 5

- To visualize (harvest) the whole root system
- At high resolution
- To perform dynamic and non destructive analyses,
- For a large number of biological units,
- Estimate structural (and functional?) traits
- Avoid oxygen, pH, nutrient unregulated conditions

➔ Study plant-plant and plant-microorganism interactions

On plants of various species (not only model plants)

Rhizotrons

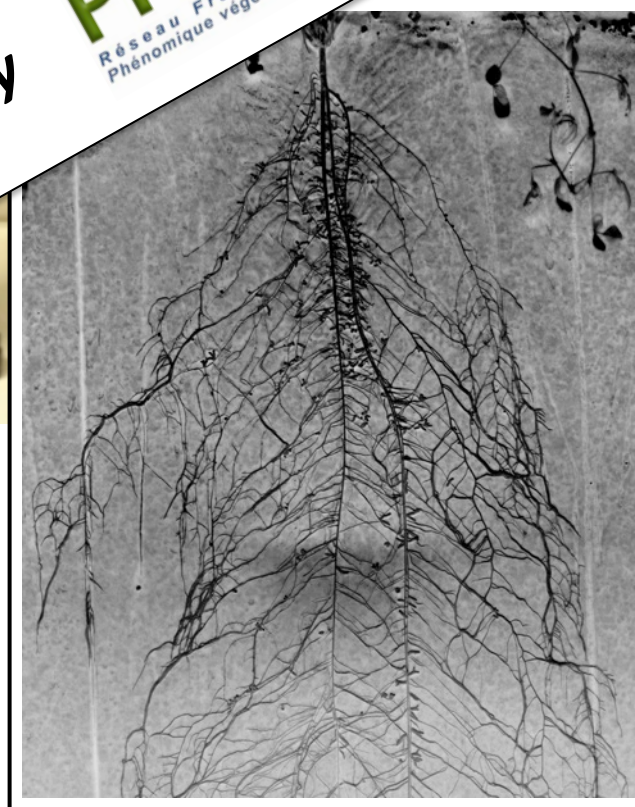
EU Licence INRA-Inoviaflow

Brushless motor



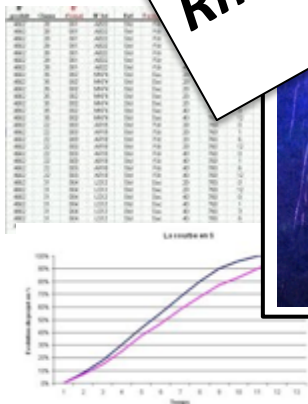
PHENOME
Réseau Français
Phénomique végétale
F P P N

Rhizotron and rhizocab financed by

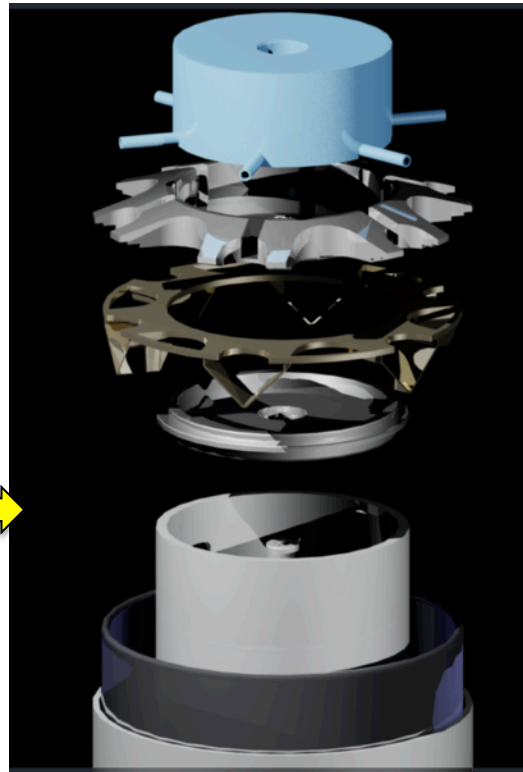
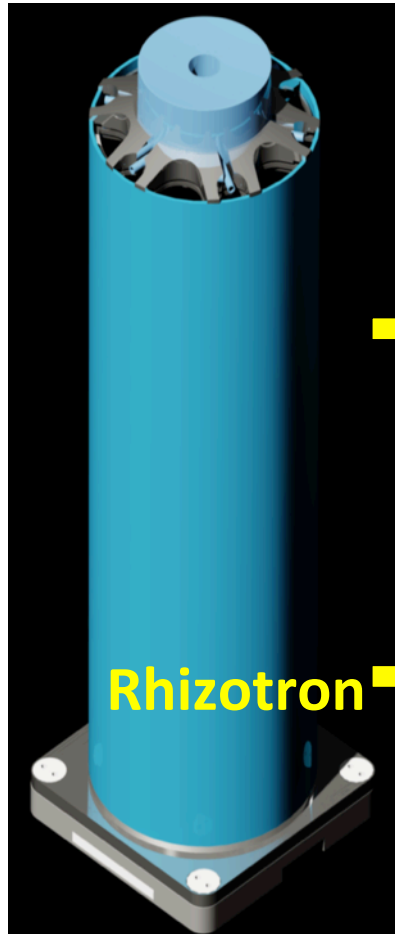


total root length....

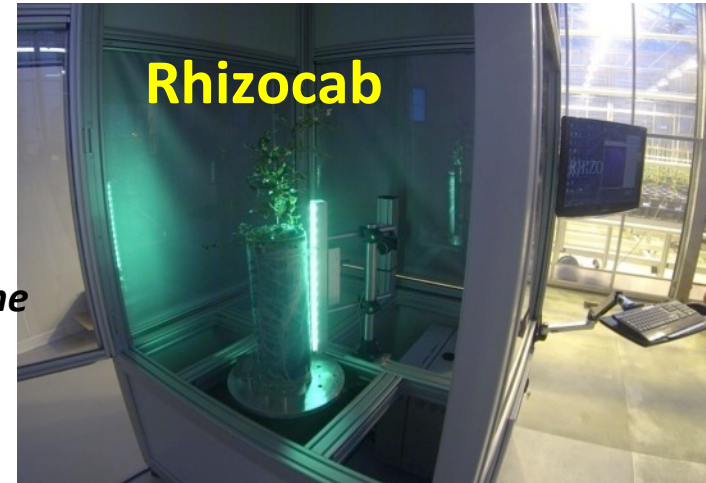
High resolution



Rhizotrons...and Rhizocab



Autonome



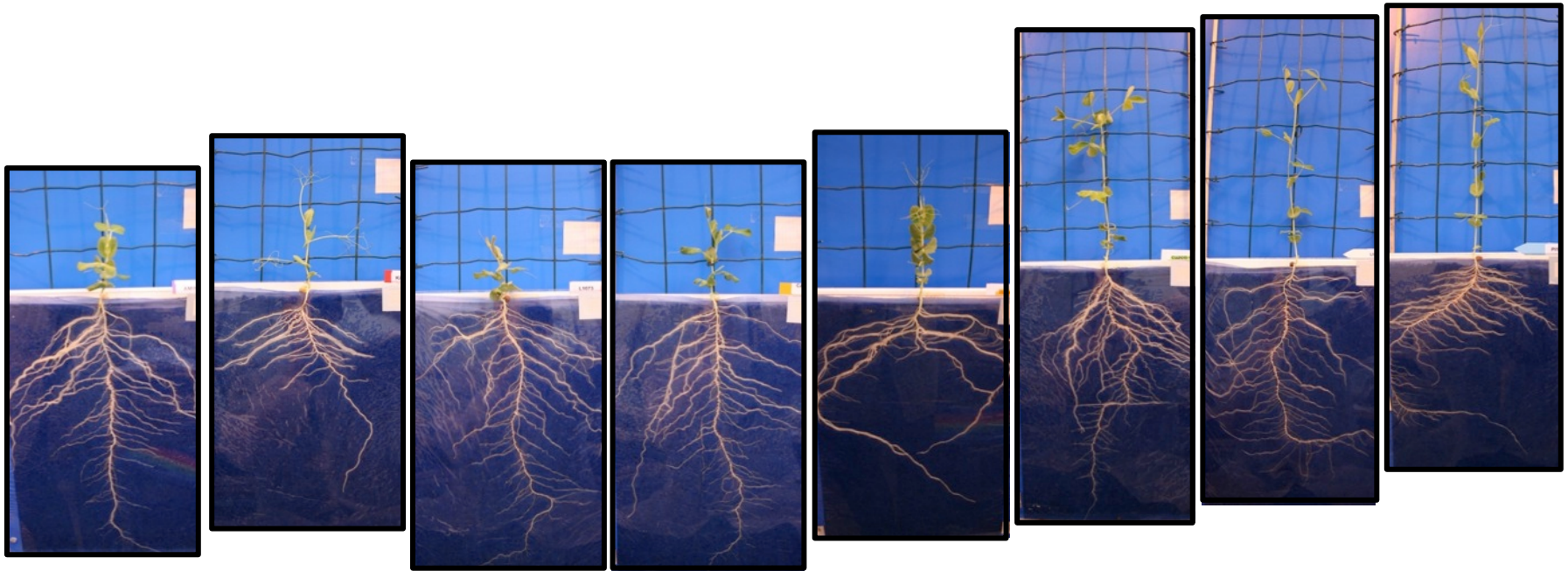
Technology transfert

*Basis
Adaptation*



Pea core collection

(coll. V Bourion, G Duc, J Burstin)



AMINO

KAYANNE

L1073

CAMEOR

ISARD

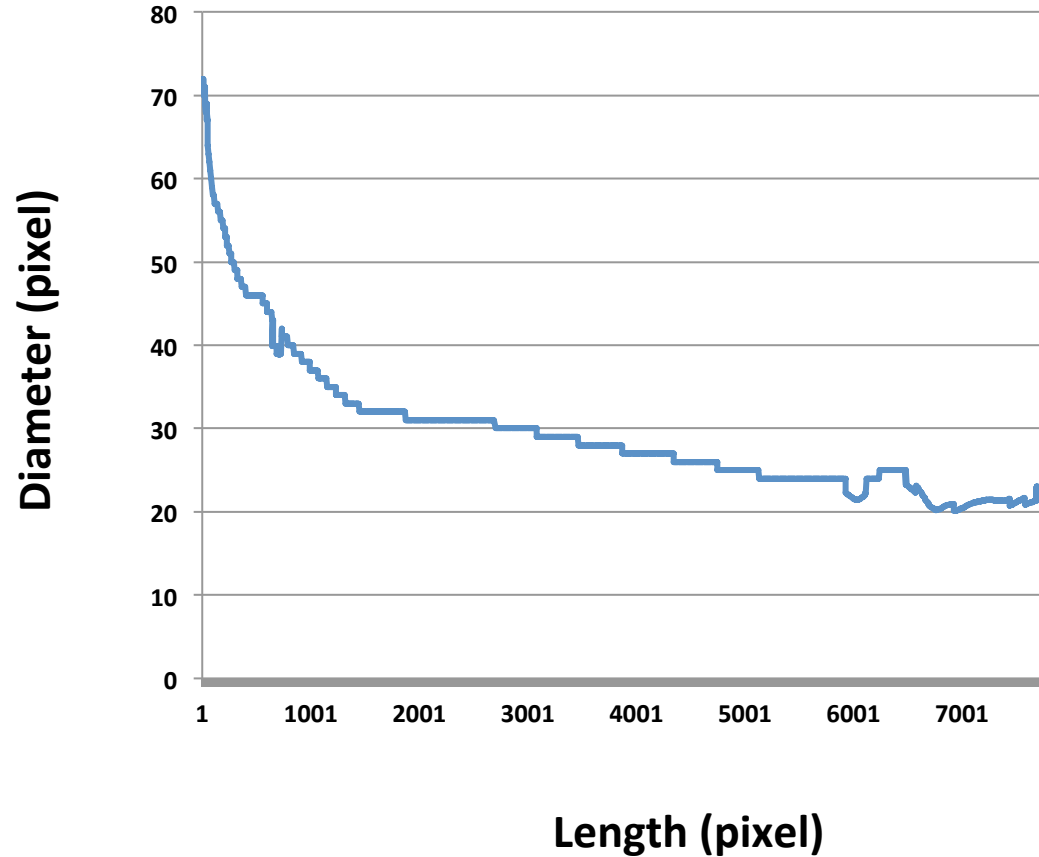
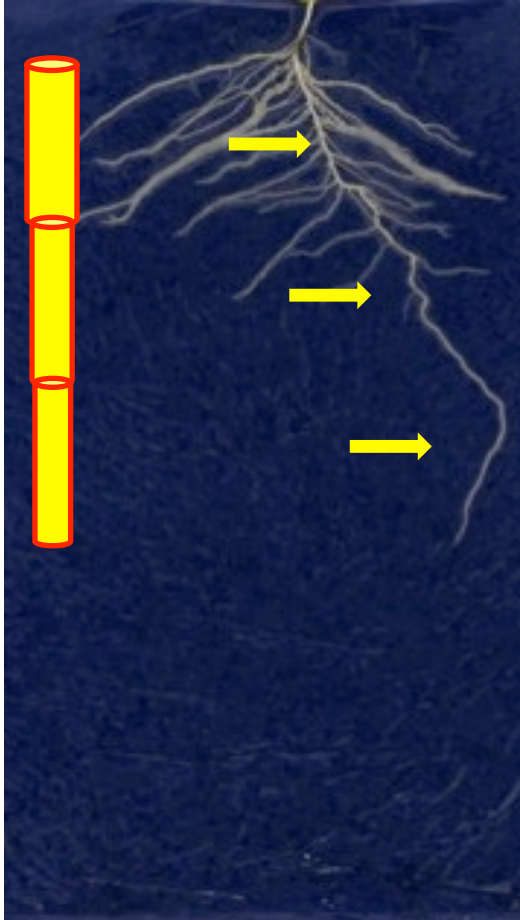
CUZCO

LIVIOLETTA

PI186093



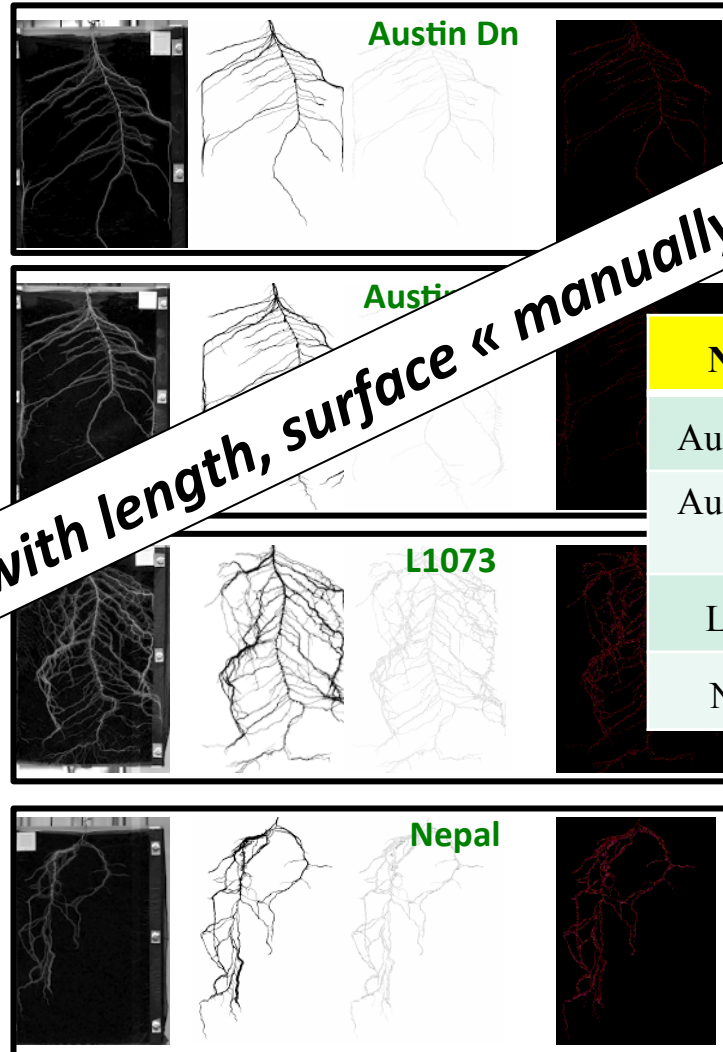
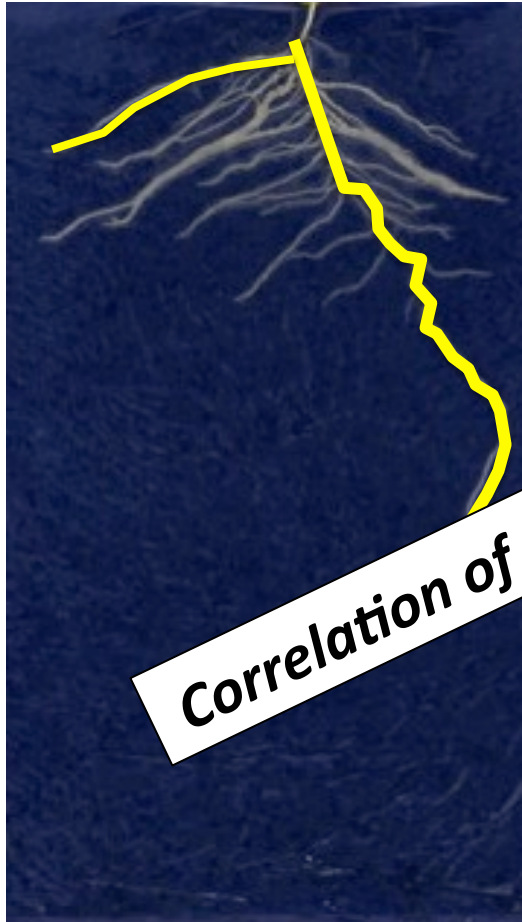
Roots: Length, Diameter





Phenotypic traits, examples

Roots: Length, Diameter, projected area

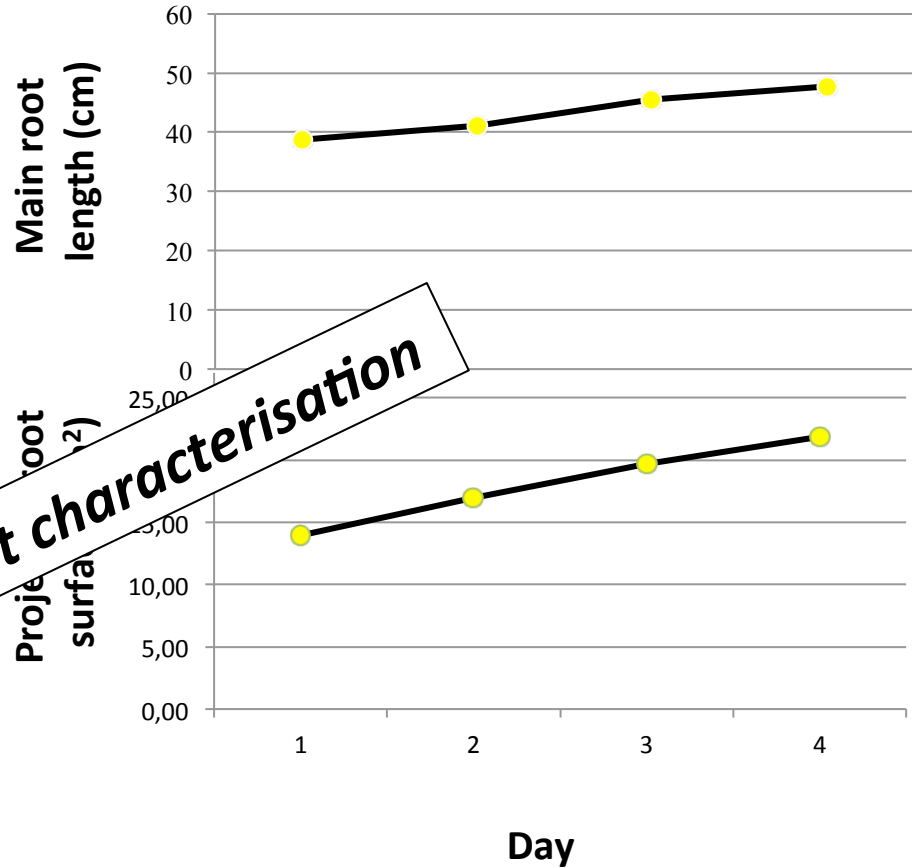
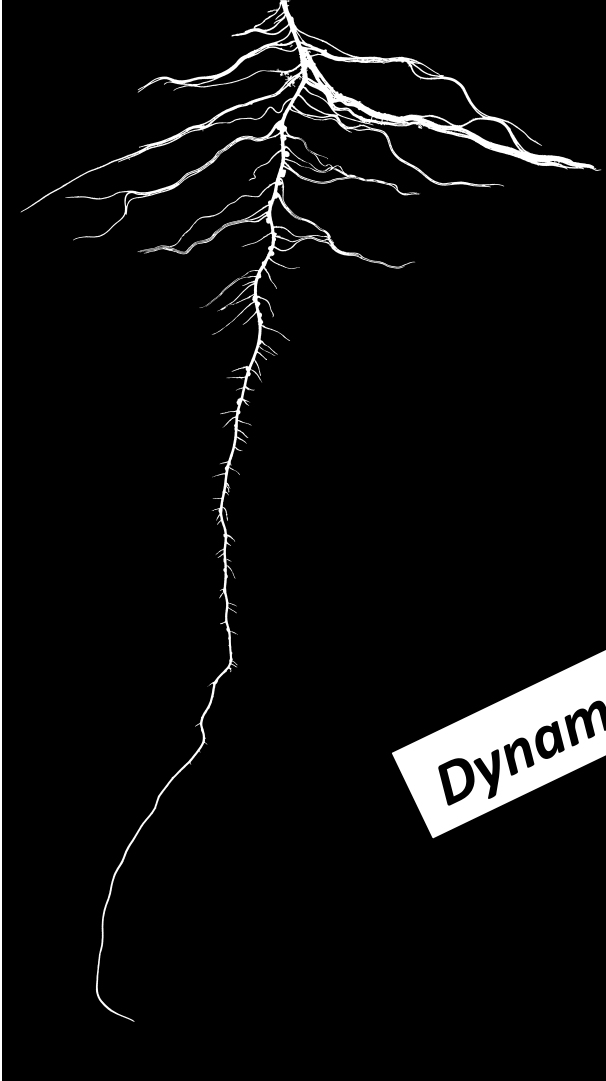


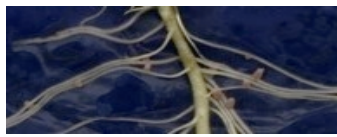
Correlation of 95% with length, surface « manually » evaluated

Name	Surface	Length
Austin Dn	38 cm ²	38cm
Austin Dn +5	58 cm ²	40cm
L1073	105 cm ²	40cm
Nepal	39 cm ²	35 cm



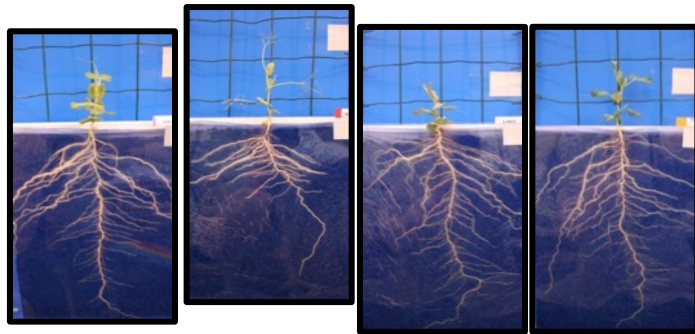
Roots: Length, Diameter, projected area





Roots: Length, Diameter, projected area, **estimated biomass**

Pea core collection (coll. V Bourion, G Duc, J Burstin)

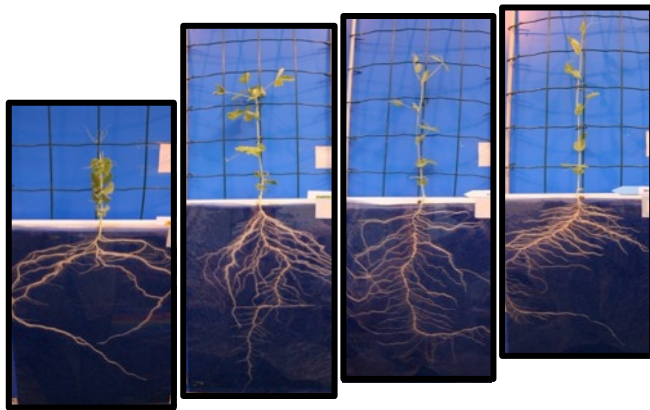


AMINO

KAYANNE

L1073

CAMEOR



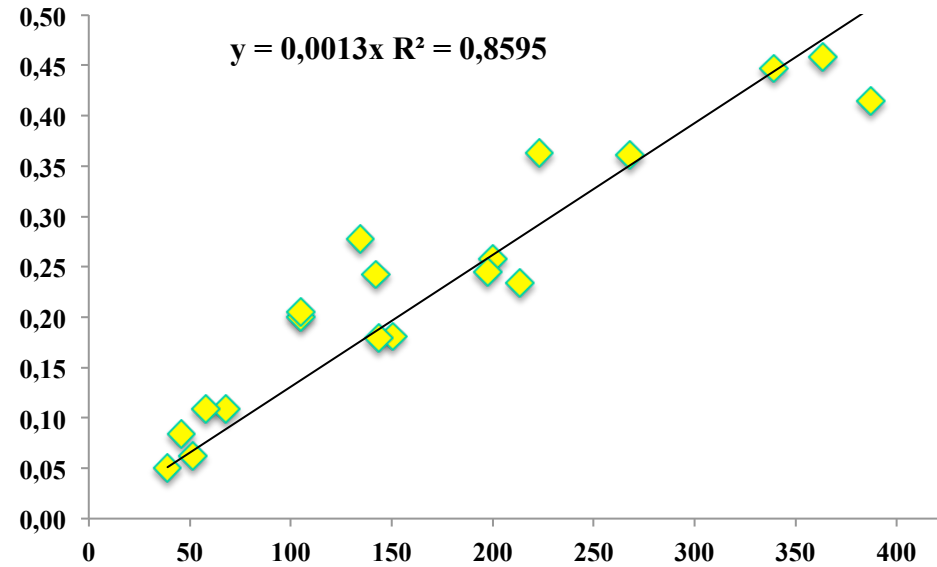
ISARD

CUZCO

LIVIOLETTA

PI186093

Measured Biomass (g/
plant)

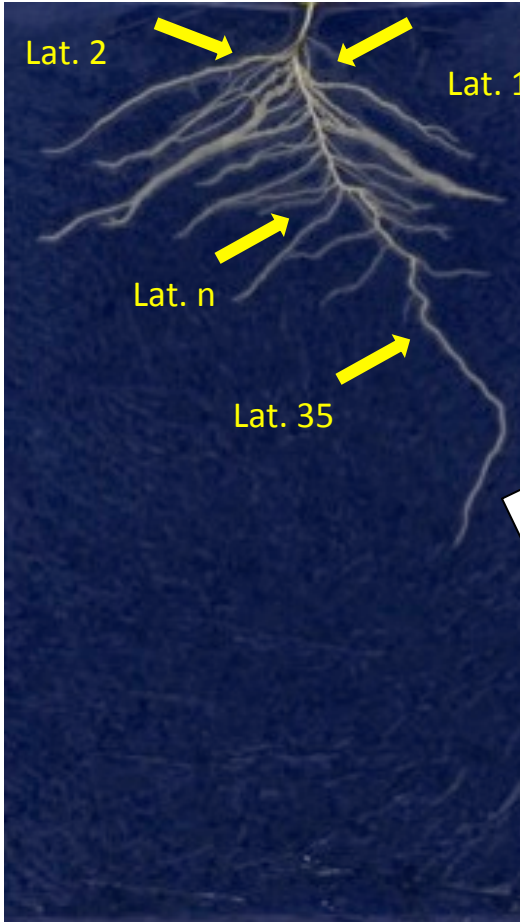


Projected Surface (cm²)

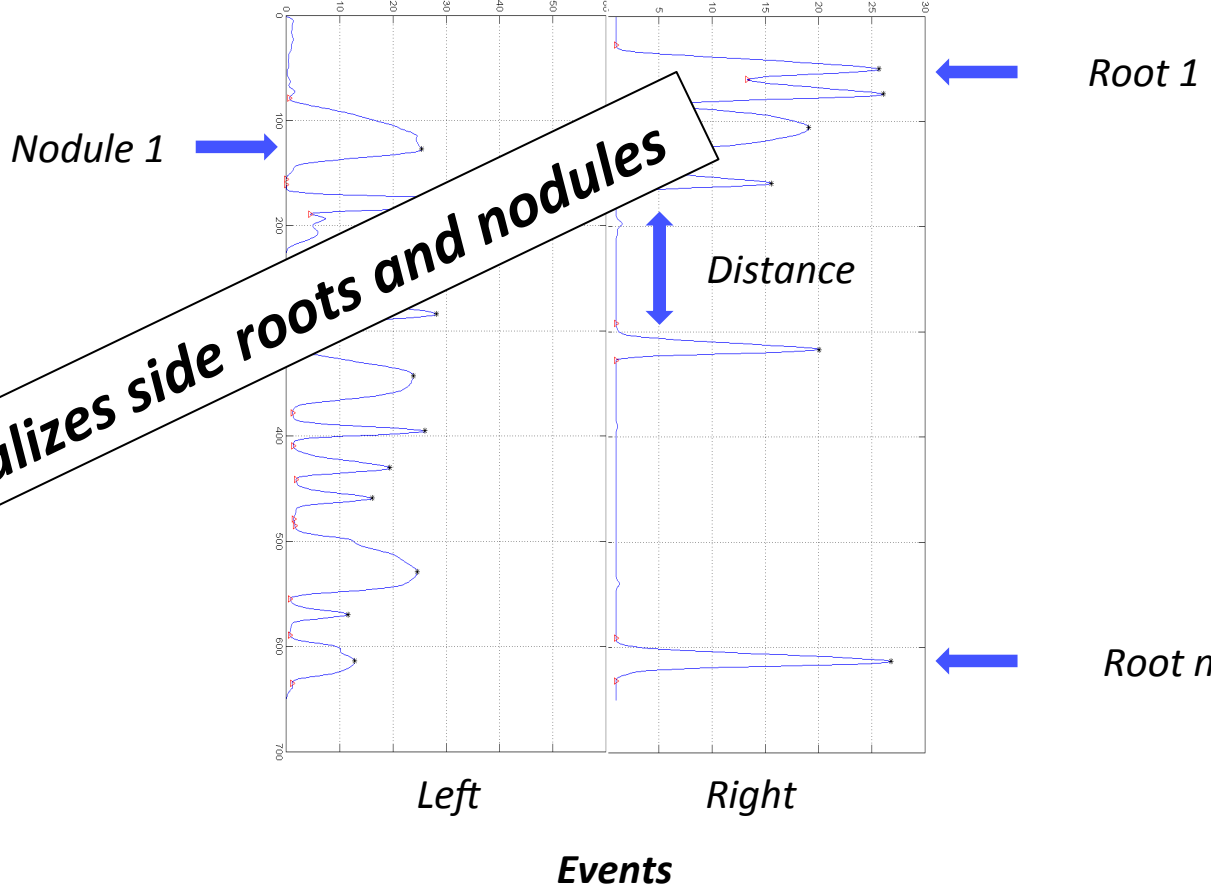


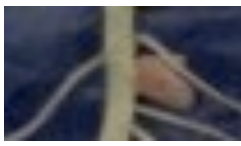
Phenotypic traits, examples

Roots: Length, Diameter, projected surface, estimated biomass, **lateral roots nodules**



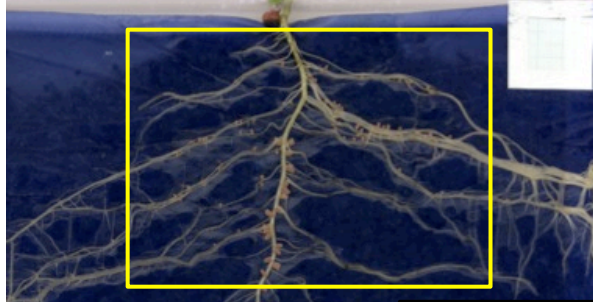
Localizes side roots and nodules



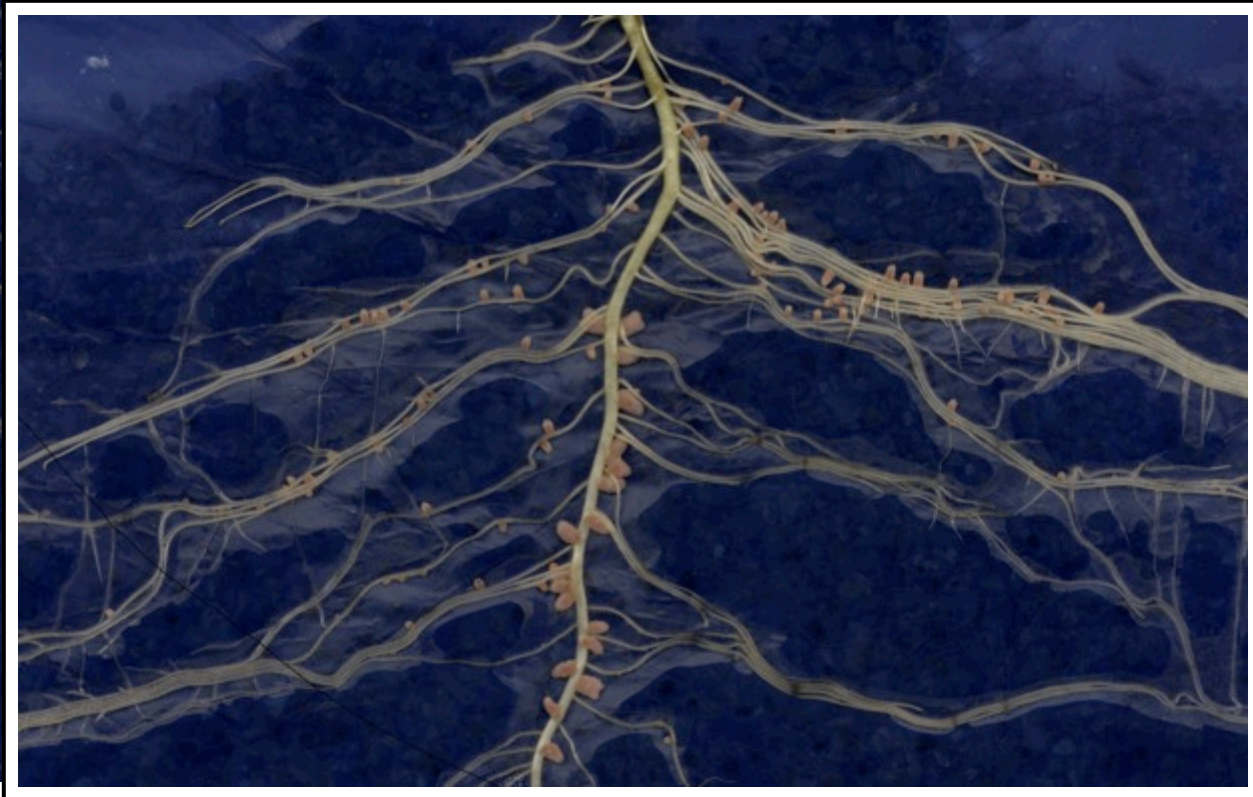


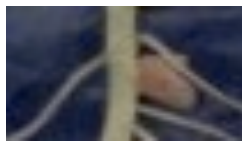
Phenotypic traits, examples

Nodules: Number, projected surface, position, color



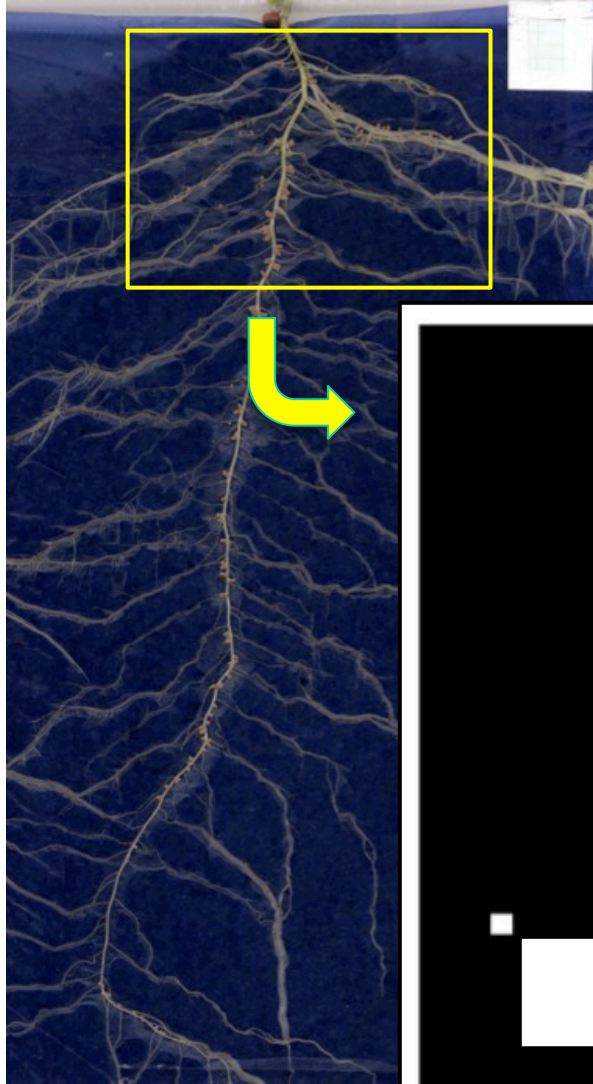
Focus on image





Phenotypic traits, examples

Nodules: Number, projected surface, position, color

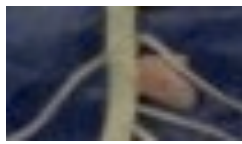


Hybrid Spaces (color + texture)

(Cointault et al, 2008)

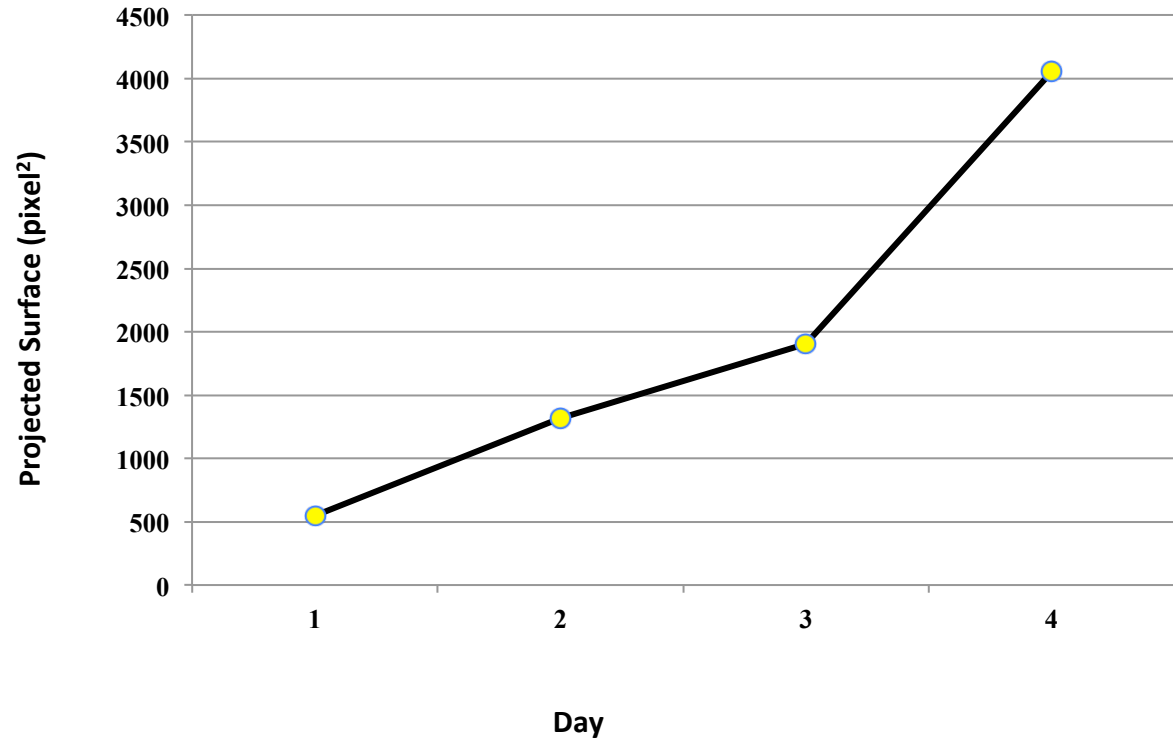
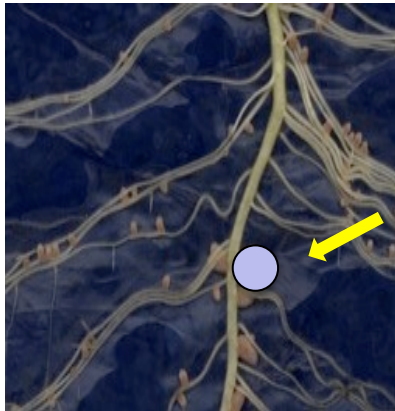
Nodules automatically detected





Phenotypic traits, examples

Nodules: Number, projected surface, position, color



Follow nodule growth dynamic

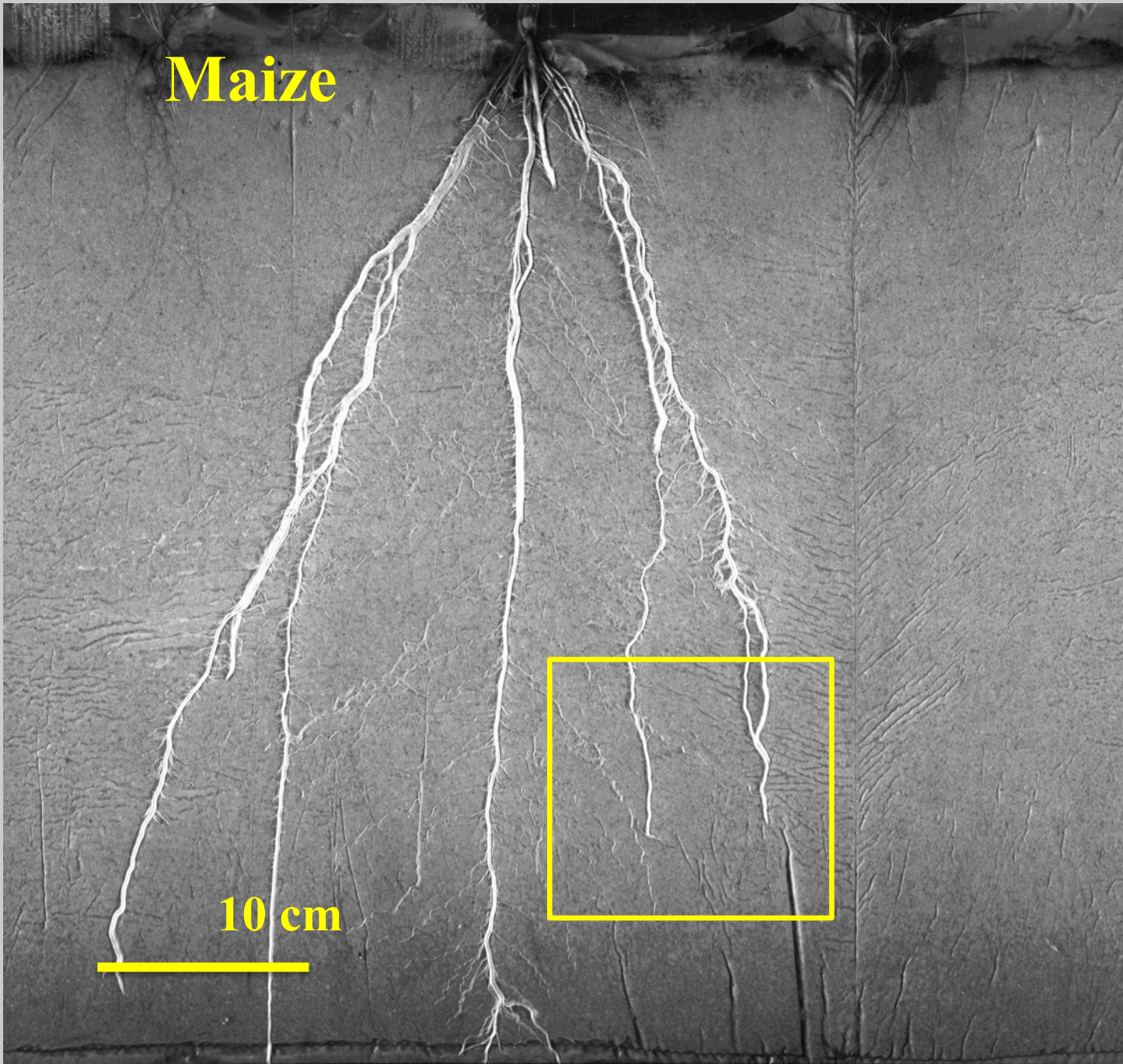
Ruffel et al. (2008), Plant Physiol. 146: 2020-2035.

Salon et al. (2009), CRAS, 332 :1022-1033.

Jeudy et al. (2010), New Phytol, New Phytol., 185:817-828.

PhD Simeng Han (unpublished)

Maize



10 cm

Maize

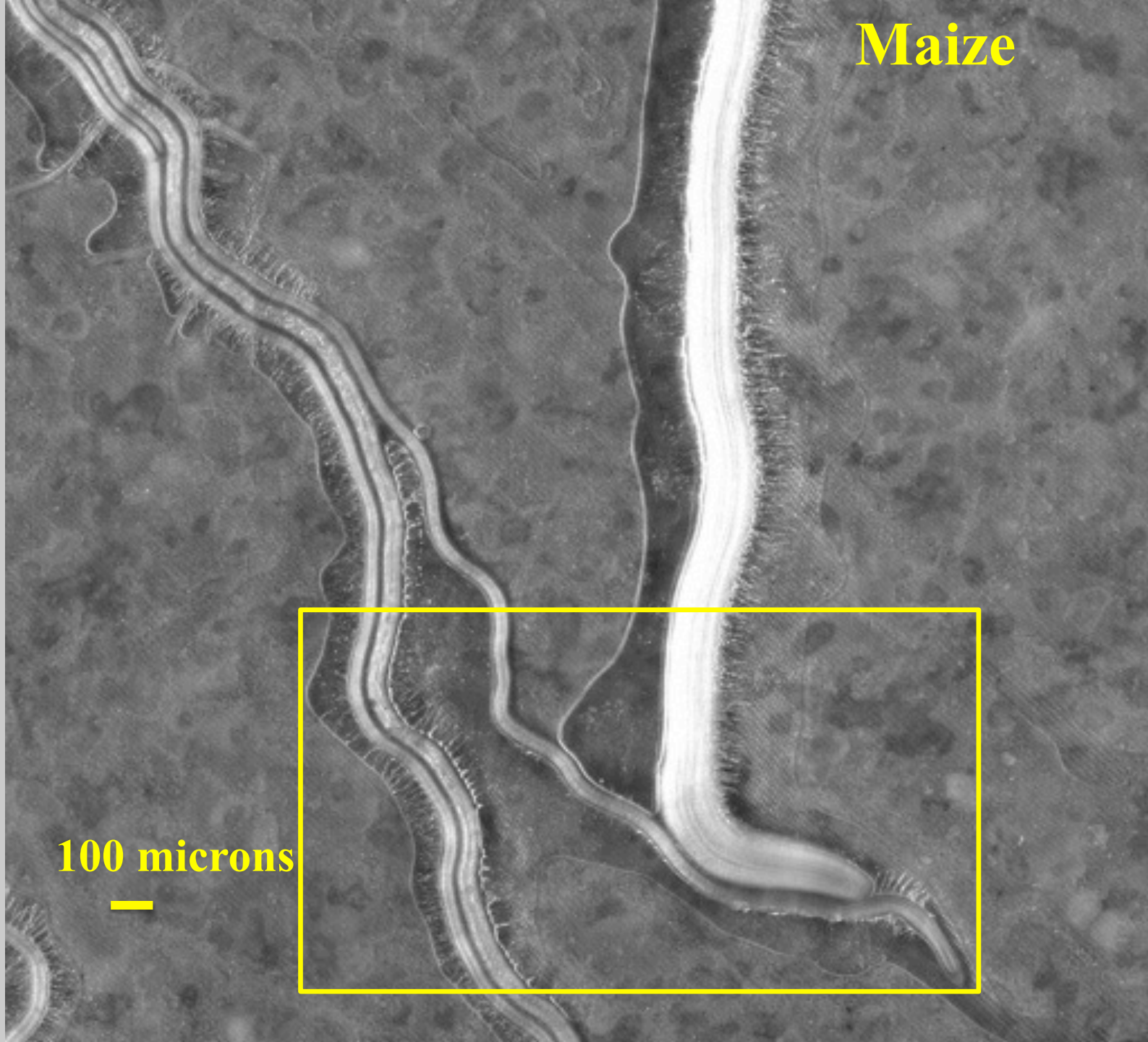
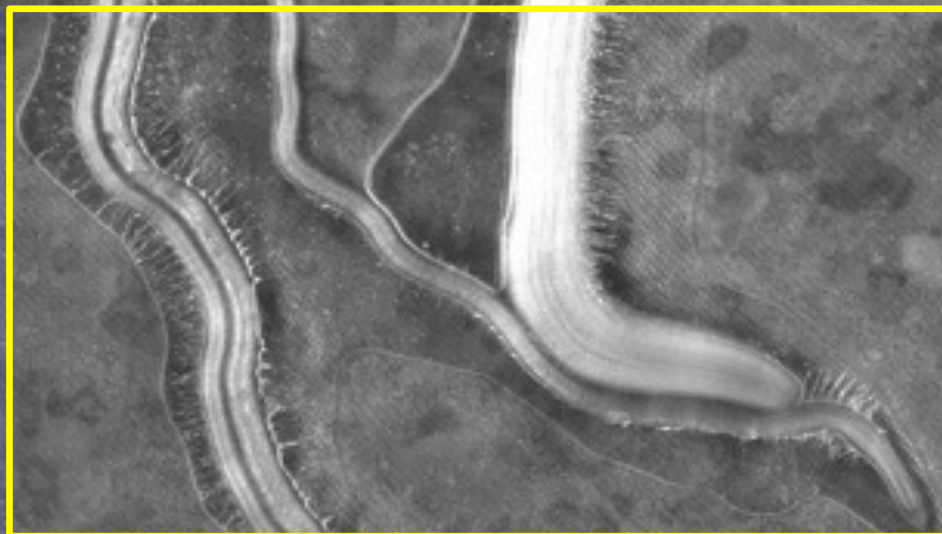


1 cm



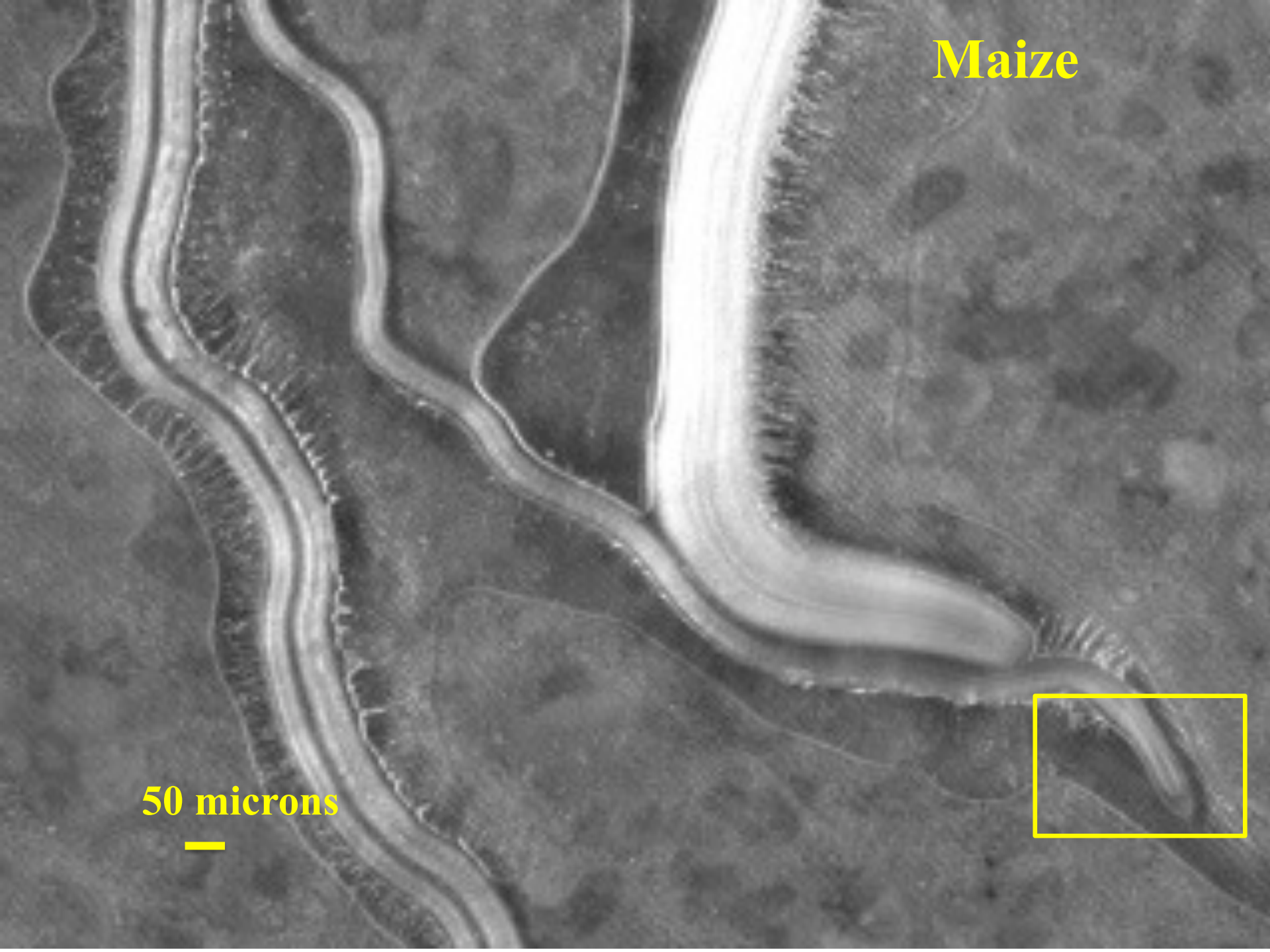
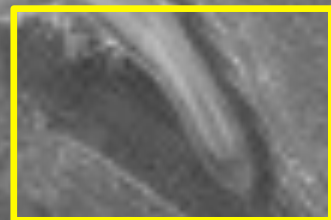
Maize

100 microns



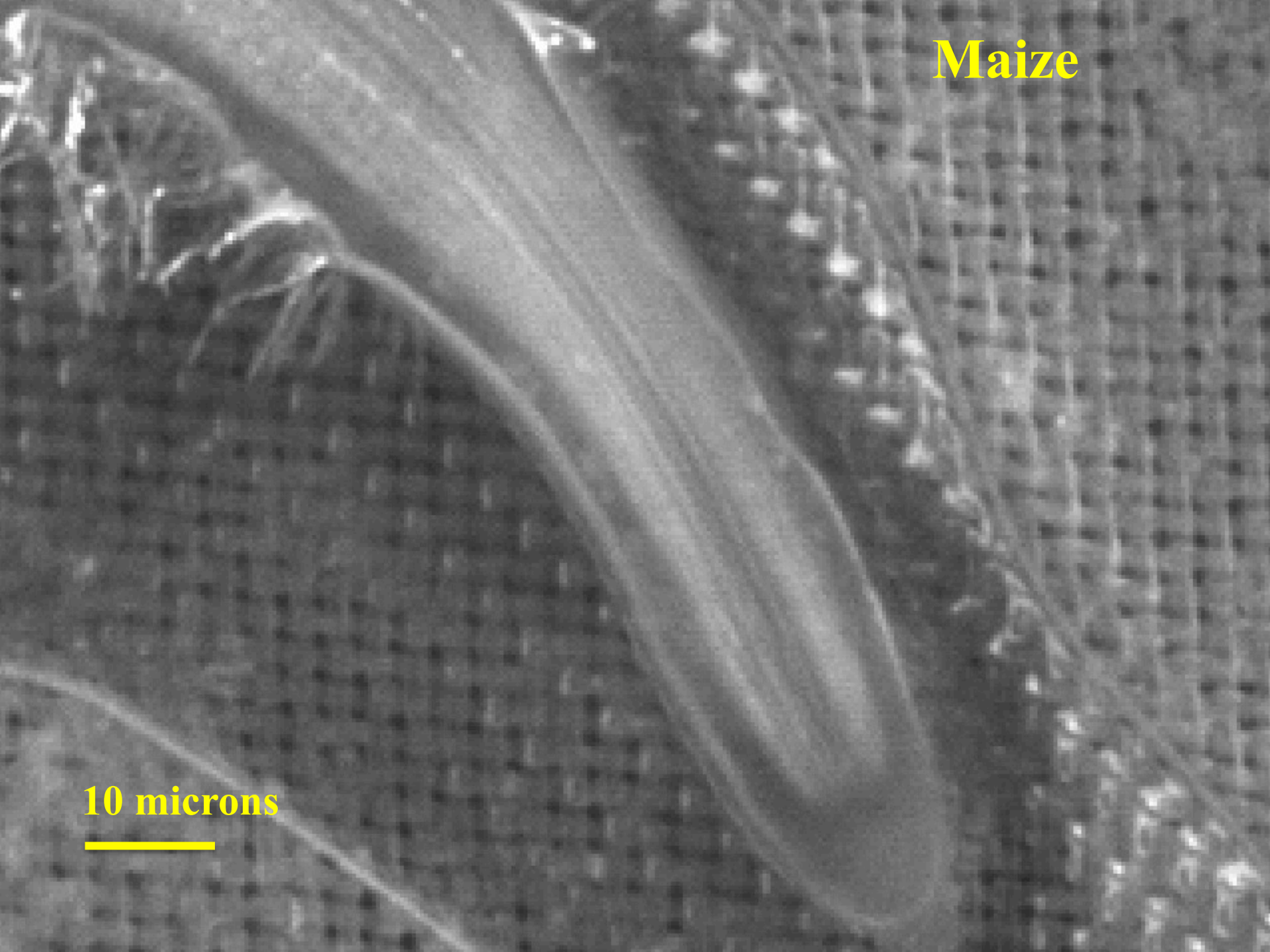
Maize

50 microns

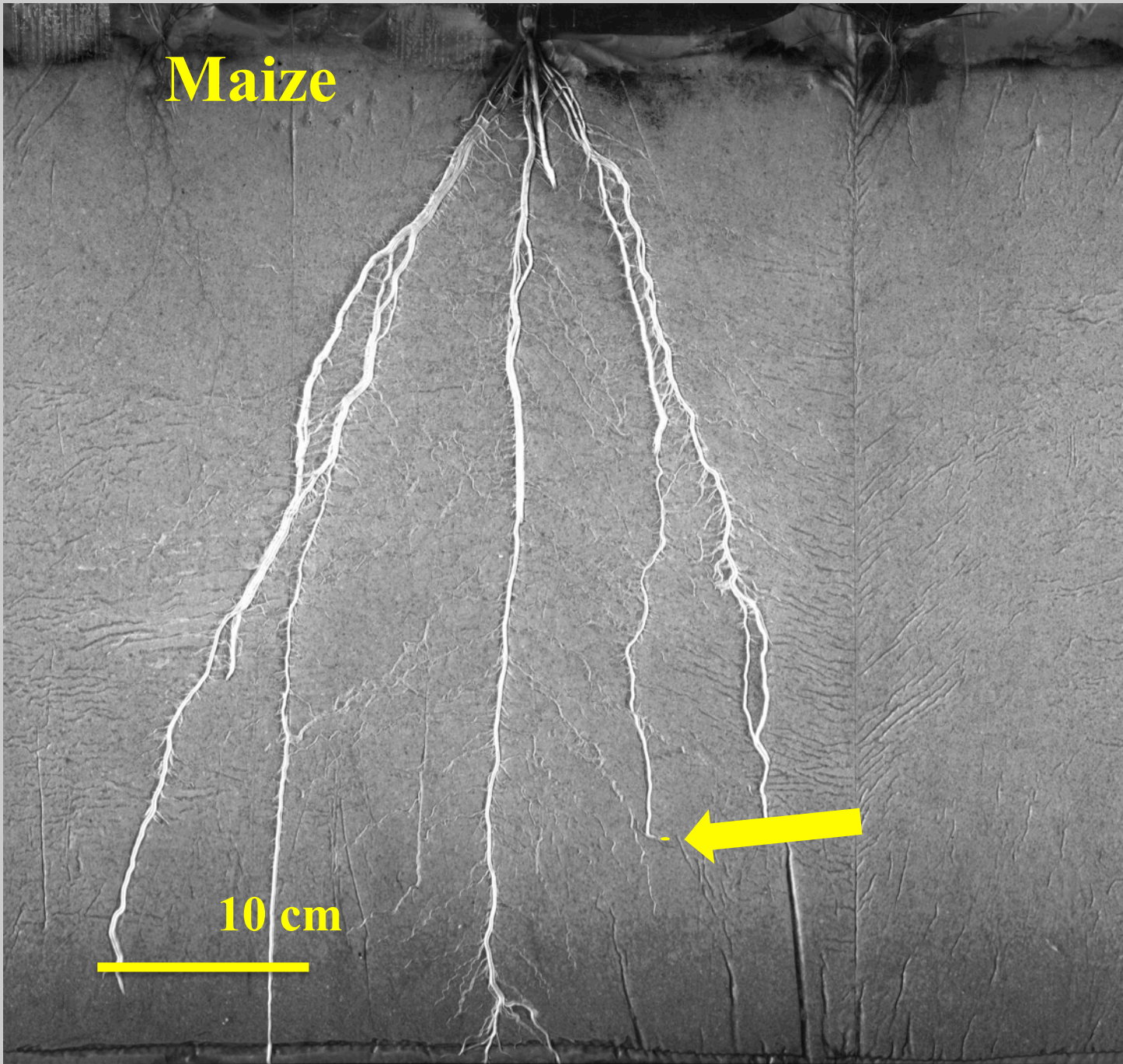


Maize

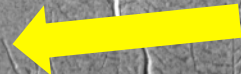
10 microns



Maize



10 cm



- Measure exhaustively and accurately environmental factors, soil water (water sensors)
- Investigate possible causes of maintaining regulation, leaf and root/restricted root capture ..)
- Think about plant relation with soil microorganisms
- An integrated view of whole plant (take into account roots as regards to HI, metabolic costs)
- Phenotyping in GH/CC => genotypic parameters in field experiments.
- Working on drought tolerance implies crop management (Tardieu JEB, 2009)
- Use models!!

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FOOD SECURITY

Any trait or trait-related allele can confer drought tolerance: just design the right drought scenario

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doi:10.1093/jxb/erz269

Abstract

Most traits associated with drought tolerance have a dual effect, positive in very severe scenarios and negative in milder scenarios, or the opposite trend. Their effects also depend on other climatic conditions such as evaporative demand or light, and on management practices. This is the case for processes associated with cell protection and with avoidance, but also for the maintenance of growth or photosynthesis, high water use efficiency, large root systems or reduced abortion rate under water deficit. Therefore, spectacular results obtained in one drought scenario may have a limited interest for improving food security in other geographical areas with water scarcity. The most relevant questions on drought tolerance are probably, 'Does a given allele confer a positive effect on yield in an appreciable proportion of years/scenarios in a given area or target population of environment (TPE)?', 'In a given site or TPE, what is the trade-off between risk avoidance and maintained performance?'; and 'Will a given allele or trait have an increasingly positive effect with climate change?' Considerable progress has already occurred in drought tolerance. Nevertheless, explicitly associating traits for tolerance to drought scenarios may have profound consequences on the genetic strategies, with a necessary involvement of modelling.

Key words: Allele, drought, drought tolerance, trait.

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PD (ABA soil water
PR...)
tment in
luated in
al conditions

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Related projects where GEAPSI-UMR Agroécologie INRA is involved



Candidate genes for drought stress response in legumes.



HT phenotyping



Combined heat and drought stress



Mediterranean network of field experimentation, data/experience

And of course...



Drought wizards

François TARDIEU



Marion PRUDENT



Rhizotrons, Rhizocab

Christian JEUDY



Christophe BAUSSARD



Platform(s) management

Llorenz CABRERA



Céline BERNARD



Image analysis

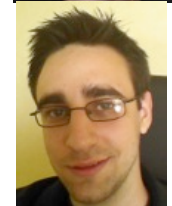
Simeng HAN



Frédéric COINTAULT



Mickael LAMBOEUF





Thank you for your attention!