Water Use Efficiency
Workshop Prague

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PHENOME
Réseau Français Phénomique végétale
FPPN

European Plant Phenotyping Network
EPPN

Determinism of biomass accumulation

Key processes to biomass accumulation

Yield = $\int_i^f$ PPFD * εa x εb x HI

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

εa % = PPFD intercepted by leaves

εb (kg mol−1) = conversion ratio of intercepted light into biomass

Yield = $\int_i^f$ ET x WUE x HI

Evapo**T**ranspiration (kg m^{-2})

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

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

Tardieu 2005 CR Géoscience

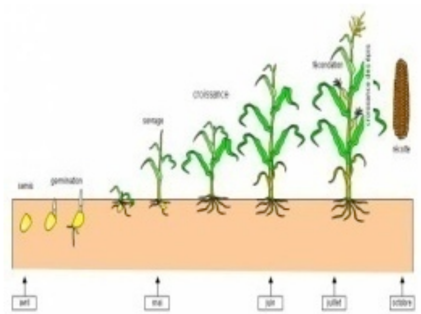
Water Use Efficiency (WUE)

… a multiscalar definition:

Seconds

$$\frac{\text{Photosynthesis}}{\text{Stomatal conductance}}$$

Days to weeks



$$\frac{\text{Yield}}{\text{Input water}}$$

Crop ccyle

$$\frac{\text{Biomass}}{\text{Transpiration}}$$

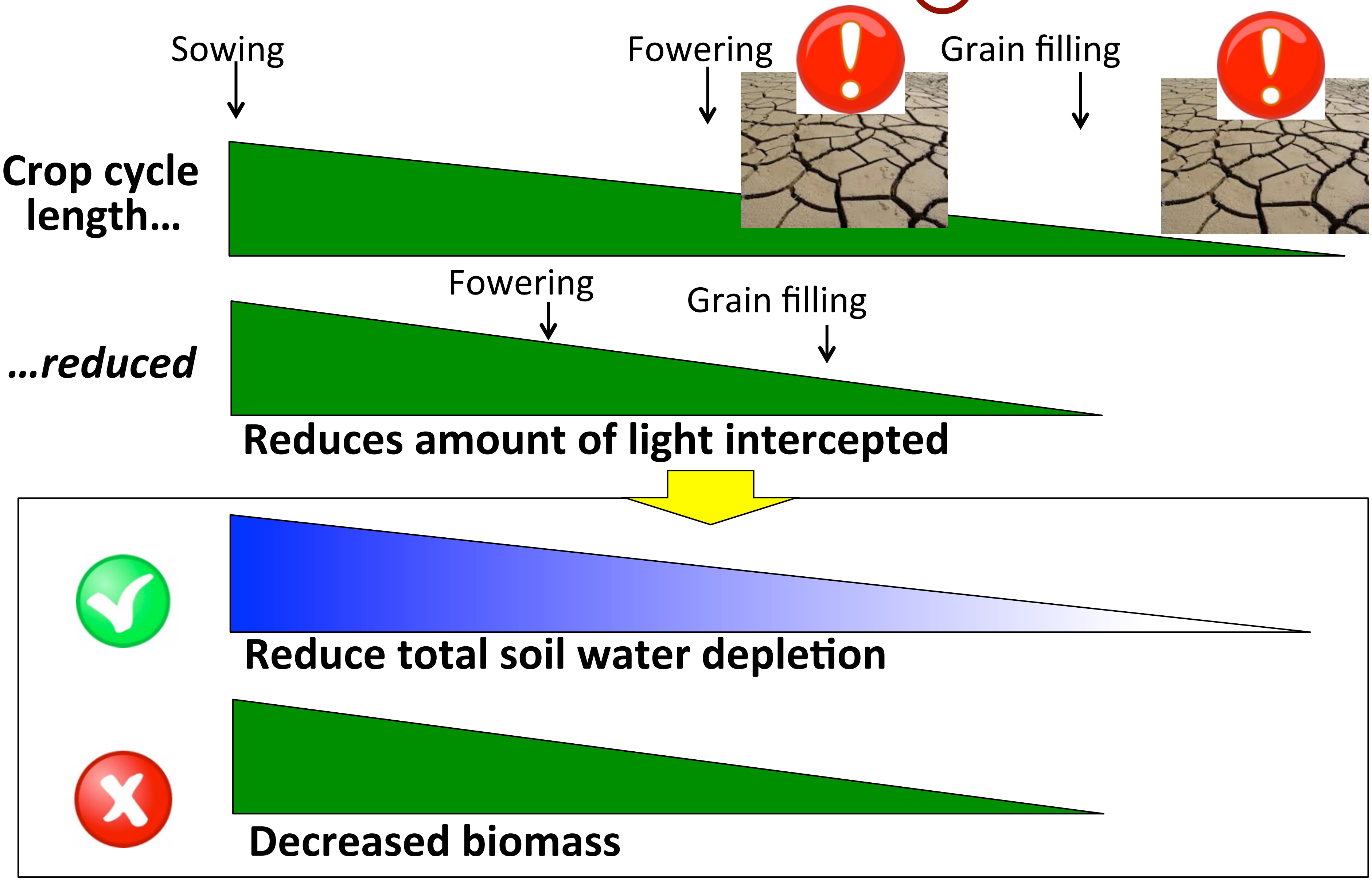
Morison et al., 2008

INRA SCIENCE & IMPACT

Escaping water deficit through ..

... changing plant phenology

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

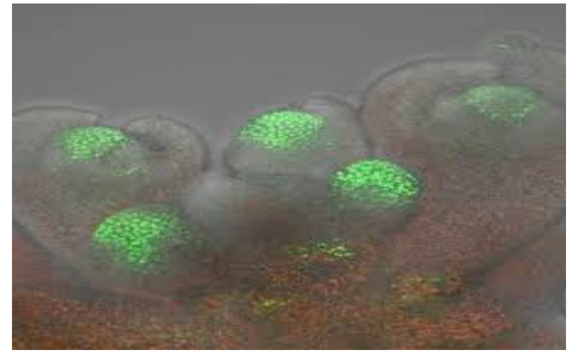


Avoidance mechanisms

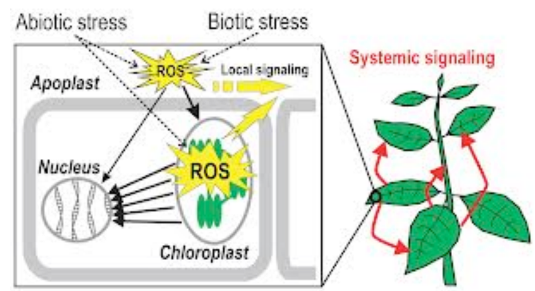
Severe drought

Tolerance confered by

Cell protection mechanisms



Accumulation of molecules (stabilise proteins, membranes, structures)



Avoids accumulation of toxic species

Plant survival

Resisting severe deficit through survival mechanisms

Avoidance mechanisms

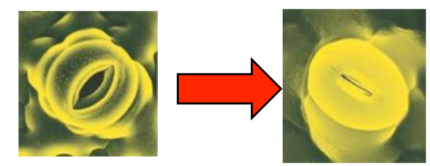
Severe drought

Water deficits in agriculture

Tolerance confered by

Cell protection mechanisms

Stomatal closure



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

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

Reduce plant demand for water

Decreases the %intercepted light

Reduces efficiency of transformation

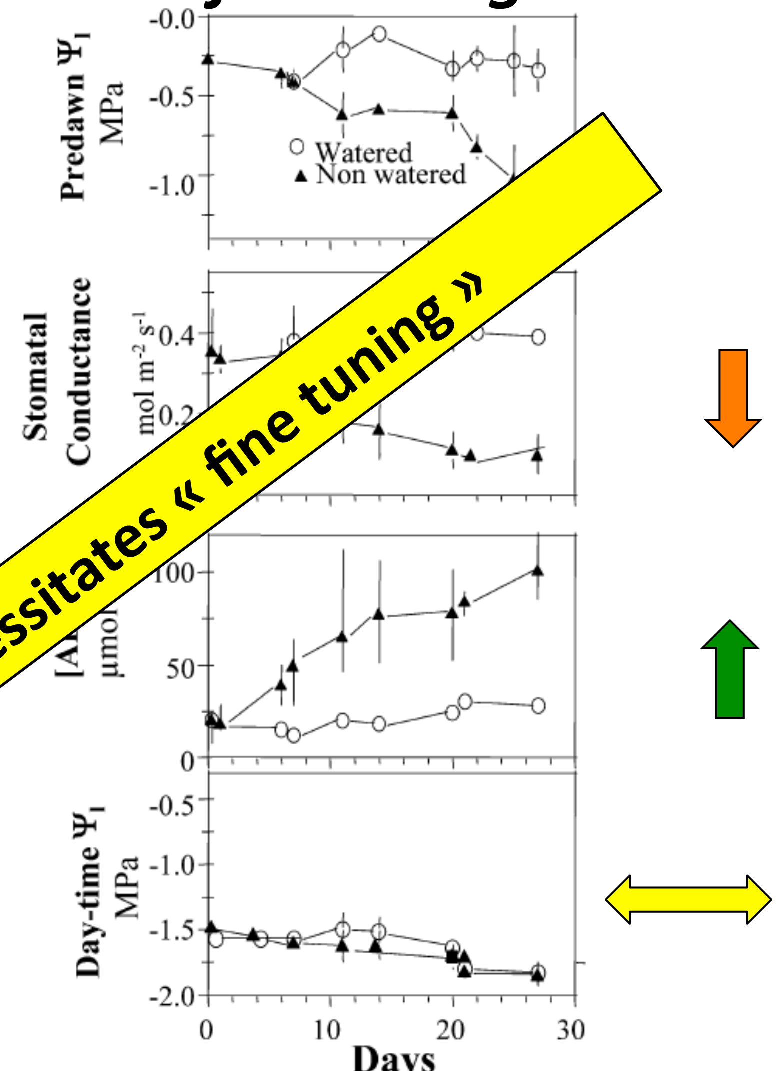
Avoidance mechanisms

Severe drought

Tolerance confered by

Cell protection mechanisms

Water deficits in agriculture

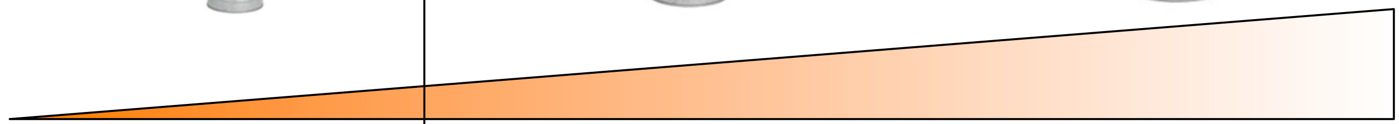


Necessitates « fine tuning »

Avoidance mechanisms

Severe drought

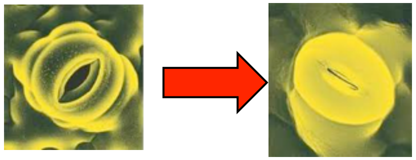
Water deficits in agriculture



Tolerance confered by

Cell protection mechanisms

Stomatal closure



Changes plant architecture, leaf growth etc (senescence)

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

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

Reduce plant demand for water

Decreases the %intercepted light

Reduces leaf size, LAI

Avoidance mechanisms

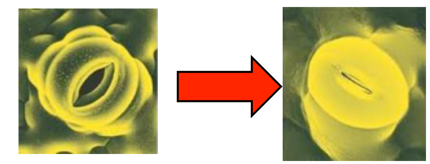
Severe drought

Water deficits in agriculture

Tolerance confered by

Cell protection mechanisms

Stomatal closure



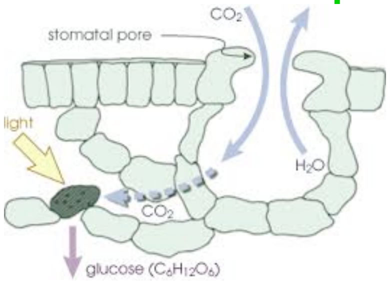
Changes plant architecture, leaf growth etc (senescence)

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

Ok in most circumstances of water deficits compatible with agriculture…

Production

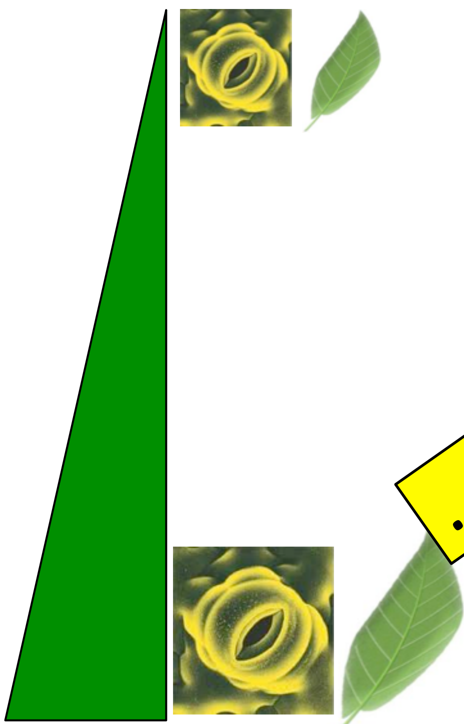
Biomass accumulation vs Stress avoidance



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 wate… …tion

Sense long… …t soil

« Stay… »

Increased leaf temperature

Decreased biomass

Early experience of a dry soil.

Decreased biomass

Stress symptoms therefore appear later

And also…

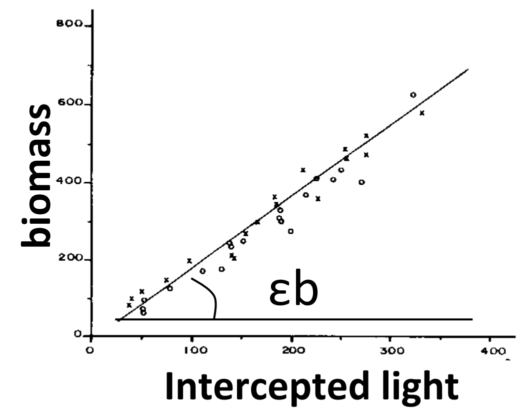
$$\mathbf{Yield} = \int_i^f \mathbf{PPFD} * \varepsilon a \times \varepsilon b \times HI$$

Large part of genetic progress of several species

εa = f(leaves orientation)

εb = f(species).

εb less variable within a given species.

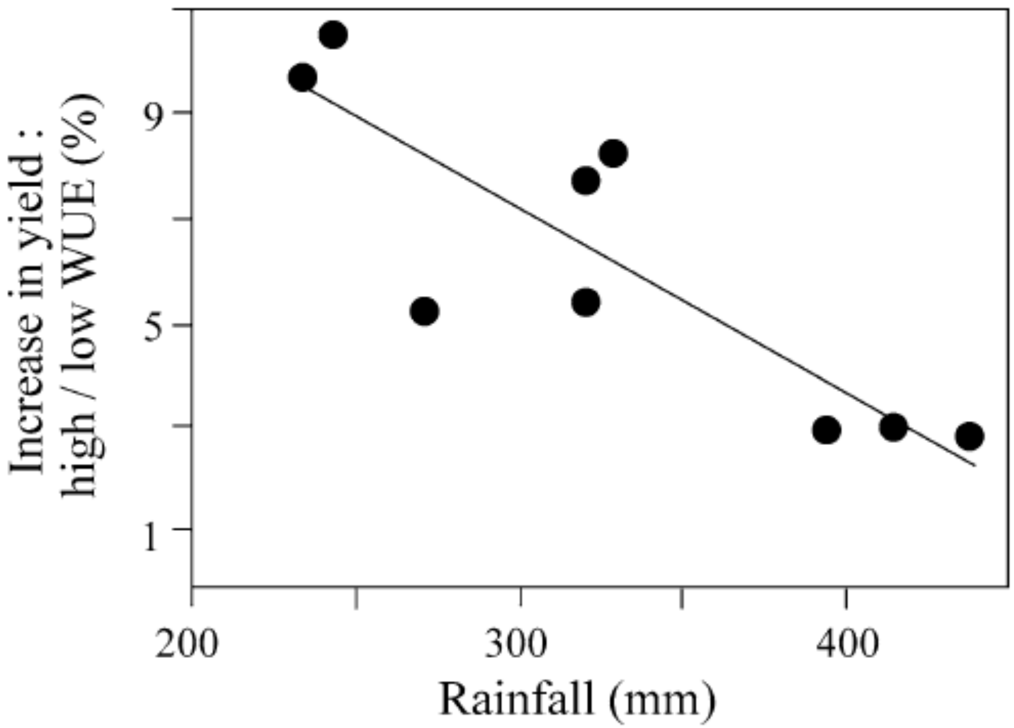


..but some success to increase RUE

… 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

Improving water-use efficiency

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

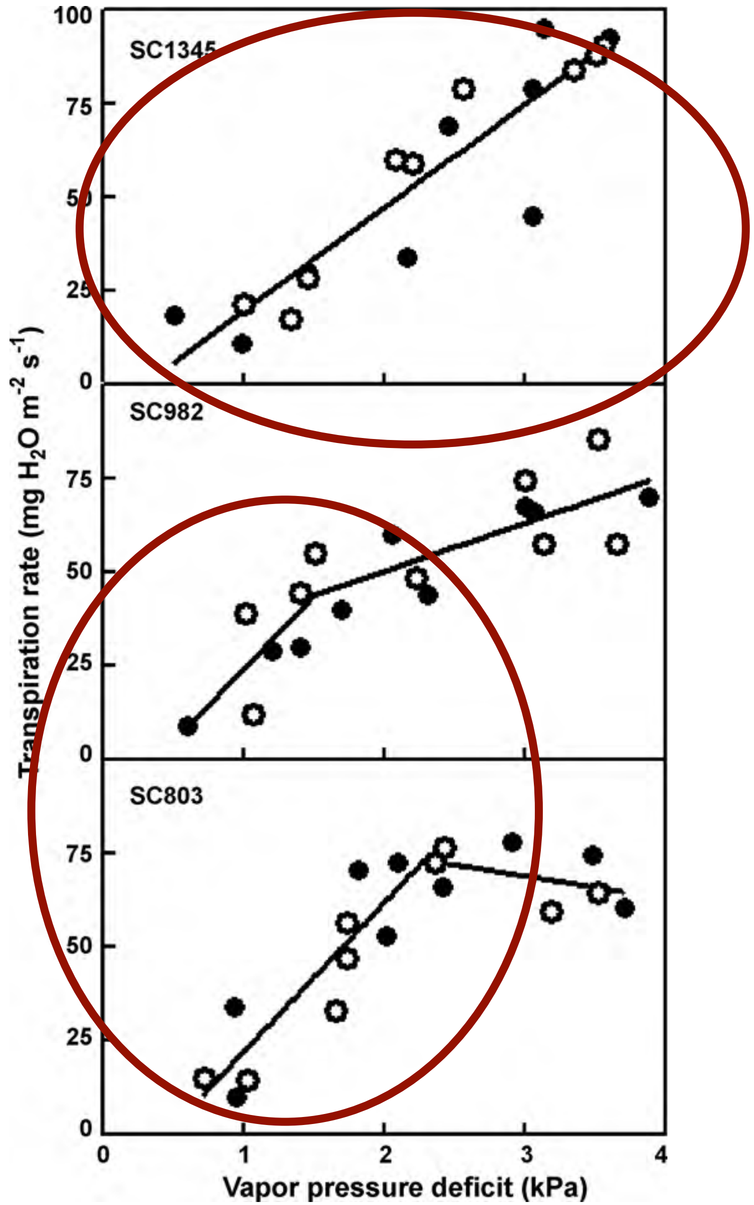
Gholipoor et al (2010) FCR

Improving water-use efficiency

Transpiration rate = (VPD)

Linear response of TR vs VPD

A Break Point in TR response to VPD



Gholipoor et al (2010) FCR

Improving water-use efficiency

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

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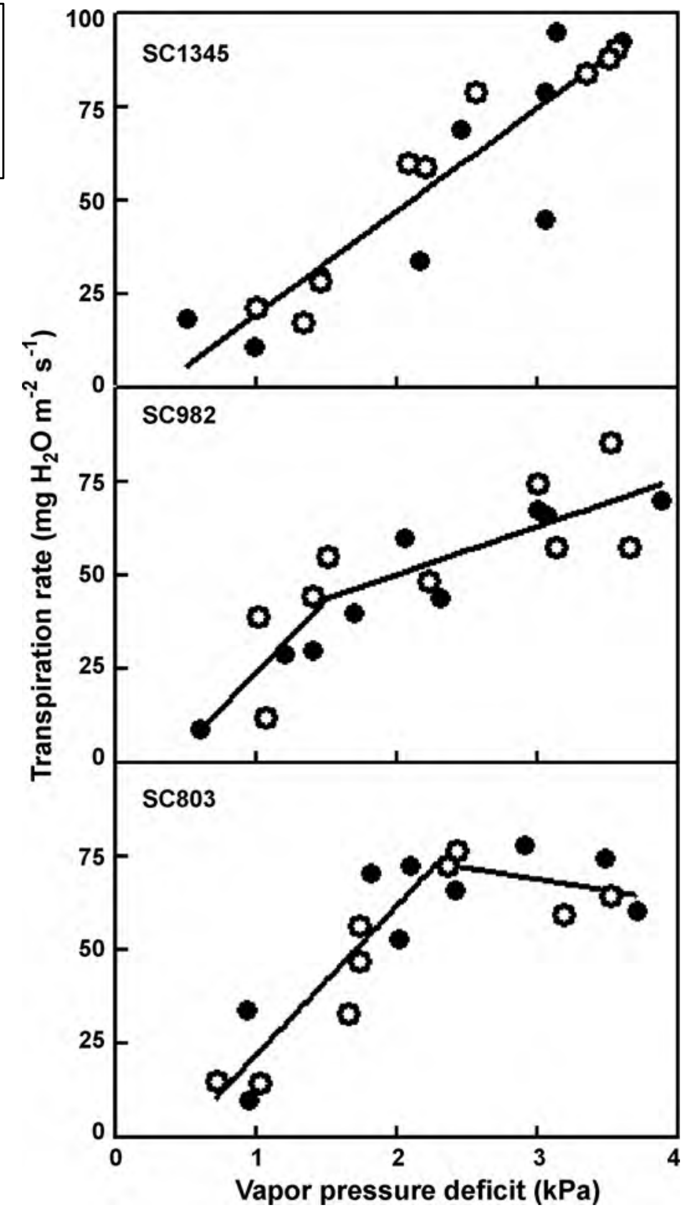


Gholipoor et al (2010) FCR

Improving water-use efficiency

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

- Without BP + low TR/VPD = **dry conditions**

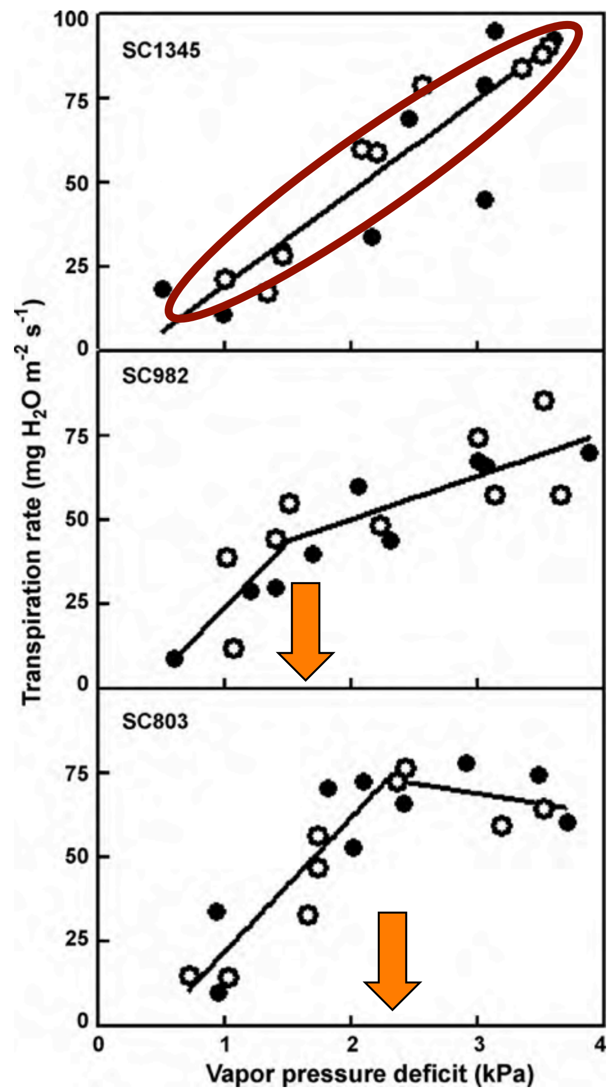
  … But restricted A, slow growing, low yielding under well-watered conditions!

- 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**.



Maintain transpiration..

… via improving size, architecture of the root system

$Yield = \int_i^f PPFD * \varepsilon a \times \varepsilon b \times HI$ **$Yield = \int_i^f ET \times WUE \times HI$**

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

Useful when a soil water reserve is root free

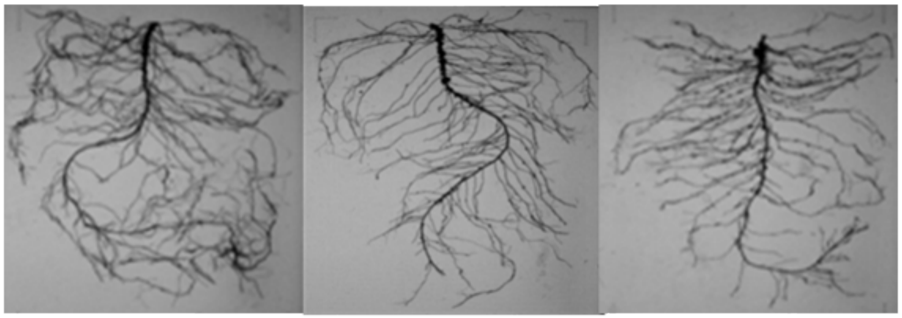
When limited amount of water (e.g., shallow soil) of little interest or even counter-productive!

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

Maintain transpiration..

… a large genetic variability for genetic progress

Natural (pea)



Bourion et l. Annals Bot. 2007

Natural (Medicago)

Mutants (MSE Pea)

Control | Ramified | Nod++ | Nod++ x Ramified

Coll . KK Sidorova

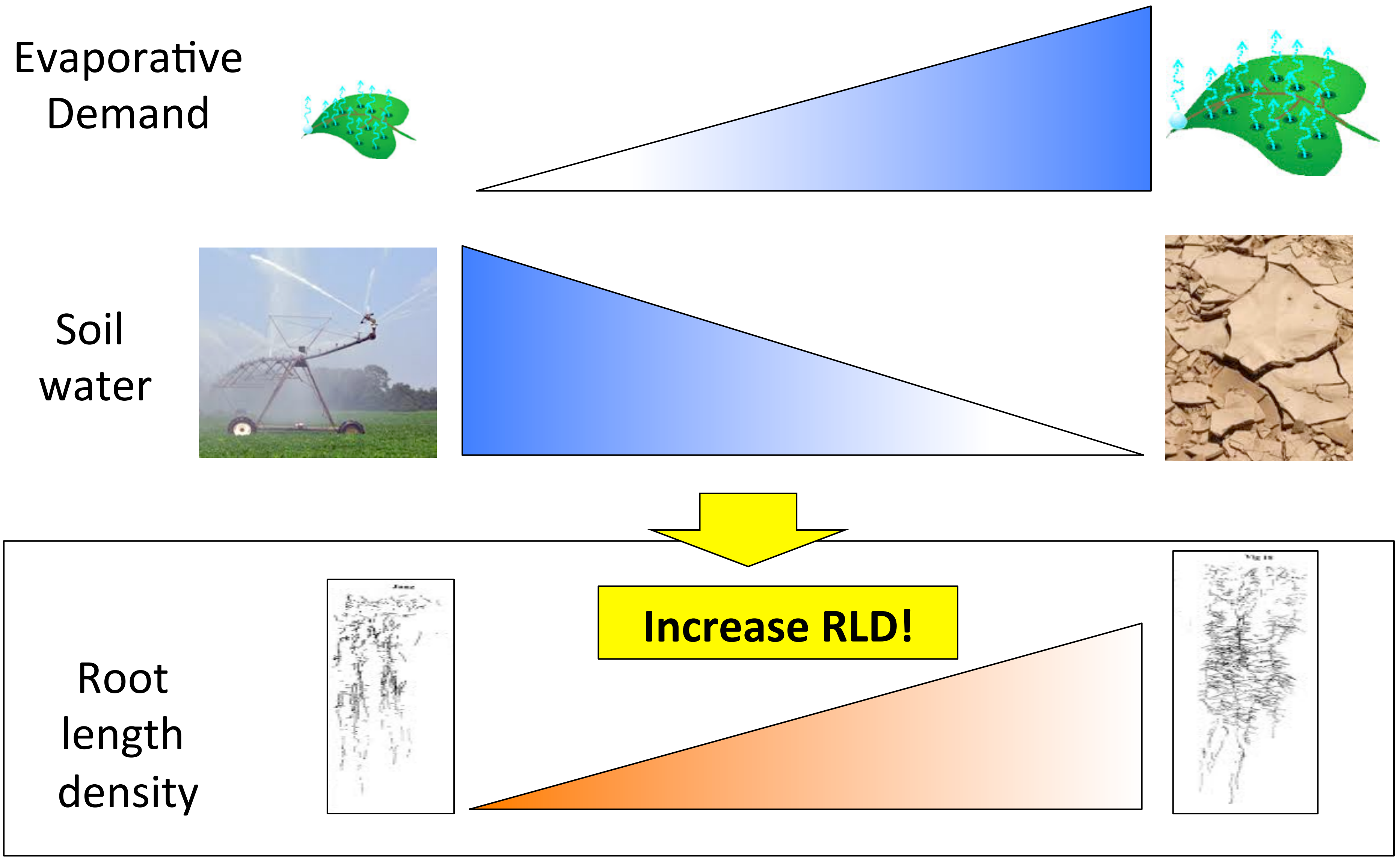
Mutants (Tnt1 *Medicago*)

Control | Long root | Ramified | Nod++

Porceddu et al. BioMed 2008

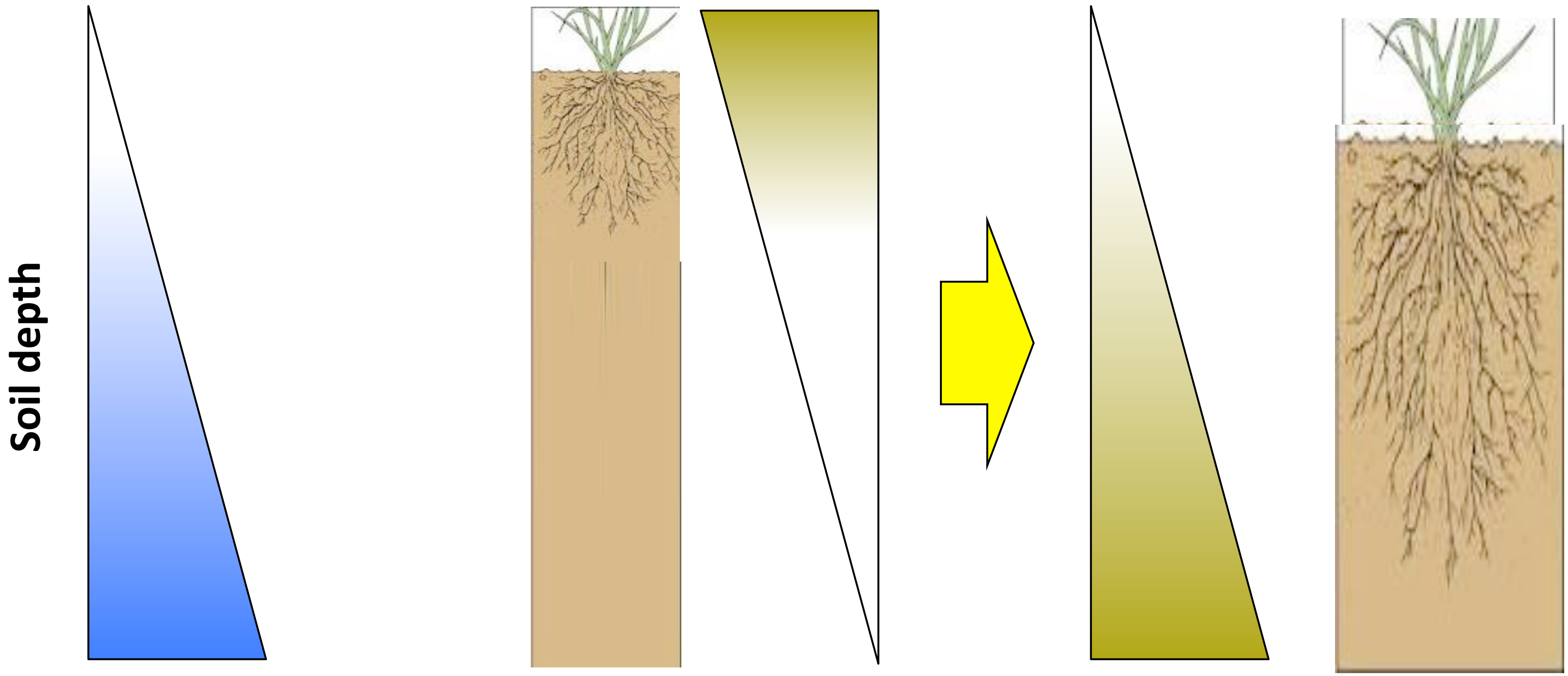
Maintain transpiration..

… a large genetic variability for genetic progress= RLD



Always increase soil exploration by roots in case of drought ?

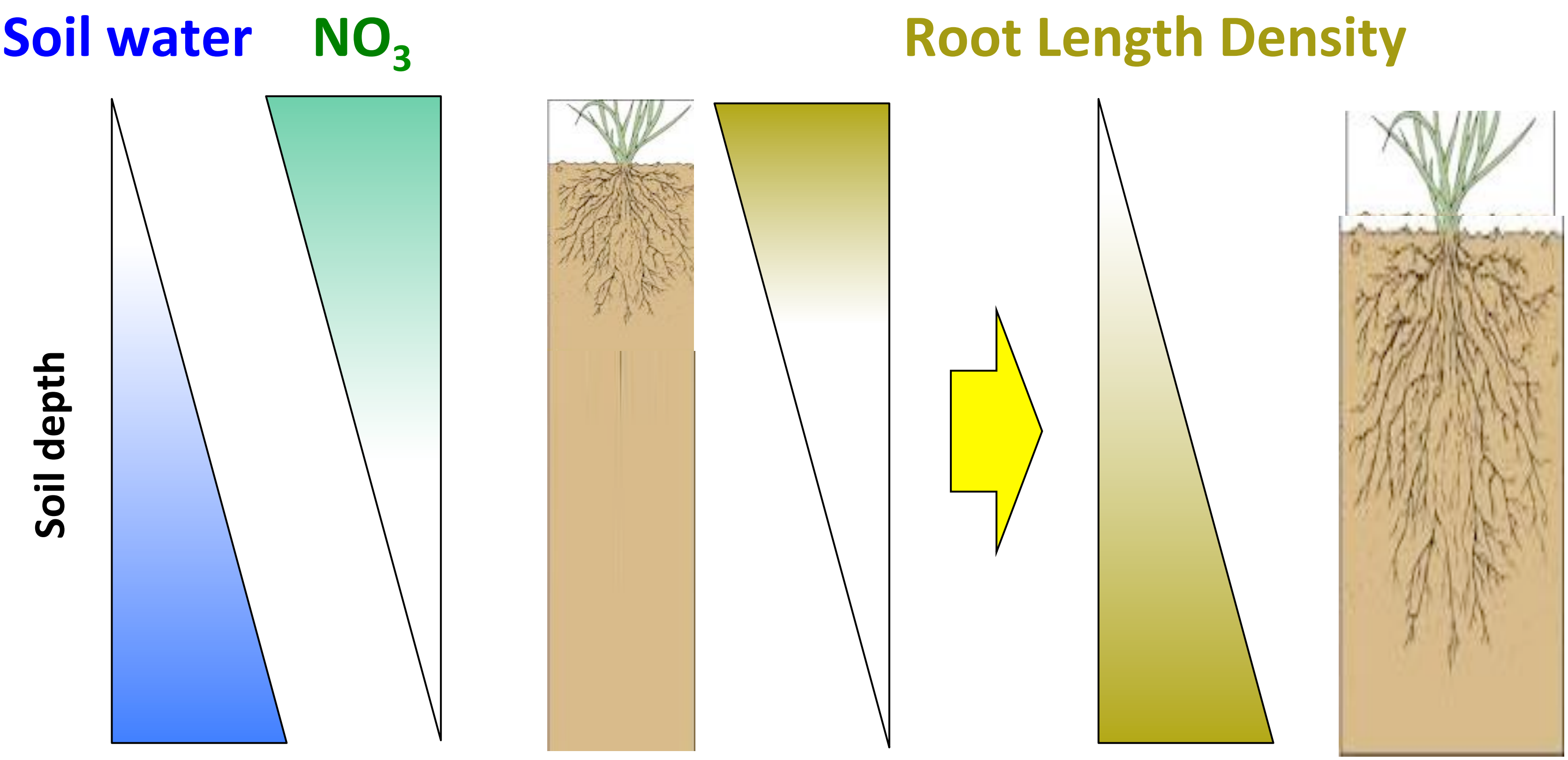
Soil water **Root Length Density**



Carbon waste for no water benefit.

Increase RLD in deeper layers!

Always increase soil exploration by roots in case of drought ?

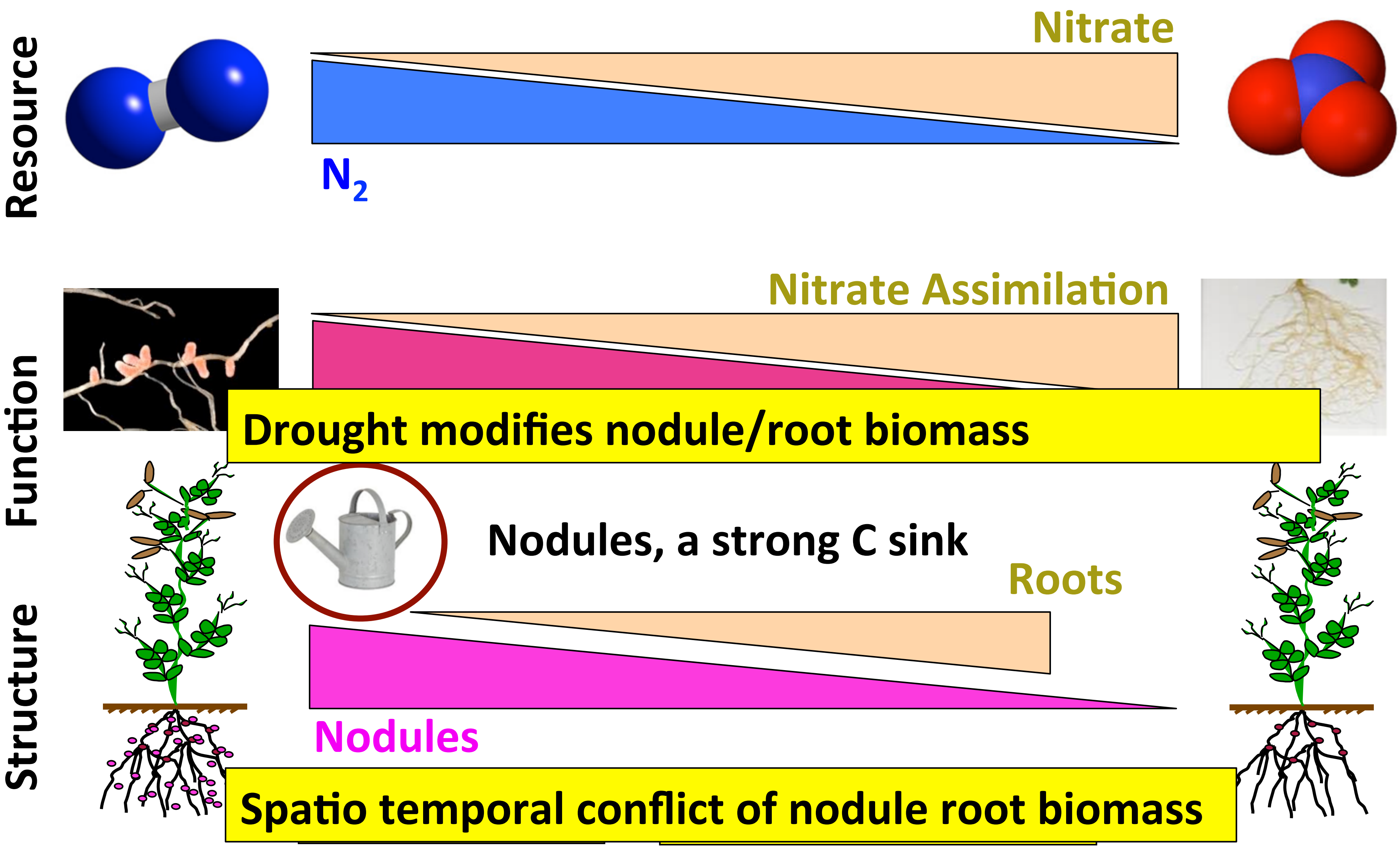


… detrimental for nutrient uptake

Always increase RLD in deeper layers?

Benjamin FCR 2006

Improving Root Systems Efficiency, rather than root biomass.



Salon et al 2001, Ag   Voisin et al 2003, AoB   Voisin et al 2003, JeB

Which root traits ?

Description »level 1" :

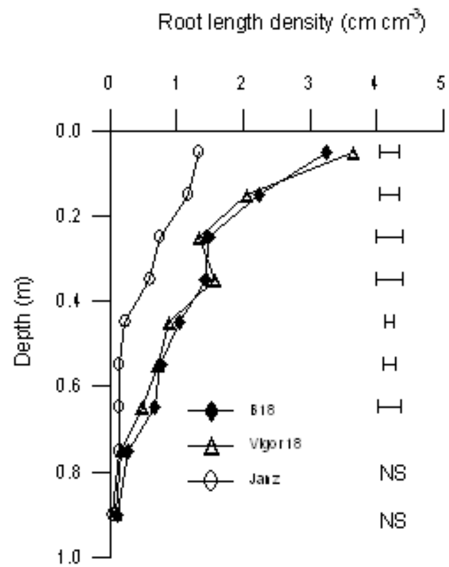
Root projected area
Nodule projected area
Nodule number
Total root length
Root prospection
Root Length Density
Root surface area to weight ratio
Root surface area to weight ratio

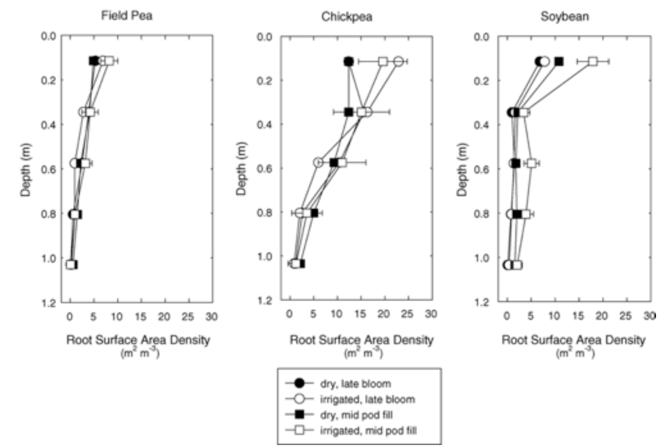
Description »level2" :

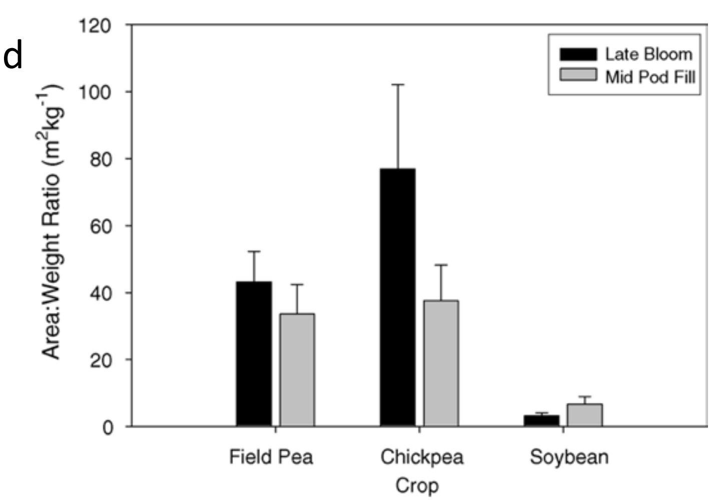
Main root length
Longest lateral root length
Number of lateral roots
Number of nodules on each root
Nodule positions (individual and by class) on all of the roots and
Apical diameter of roots

« Convention » :

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



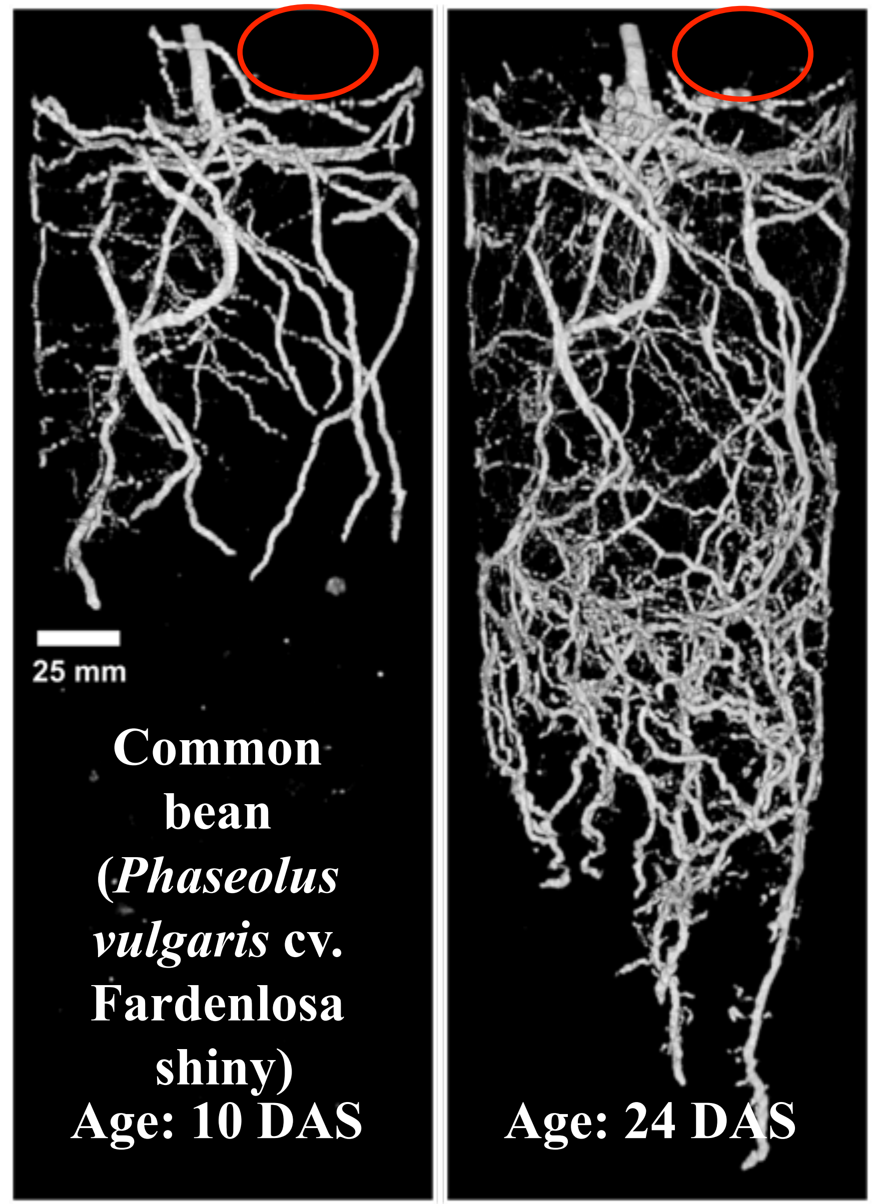




Which tools ?

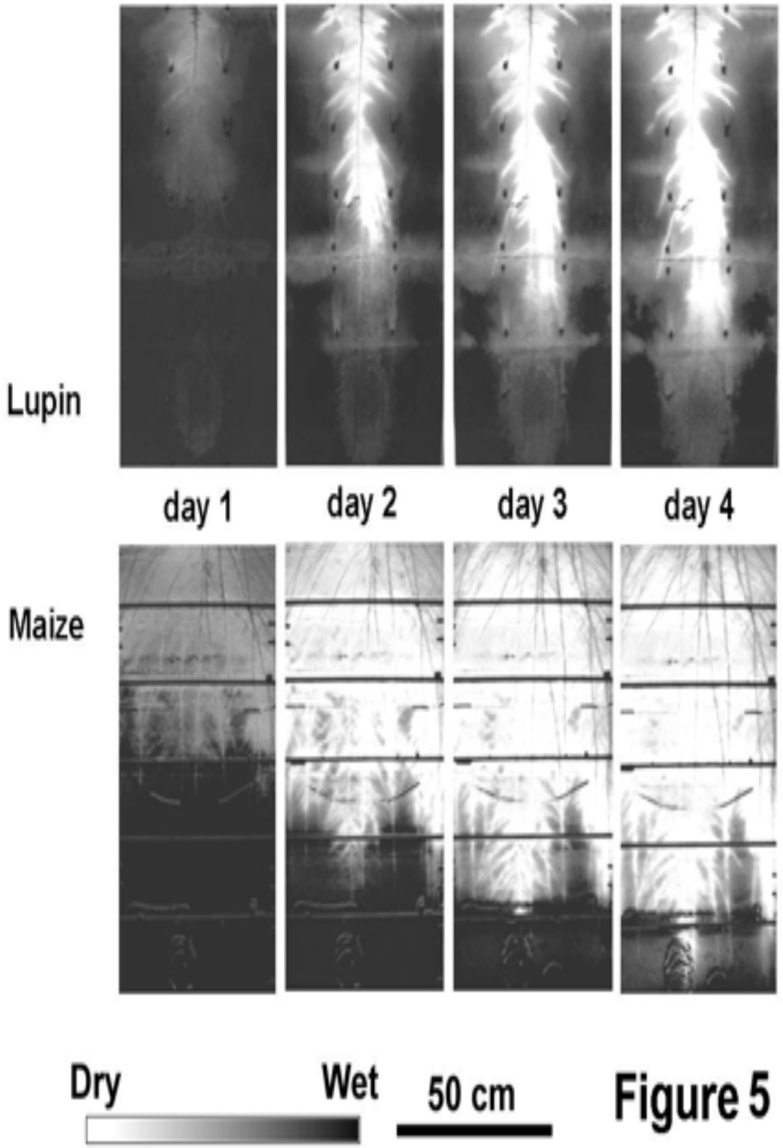
Magnetic Resonance Imaging

- 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

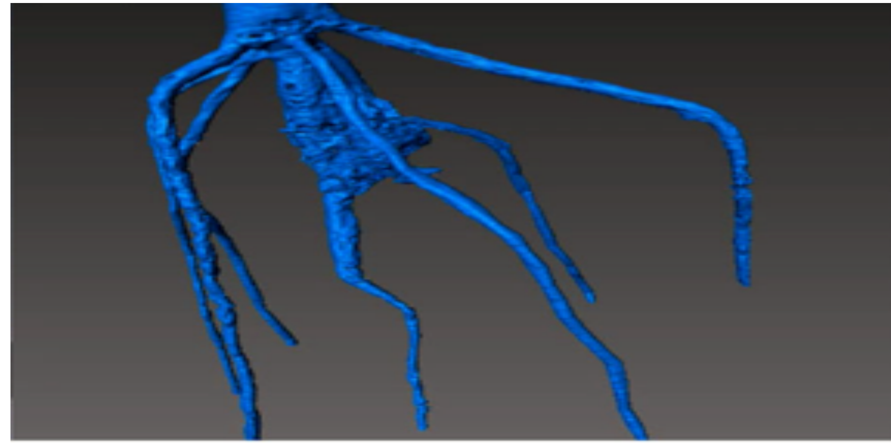


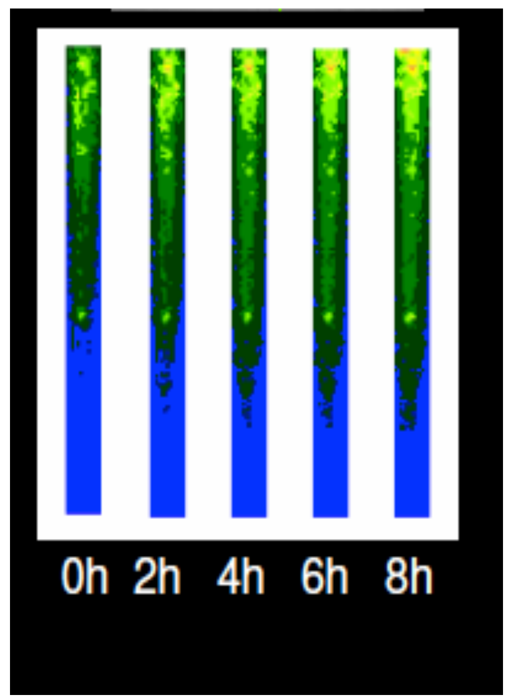
Courtesy R. Metzner,, C. Windt., ForschungszentrumJulich

Which tools ?

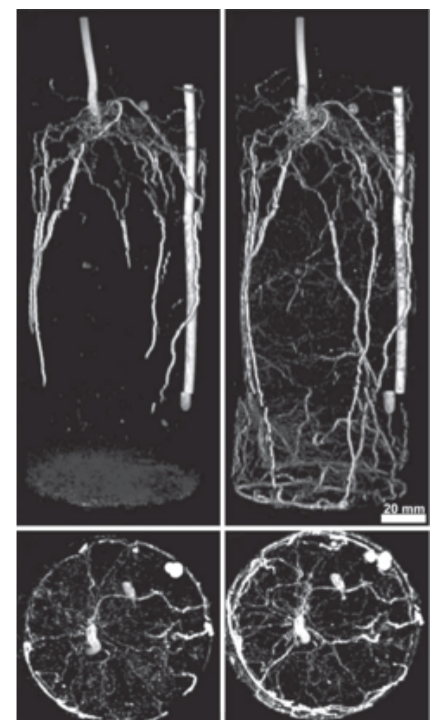


Lupin
day 1
day 2
day 3
day 4
Maize
Dry
Wet
50 cm
Figure 5





0h
2h
4h
6h
8h



20 mm

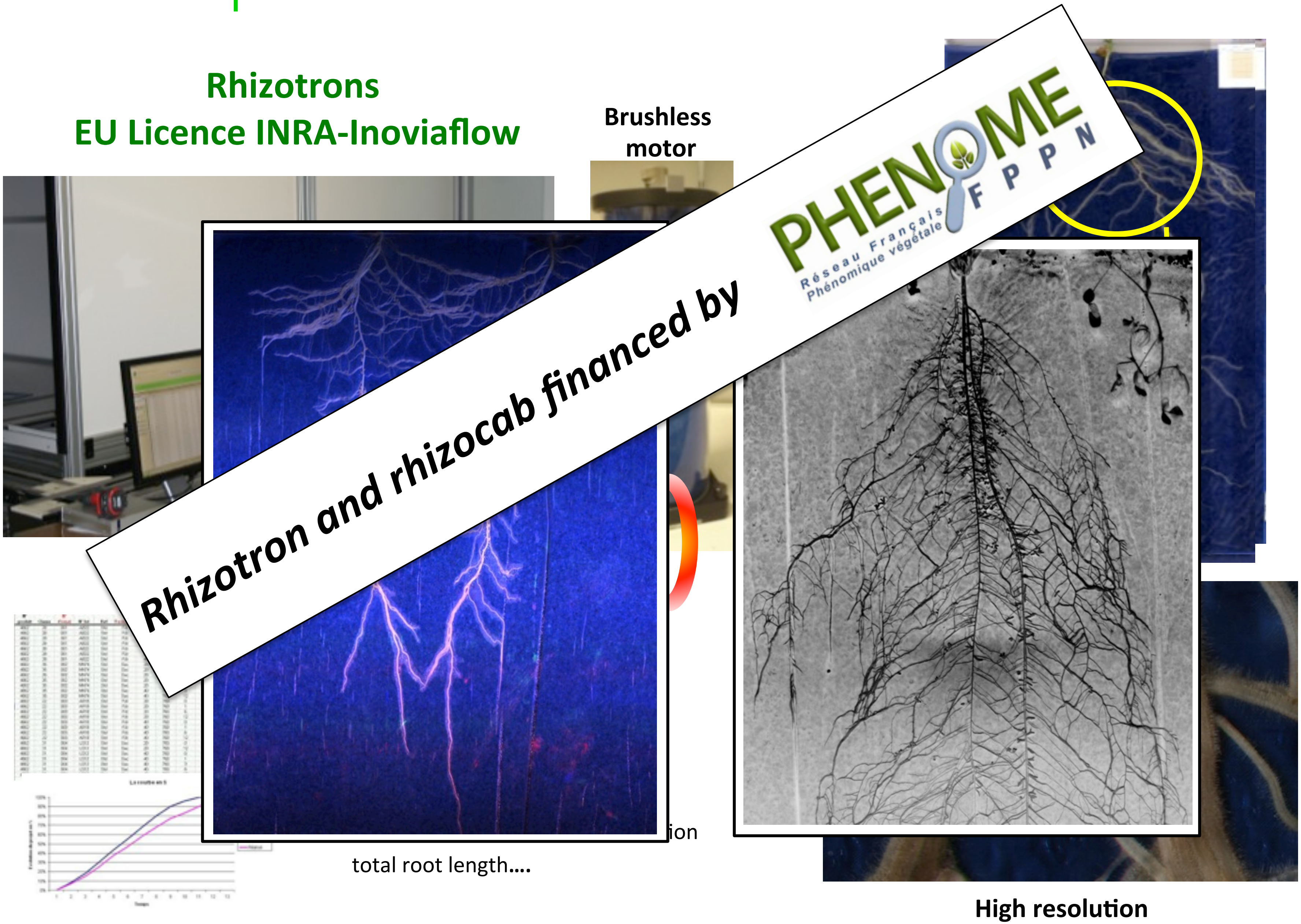
Pre requisites to access root architecture?

- 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

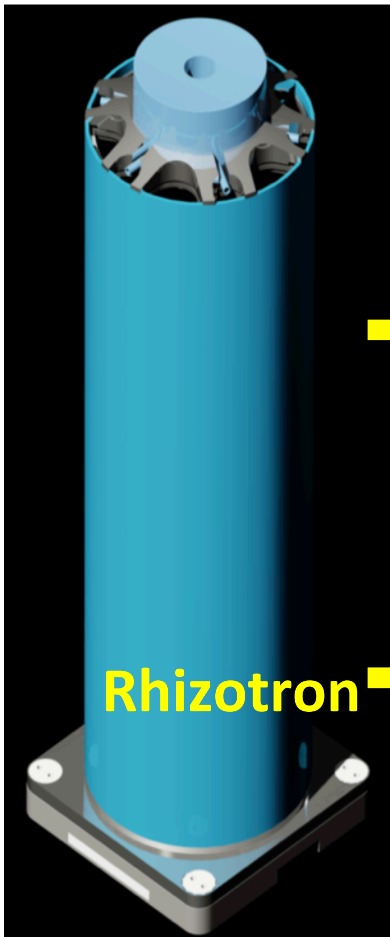
On plants of various species (not only model plants)

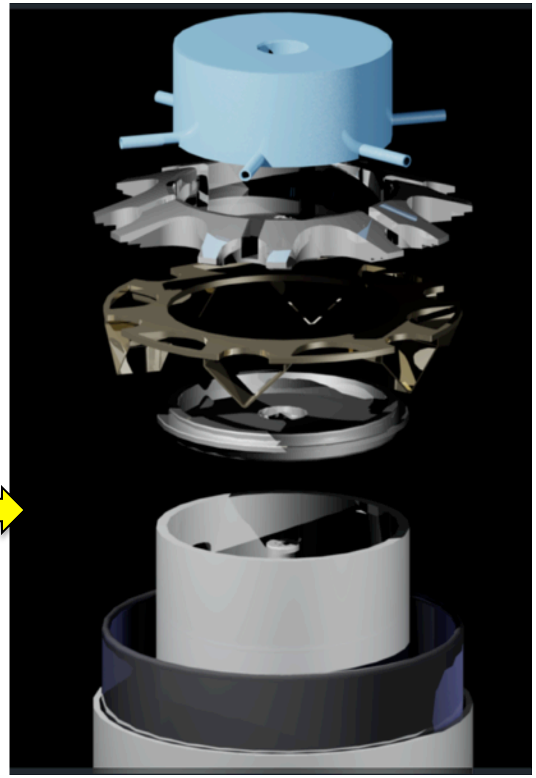
Rhizotrons…



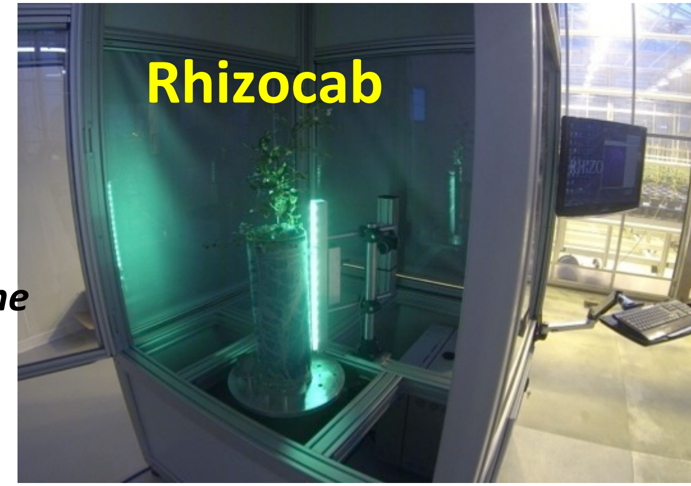
Rhizotrons
EU Licence INRA-Inoviaflow
Brushless motor
Rhizotron and rhizocab financed by
PHENOME
FPPN
Réseau Français Phénomique végétale
ion
total root length….
High resolution

Rhizotrons…and Rhizocab





Autonome



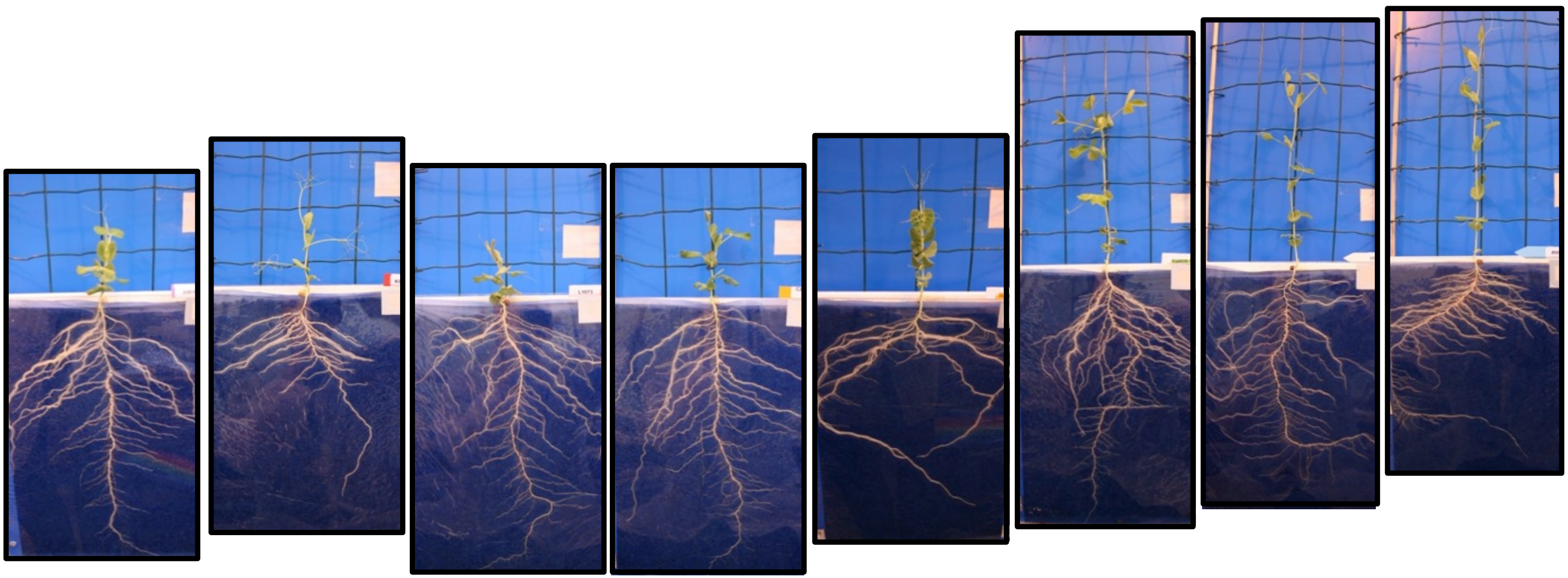
Technology transfert

Basis Adaptation

Phenotypic traits, examples

Pea core collection

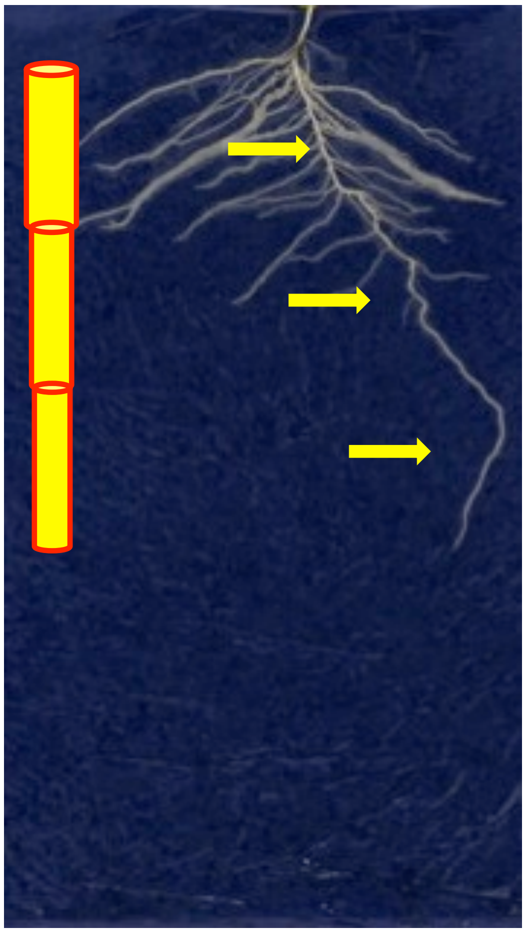
(coll. V Bourion, G Duc, J Burstin)

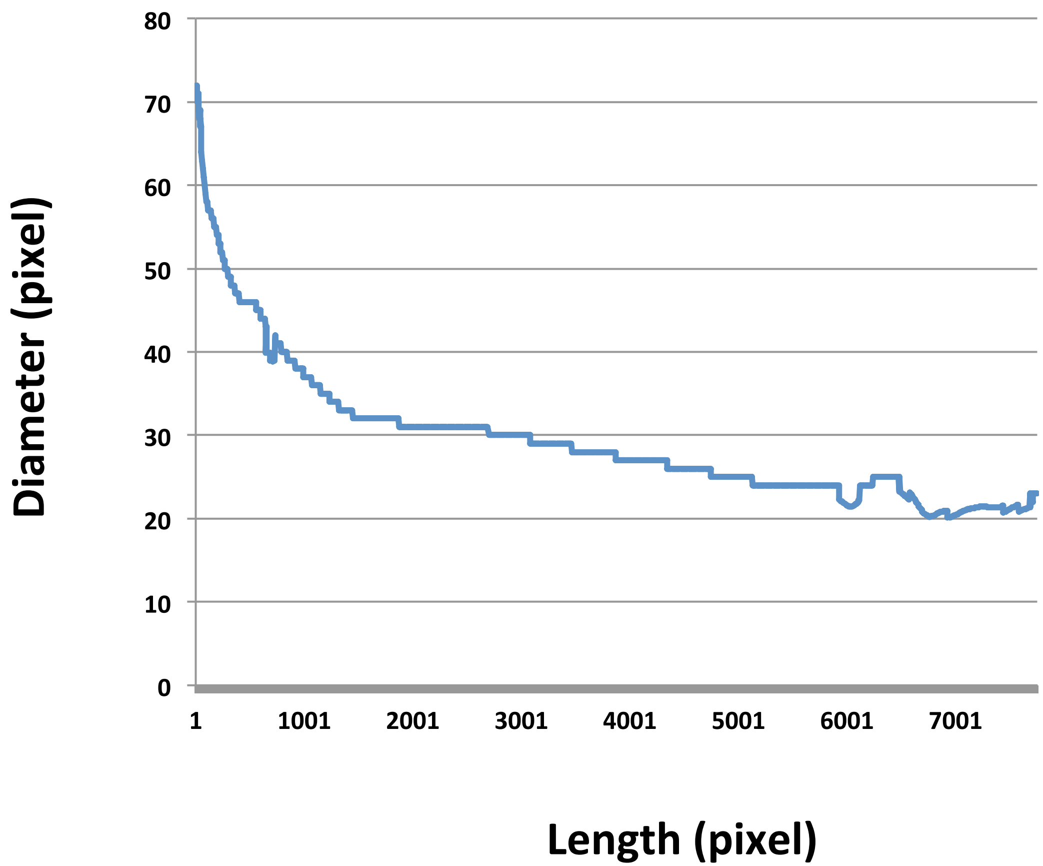


AMINO KAYANNE L1073 CAMEOR ISARD CUZCO LIVIOLETTA PI186093

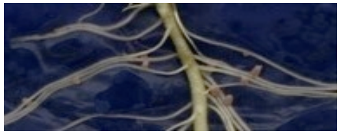
Phenotypic traits, examples

Roots: Length, Diameter



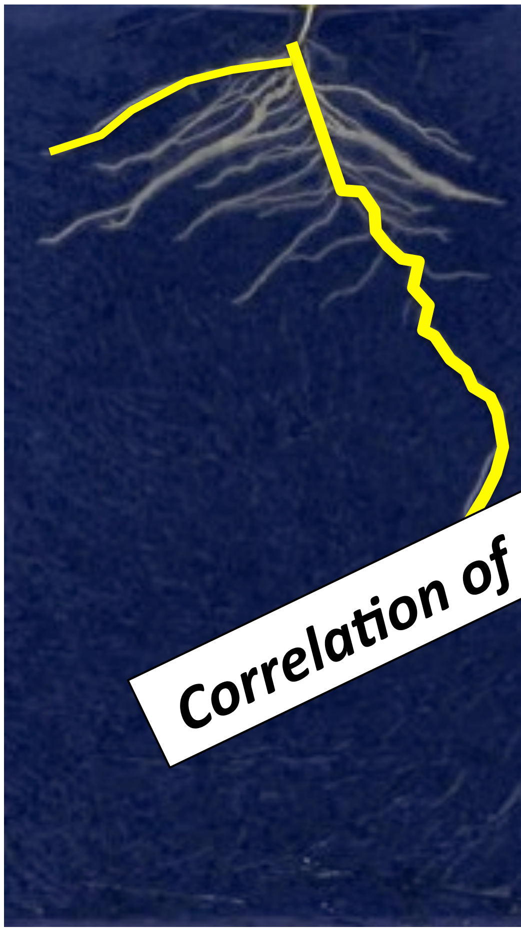


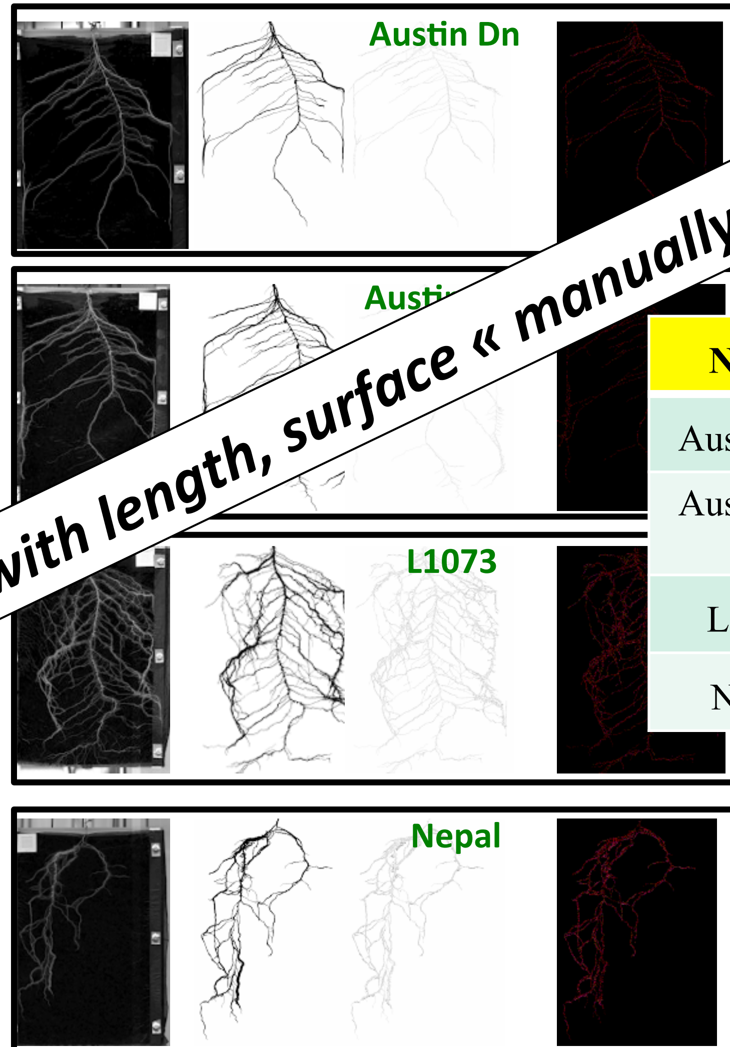
PhD Simeng Han (unpublished)



Phenotypic traits, examples

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

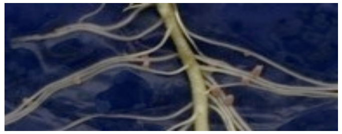




Correlation of 95% with length, surface « manually » evaluated

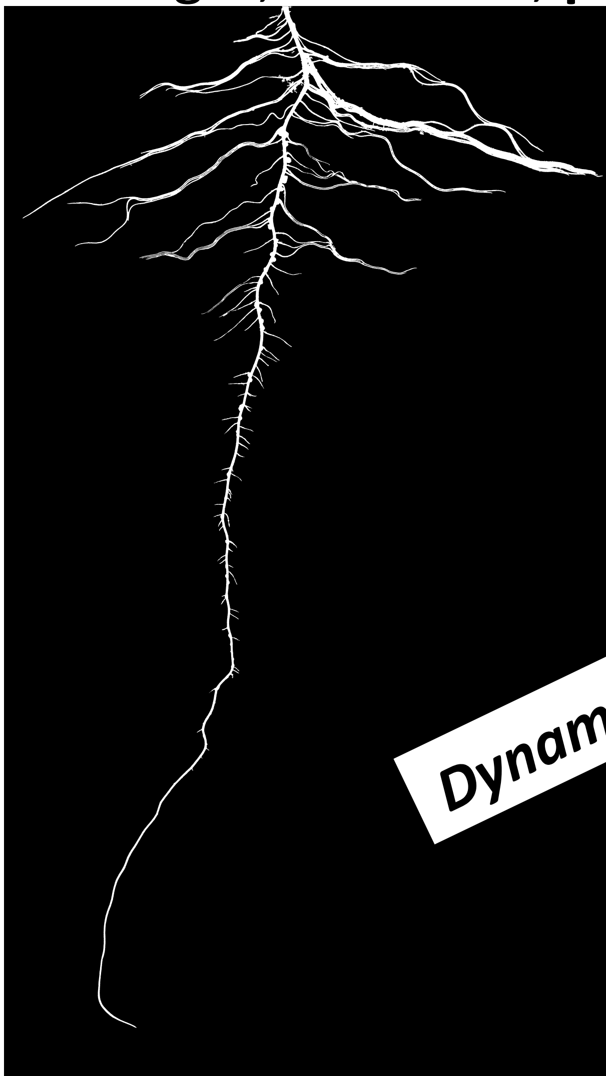
Name	Surface	Length
Austin Dn	38 cm^2	38cm
Austin Dn +5	58 cm^2	40cm
L1073	105 cm^2	40cm
Nepal	39 cm^2	35 cm

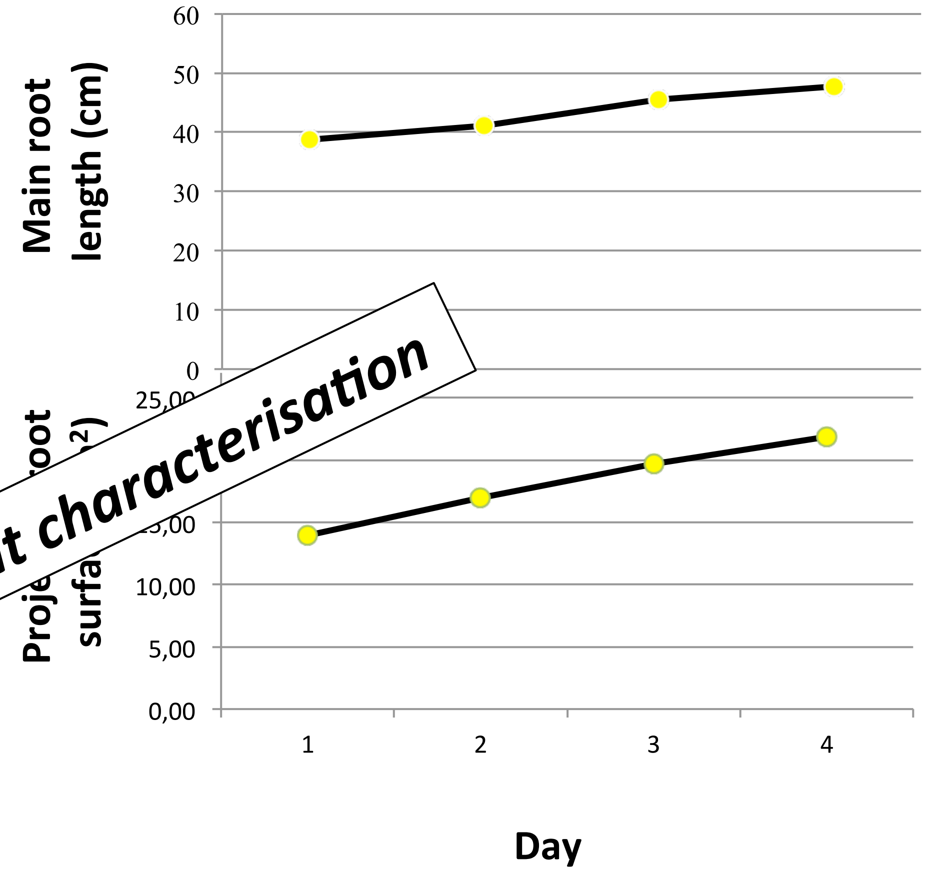
PhD Simeng Han (unpublished)



Phenotypic traits, examples

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

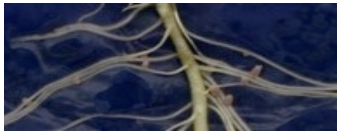




Dynamic trait characterisation

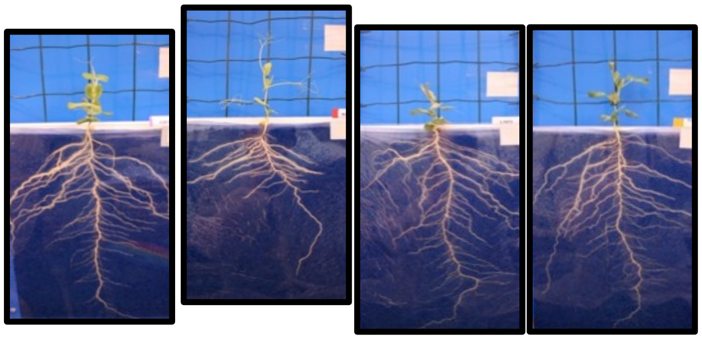
PhD Simeng Han (unpublished)

Phenotypic traits, examples

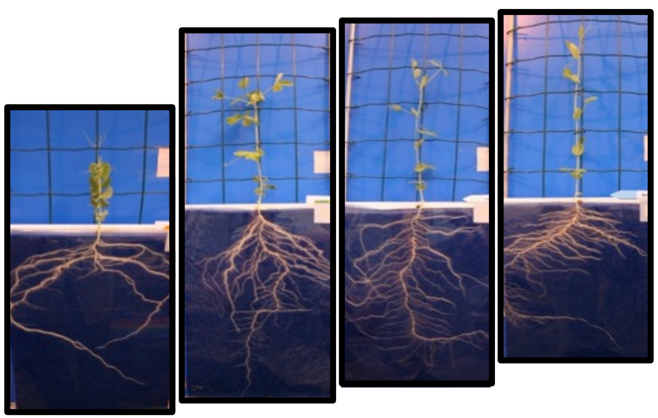


Roots: Length, Diameter, projected area, **estimated biomass**

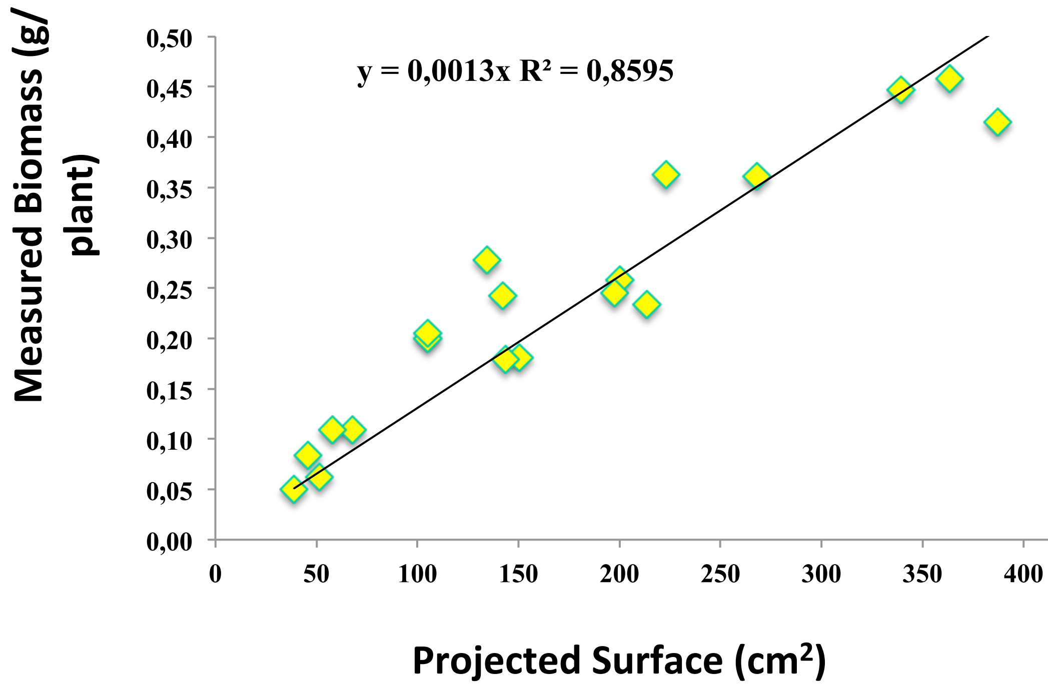
Pea core collection (coll. V Bourion, G Duc, J Burstin)



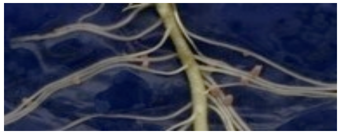
AMINO **KAYANNE** **L1073** **CAMEOR**



ISARD **CUZCO** **LIVIOLETTA** **PI186093**

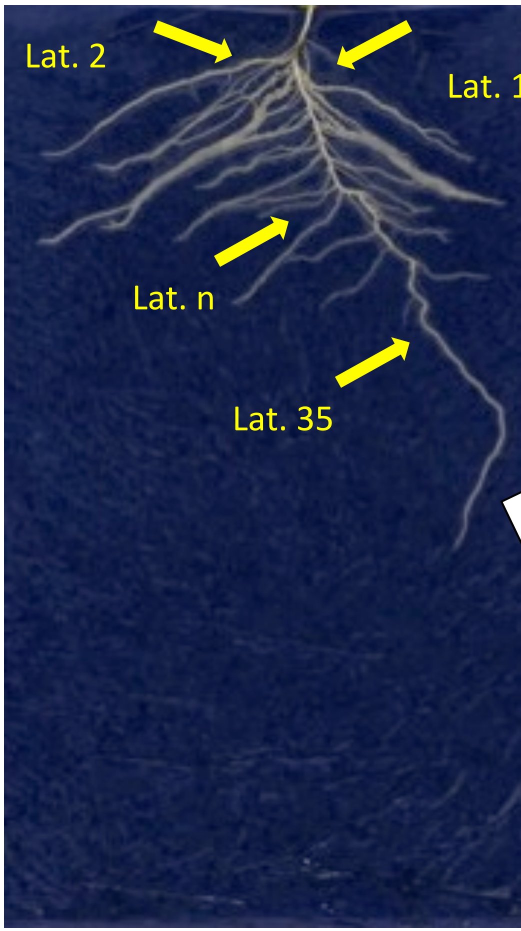


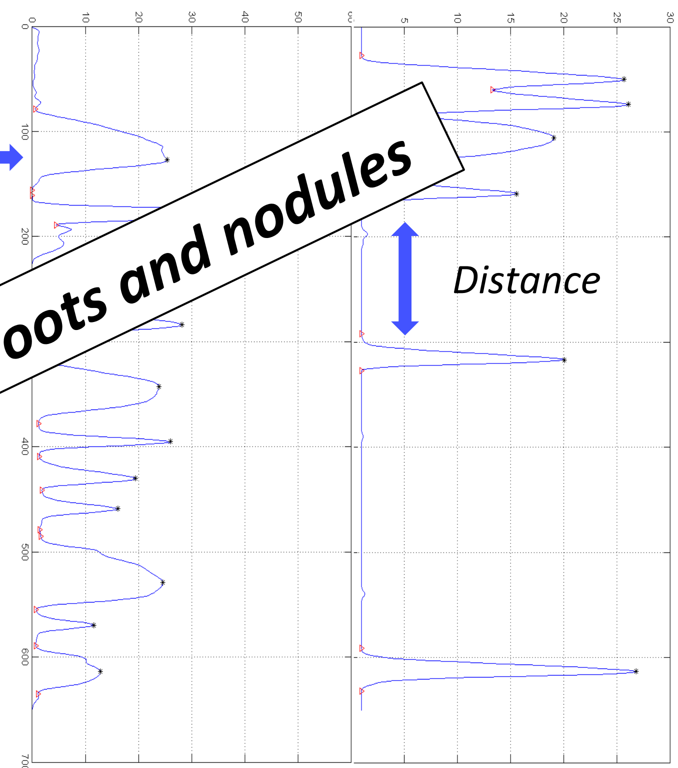
PhD Simeng Han (unpublished)



Phenotypic traits, examples

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





Localizes side roots and nodules

Events

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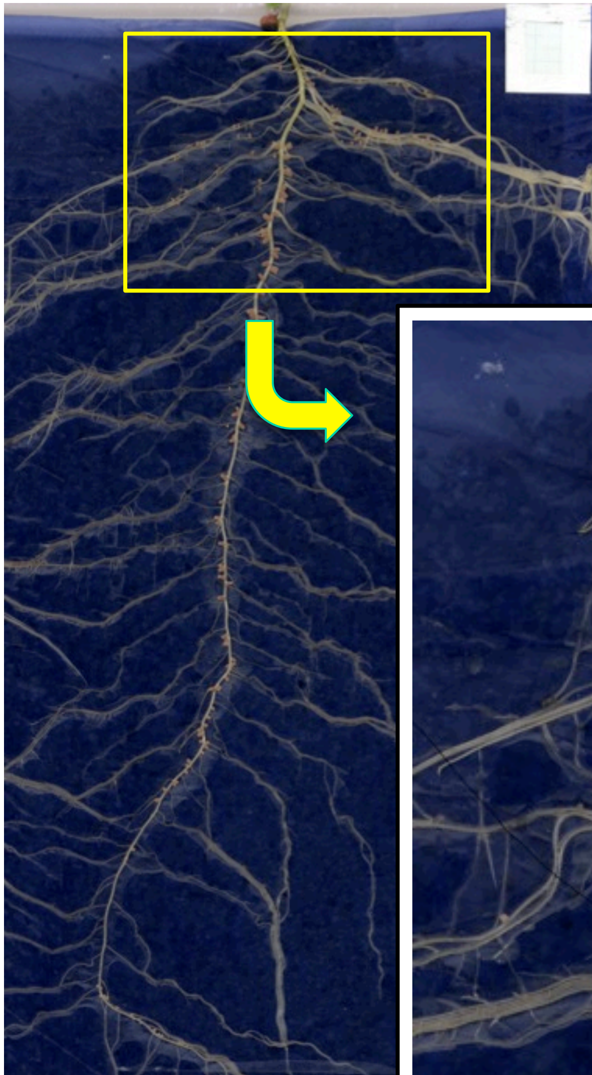
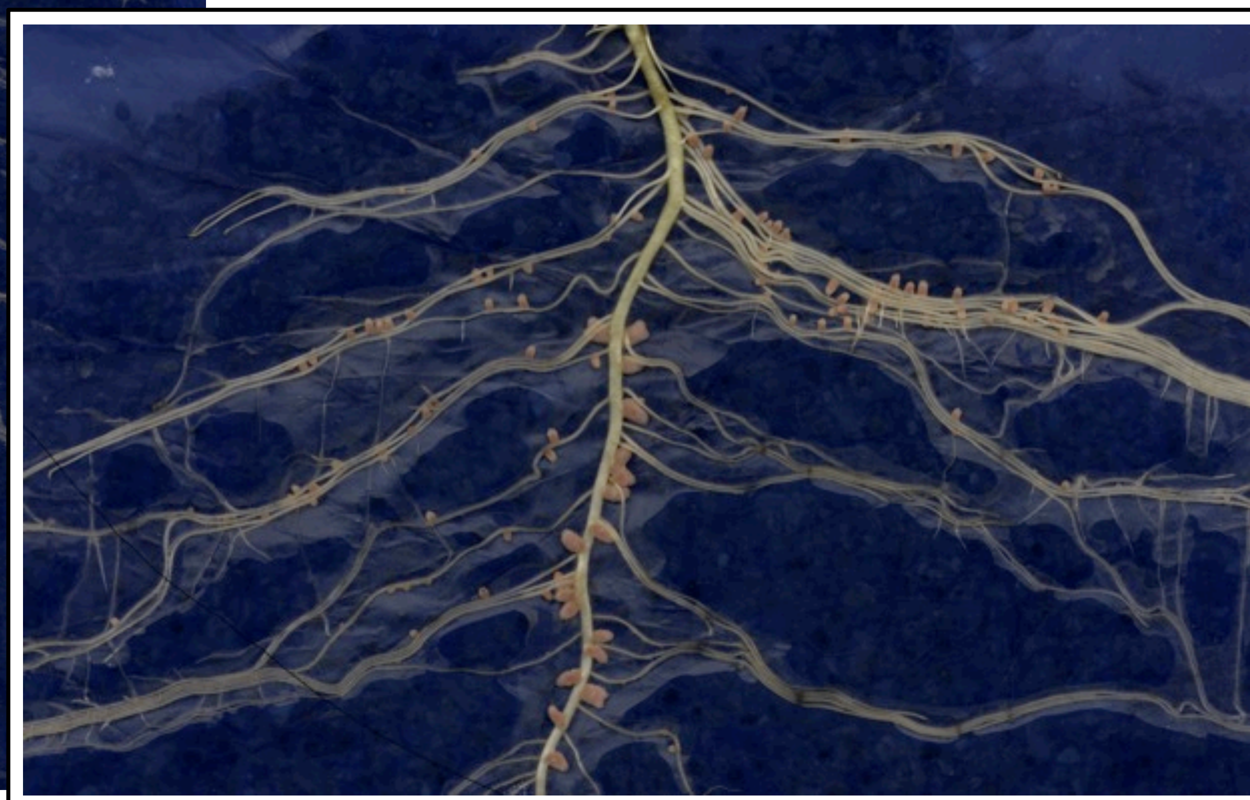
Phenotypic traits, examples

Nodules: Number, projected surface, position, color



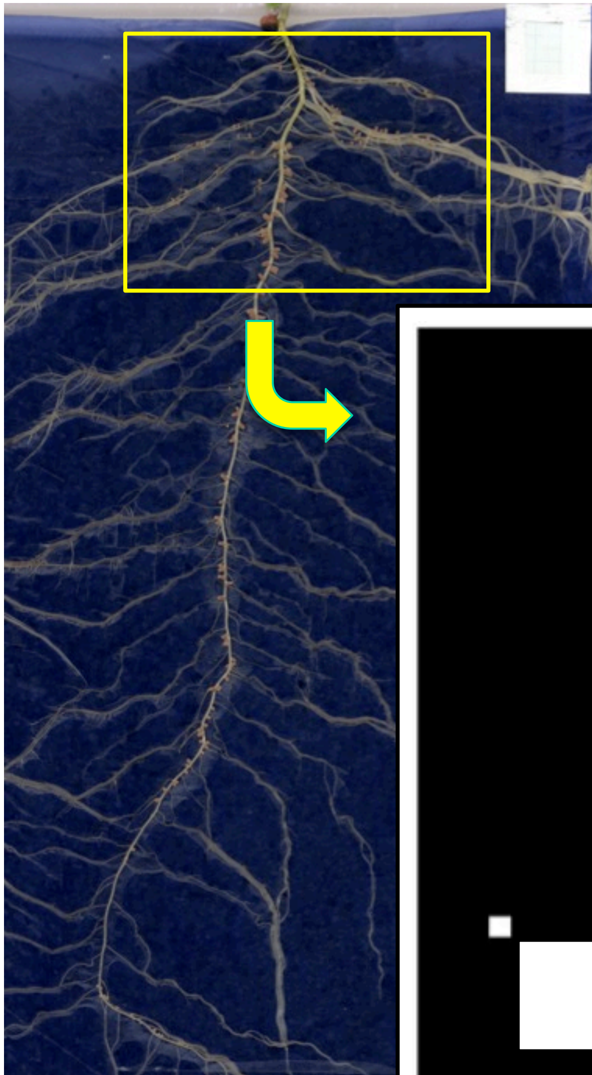
Focus on image



PhD Simeng Han (unpublished)

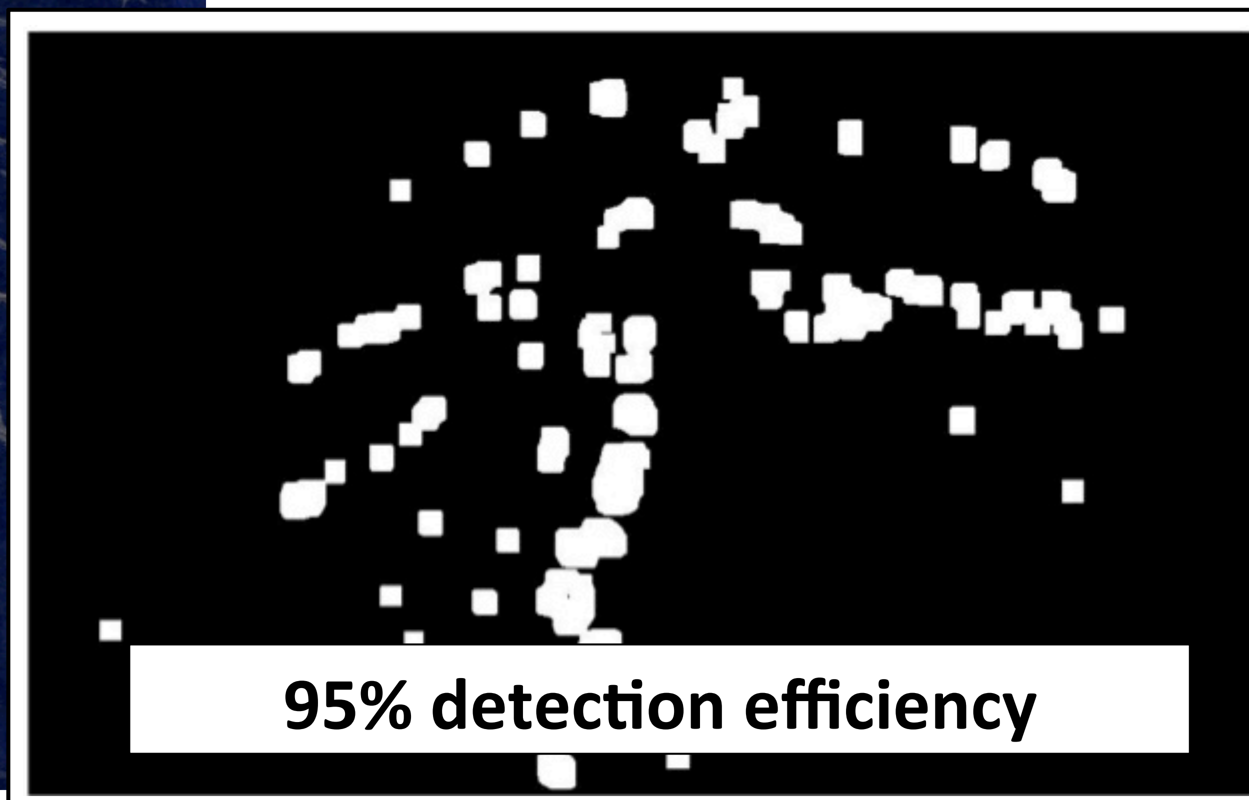
Phenotypic traits, examples

Nodules: Number, projected surface, position, color



Hybrid Spaces (color + texture)
(Cointault et al, 2008)

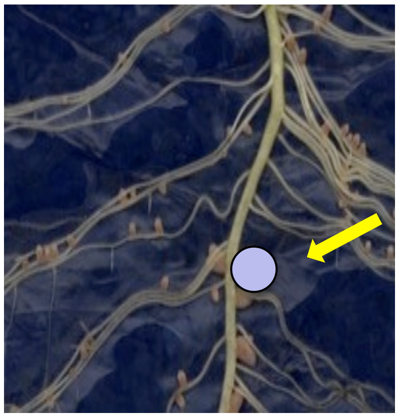
Nodules automatically detected

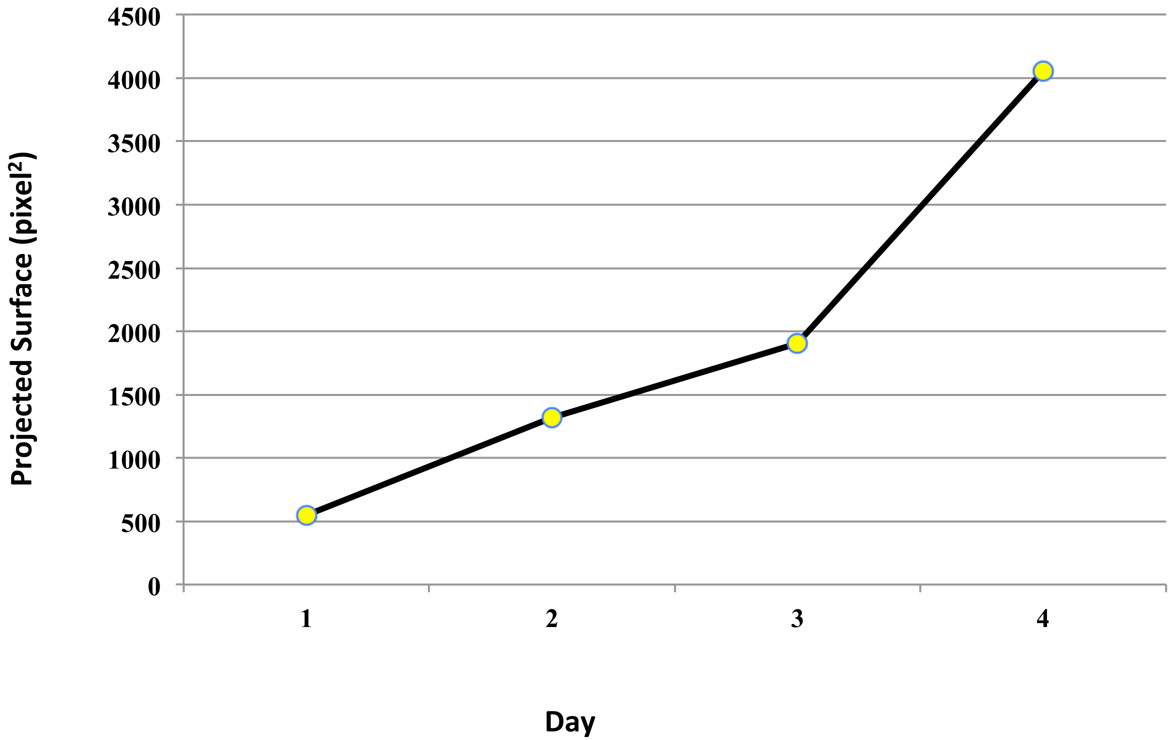


PhD Simeng Han (unpublished)

Phenotypic traits, examples

Nodules: Number, projected surface, position, color





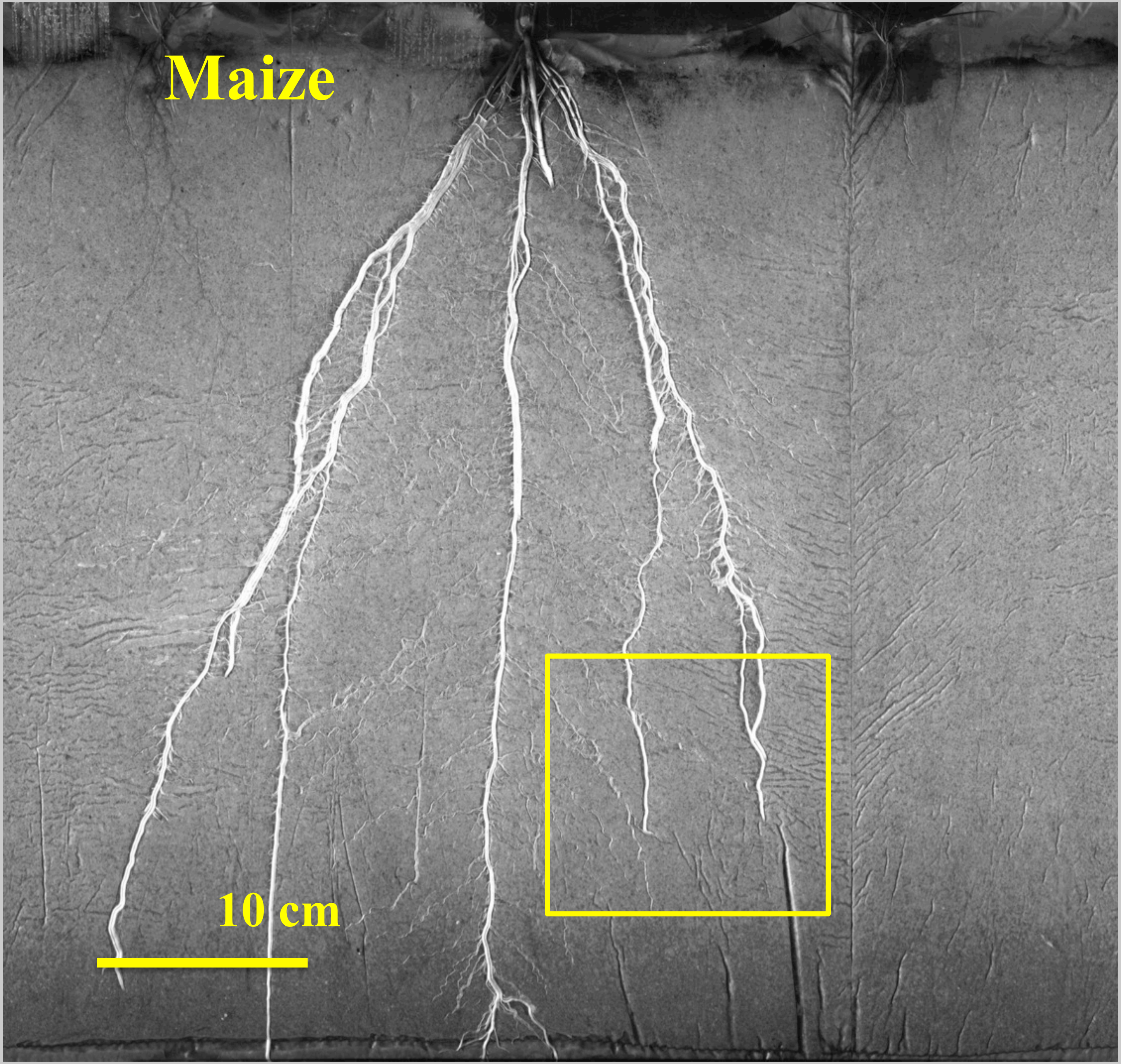
Follow nodule growth dynamic

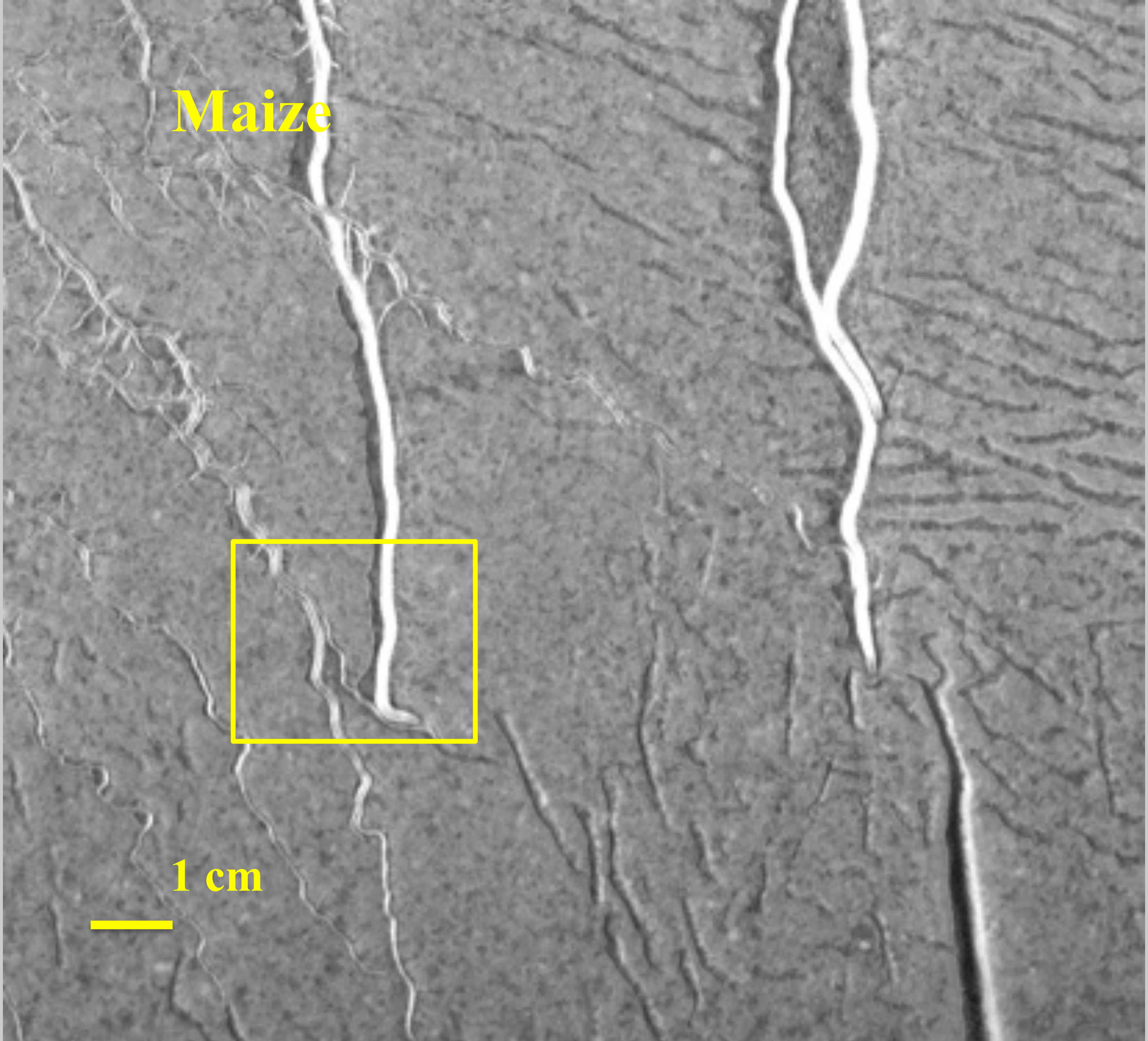
Ruffel et al. (2008), Plant Physiol. 146: 2020-2035.

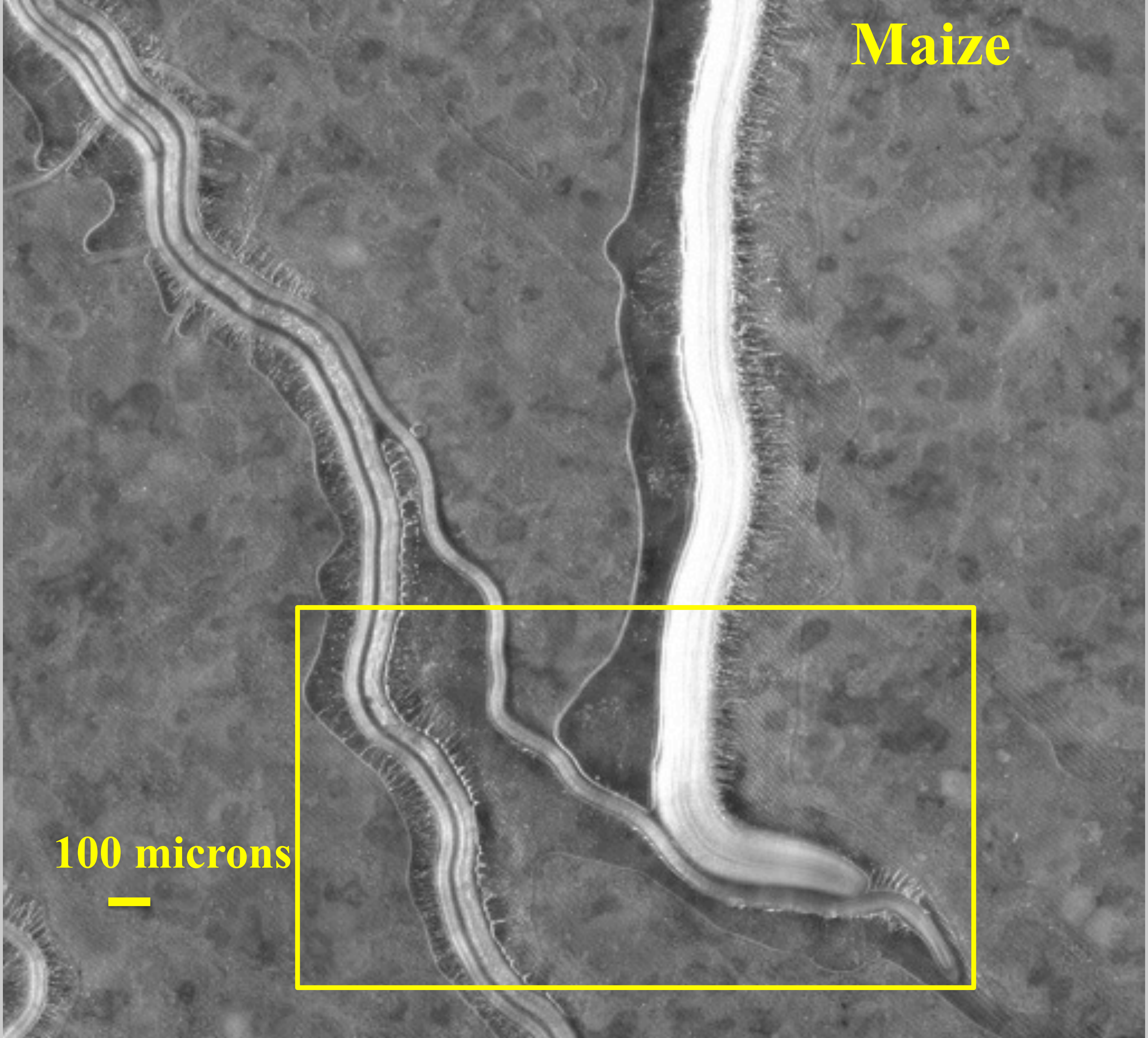
Salon et al. (2009), CRAS, 332 :1022-1033.

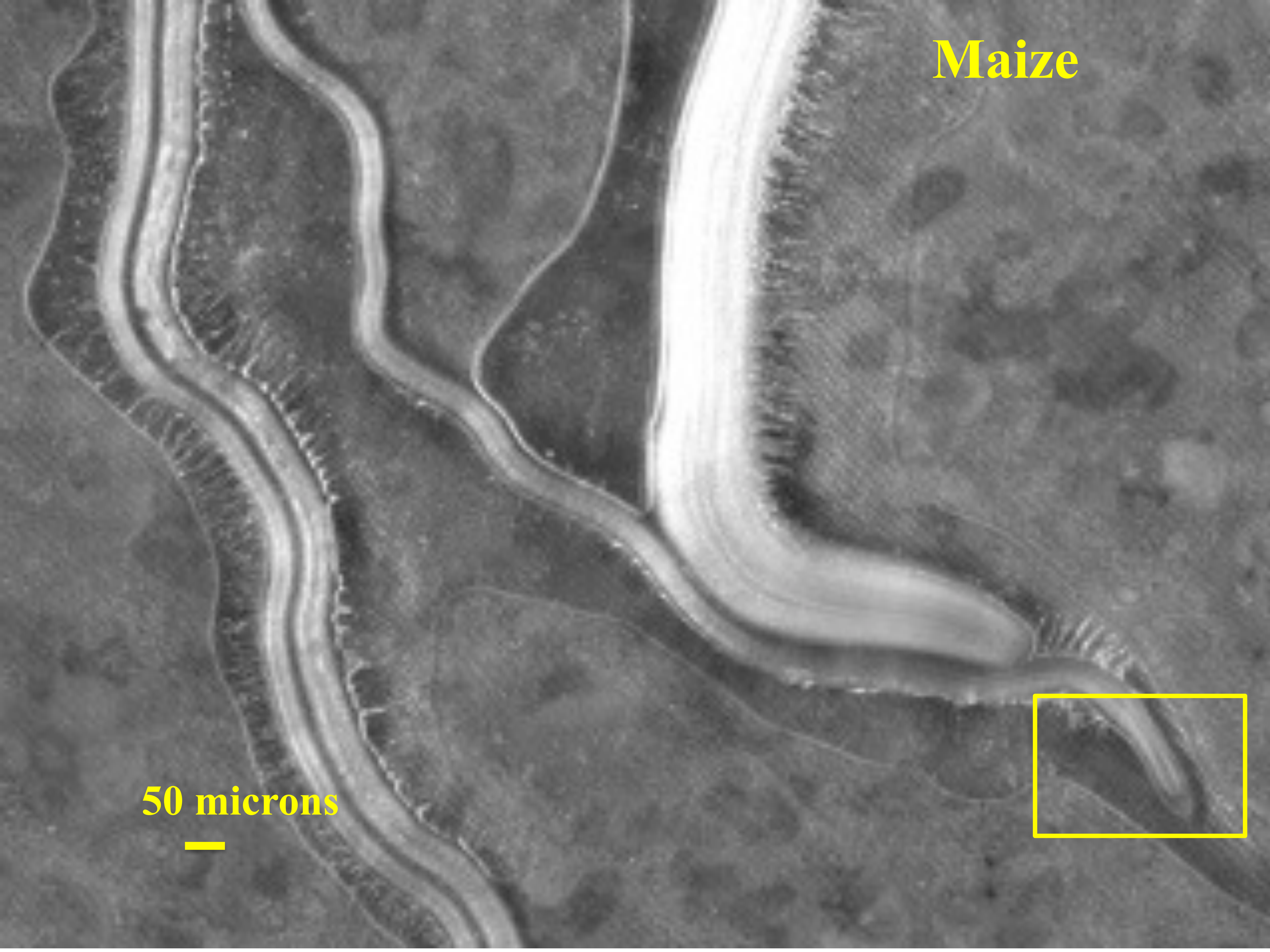
Jeudy et al. (2010), New Phytol, New Phytol., 185:817-828.

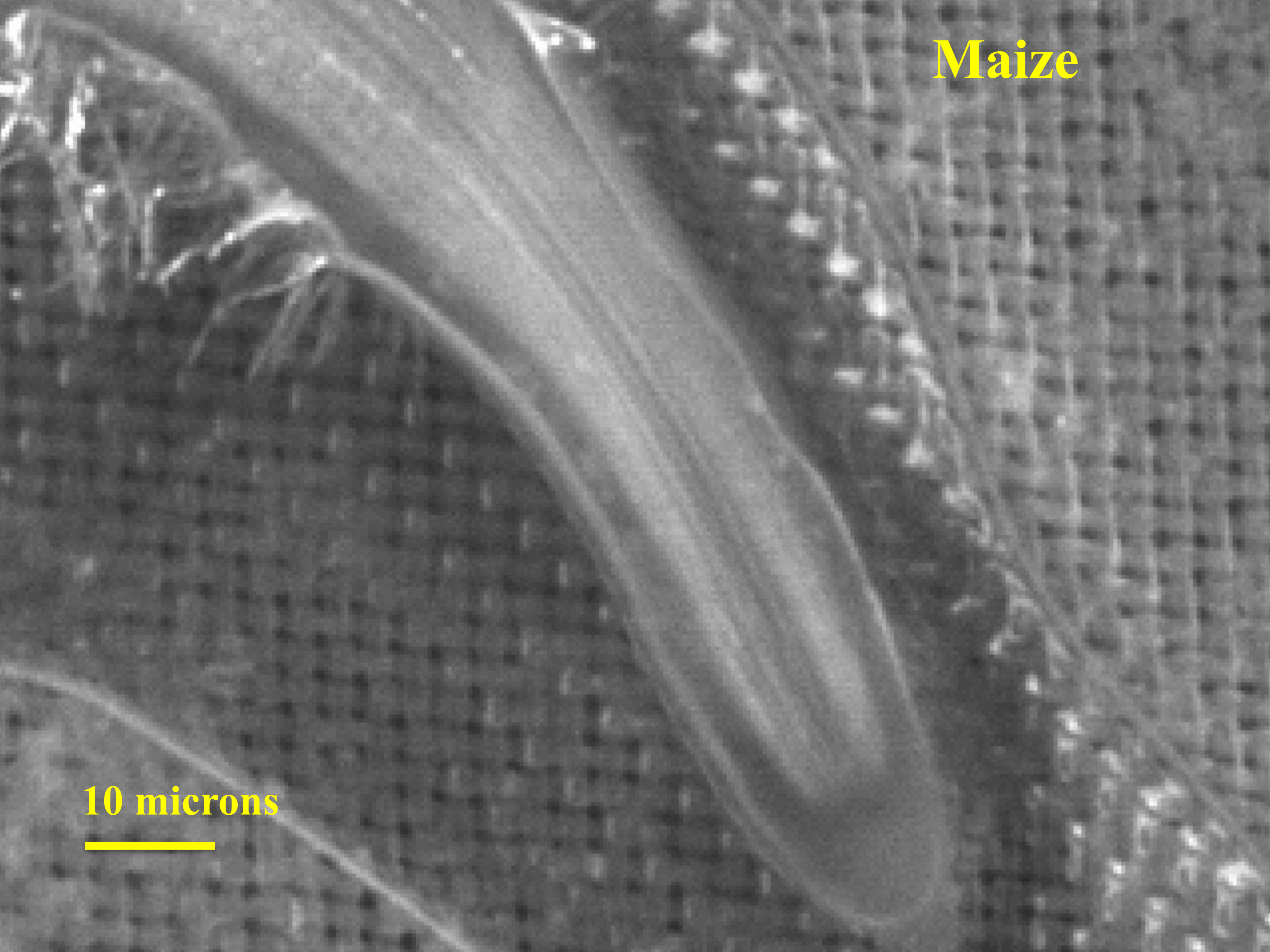
PhD Simeng Han (unpublished)

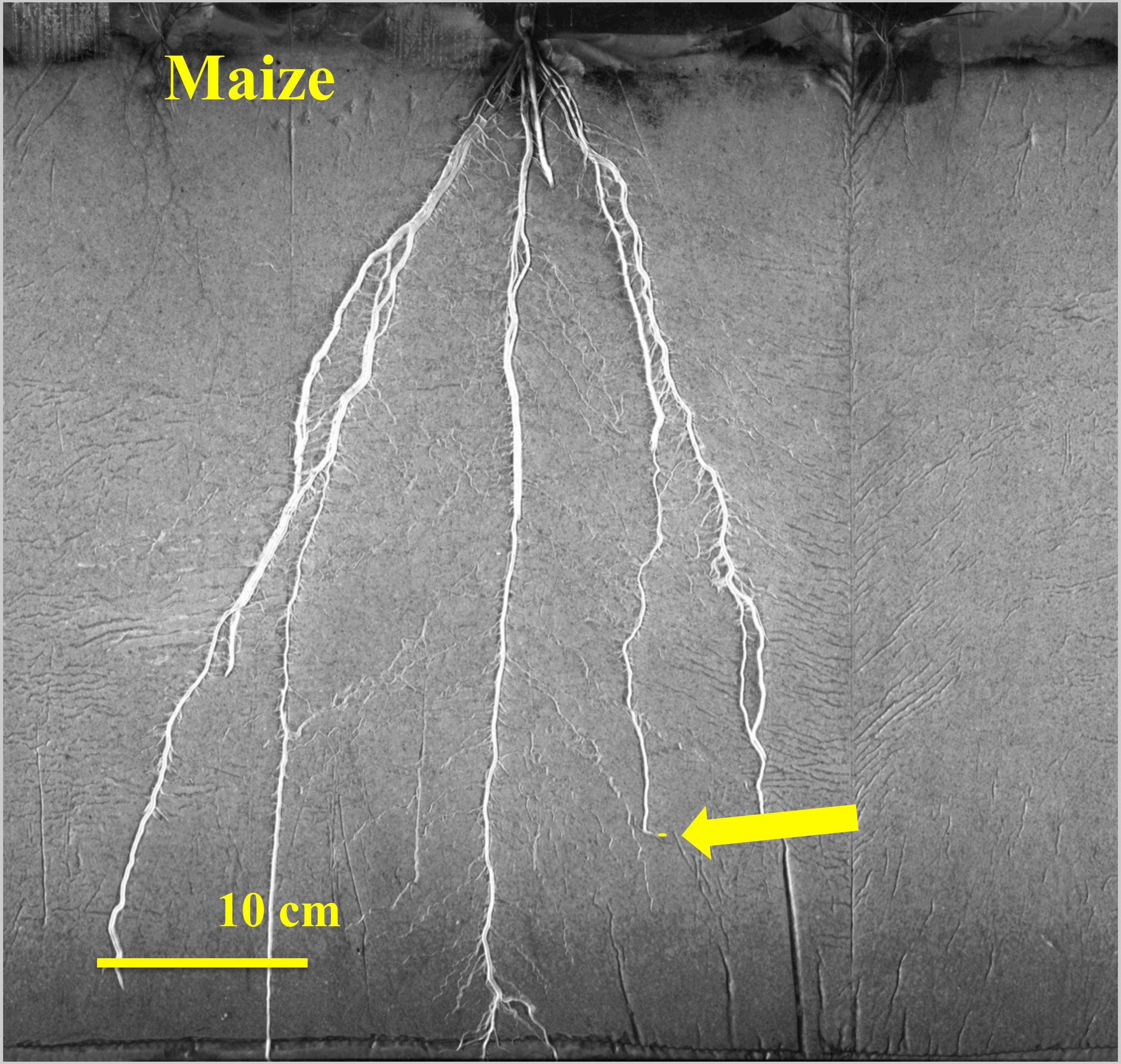

Maize
10 cm


Maize
1 cm


Maize
100 microns


Maize
50 microns


Maize
10 microns


Maize
10 cm

Conclusion, needs etc

- Measure exhaustively and accurately environmental factors, soil water (water sensors)
- Investigate possible causes of maintair PD (ABA regulation, leaf and root/restricted roo soil water capture ..)
- Think about plant relation with soil mi PR…)
- An integrated view of whole plant (tak tment in roots as regards to HI, metabolic costs
- Phenotyping in GH/CC => genotypic pa luated in field experiments.
- Working on drought tolerance implies l conditions and crop management (Tardieu JEB, 20
- 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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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.

Introduction

The scientific community has a large responsibility when it announces spectacular results on the drought tolerance of plants, a topic with direct consequences on the food security of millions of people. Agriculture is facing a declining water availability, a reduction in arable land, and strongly increasing demand for harvested products. Predictions of climate change indicate an increased variability of rainfall in the next 40 years and an increased risk of high temperature (IPCC, 2007; Battisti and Naylor, 2009), that will cause appreciable limitations of yield (Tebaldi and Lobell, 2008; Brisson *et al.*, 2010). Food security requires investments in this domain, in particular with new genotypes that can at least maintain an acceptable productivity under reduced water availability. During recent decades, an appreciable part of the academic effort and the most spectacular results have been associated with the identification of single genes that would confer drought tolerance, mostly in controlled conditions. Surprisingly, these results have been obtained via a large variety of processes and mechanisms, for example, cell protection mechanisms (Garg *et al.*, 2002; Castiglioni *et al.*, 2008), detoxification of reactive oxygen species (Sunkar *et al.*, 2003; Yang *et al.*, 2007), hormone balance (Iuchi *et al.*, 2001; Rivero *et al.*, 2007) or the manipulation of a transcription factor (Nelson *et al.*, 2007; Oh *et al.*, 2009).

Taken together, these results may either suggest that individual mechanisms acting on very different pathways can bring a spectacular increase in drought tolerance, or that drought tolerance is such a vague concept that very different results can fit into it. It is clear that plant survival and plant performance under water deficit depend on different mechanisms, quantitative trait loci (QTL), and sets of genes (Tardieu, 1996; Skirycz *et al.*, 2011), although they are often grouped under the same concept. Furthermore, an allele associated with a given gene or QTL have different effects depending on environmental scenarios (Chenu *et al.* 2009). A given gene polymorphism may therefore bring spectacular results in a given drought scenario but not in others. In a provocative way, one can argue that any trait-related gene polymorphism can bring drought tolerance, provided that the appropriate scenario to demonstrate this tolerance is identified by model-based reverse engineering.

The most striking example of a contradictory effect is the duration of the plant cycle, largely determined by genes affecting flowering time. Simple computer simulations and agronomic experience show that a long cycle duration tends to improve yield under favourable conditions because it increases the amount of intercepted light (Monteith, 1977), but that it

Related projects where GEAPSI-UMR Agroécologie INRA is involved

PHENOME – Réseau Français Phénomique végétale – FPPN: Candidate genes for drought stress response in legumes.

ABSTRESS – improving the resistance of legume crops to combined Abiotic and Biotic STRESS: HT phenotyping

LEGATO: Combined heat and drought stress

arimnet: Mediterranean network of field experimentation, data/experience

And of course… European Plant Phenotyping Network EPPN

Thanks!!

Drought wizards

François TARDIEU

Marion PRUDENT

Platform(s) management

Llorenz CABRERA

Céline BERNARD

Rhizotrons, Rhizocab

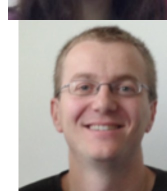
Christian JEUDY

Christophe BAUSSARD

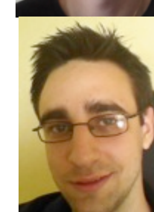
Image analysis

Simeng HAN

Frédéric COINTAULT



Mickael LAMBOEUF




Thank you for your attention!