University of Natural Resources and Life Sciences, Vienna
Department of Crop Sciences

The roots of water and nutrient (P) efficiency

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Contents

- What is water and nutrient (P) efficiency?
- Why is water and nutrient (P) efficiency important?
- How can water and nutrient (P) efficiency be improved - the role of roots?

Prologue:
Resource use efficiencies – use with care!

$$\textbf{Resource use efficiency} = \frac{\textbf{Desired output}}{\textbf{Limited resource input}}$$

- Desired output in agronomy is usually yield.
- Limited resources are water, nutrients, soil (radiation?).
- Increase can be due to (i) more output, (ii) less input or (iii) both.

Resource use efficiency can be partitioned

$$\textbf{Acquisition efficiency} = \frac{\textbf{Resource uptake}}{\textbf{Limited resource supply}}$$

$$\textbf{Utilization efficiency} = \frac{\textbf{Output}}{\textbf{Resource uptake}}$$

- **Acquisition:**
  mainly physico-chemical; roots critical for soil resources
- **Utilization:**
  mainly physiological; critical for water, N (less for P)

Definitions of Water Use Efficiency (WUE)

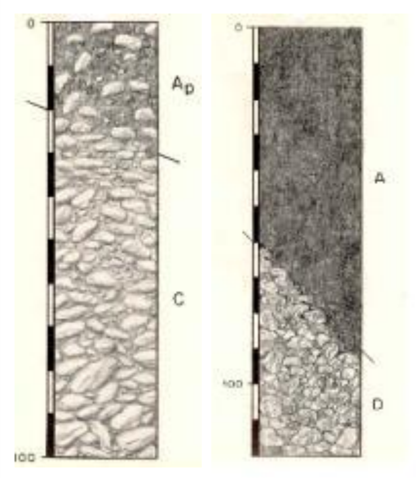
Term	Definition	Scale	Reference
Gas exchange WUE measures			
Intrinsic WUE	$WUE_{\mathrm{int}} = \frac{A}{g_s}$	Stomata	Jones (2004a)
Instantaneous WUE	$WUE_{inst} = \frac{A}{T}$	Leaf	Polley (2002)
Integrative WUE measures			
Transpiration efficiency	$TE = \frac{M}{T}$	Biomass	Gregory (2004)
Water productivity	$WP = \frac{Yield}{T}$	Yield	Pereira et al. (2002)
Irrigation WUE	$WUE_I = \frac{Yield}{Irrigation}$	Yield	Howell (2001)

WUE water use efficiency, *TE* transpiration efficiency, *WP* water productivity, *A* assimilation, g_s stomatal conductance, *T* transpiration, *M* biomass

(Raza et al. 2012)

Environmental impact

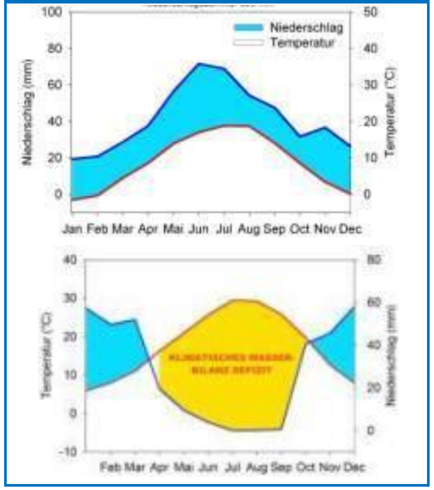
Soil



Shallow and light

Soils with a shallow root zone and/or high sand content have a low water holding capacity and are quickly depleted.

Climate



Timing, intensity and duration of drought

A homogeneous rainfall distribution during the vegetation period with high frequency in summer and during critical growth stages is essential.

Soils with high water holding capacity and climates with low proportion of rainfall during the growing season are **storage driven**. Most important for yield is to **secure off-season moisture** for the main crop.

Soils with low storage capactiv and high proportion of rainfall during the growing season are **supply driven**. All measures for a **productive use of incoming rainfall** are essential for yield.

Mechanisms of drought resistance according to Levitt (1980)

Drought resistance

Avoidance

MAXIMIZE UPTAKE

- Rooting depth
- Shoot:root ratio
- Osmotic adjustment

Optimizing water uptake essential for yield security; compatible with hight yield potential

MINIMIZE LOSSES

- Stomata closure
- Leaf rolling
- Waxy layers

Conservative water use; might be linked to lower yield potential

Escape

- Early ripening
- Carbohydrate remobilization from stem
- Developmental plasticity

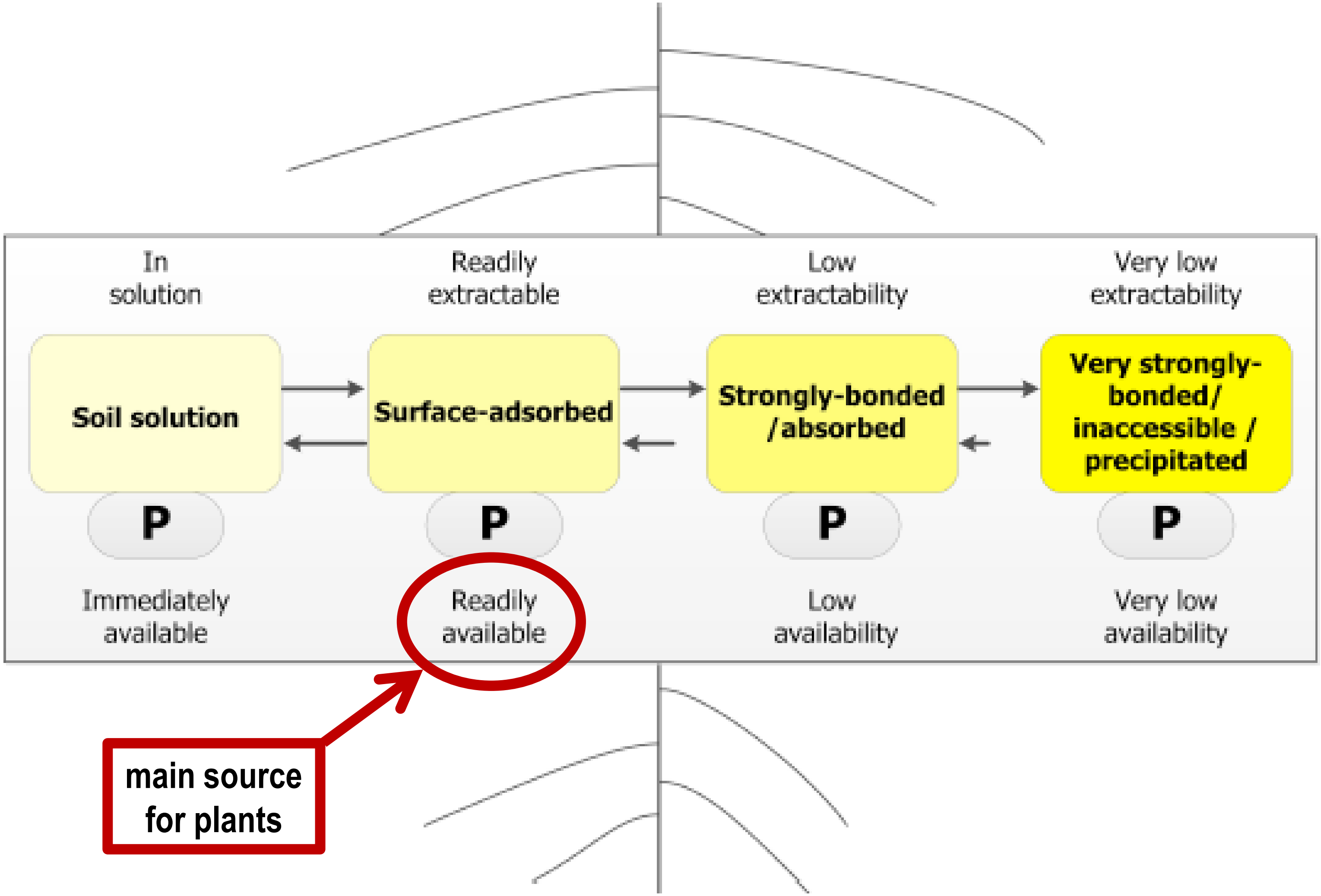
Reduced growing time; in case of optimum growing conditions limitation of yield

Tolerance

- Dehydration tolerance
- Membrane stability
- Succulence

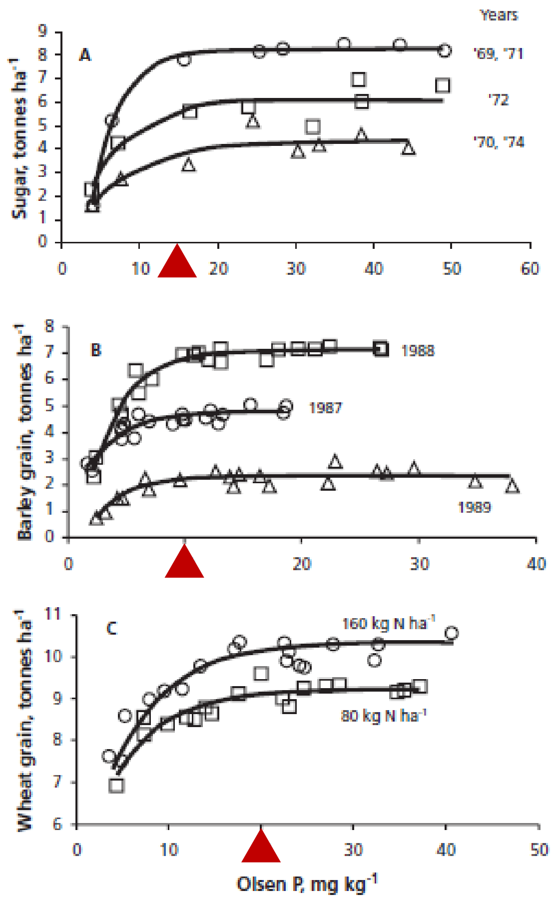
Survival mechanisms for natural vegetation; relevant only under extreme drought conditions

Conceptual pools of inorganic phosphorus in soil
(adapted from Syers et al. 2008)



Critical P level concept according to Syers et al. 2008

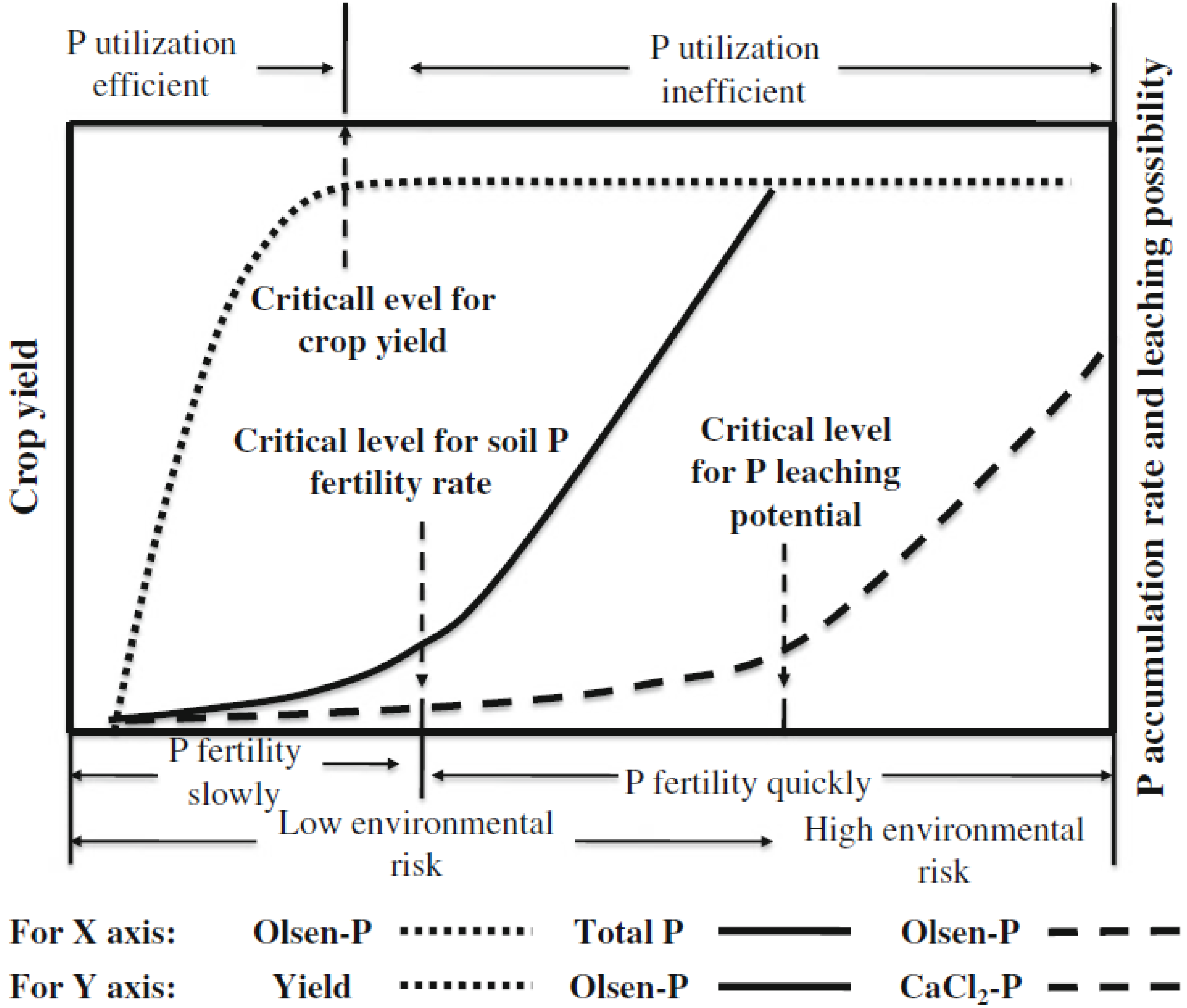
FIGURE 4
Response to Olsen P of sugar beet, barley and winter wheat grown on different soils at three sites in the southeast of the United Kingdom



Source: Adapted from Johnston (2005)

▲ Critical P level

Extended Critical P concept according to Bai et al. 2013



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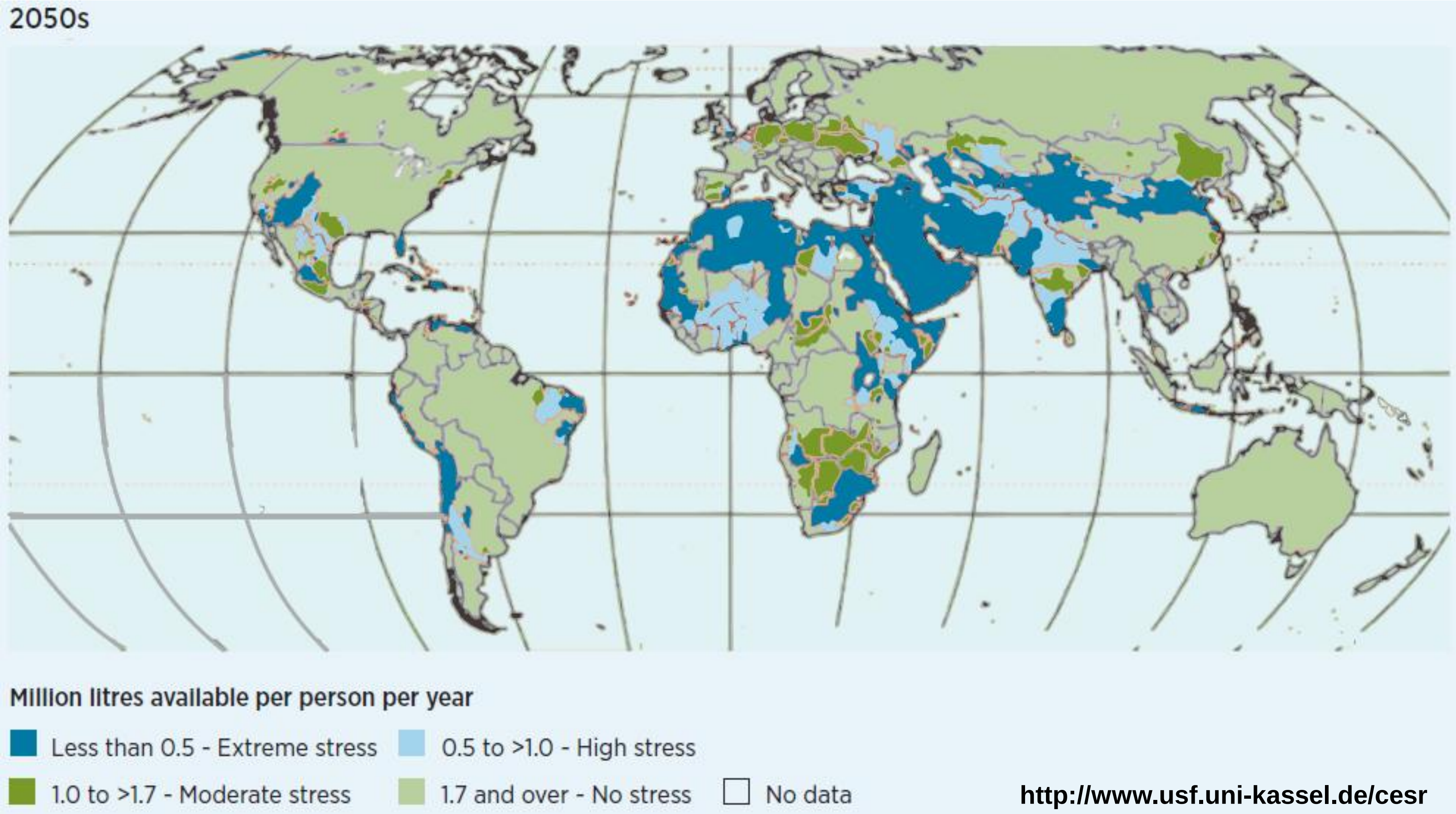
Global forecast of water availability in 2050s



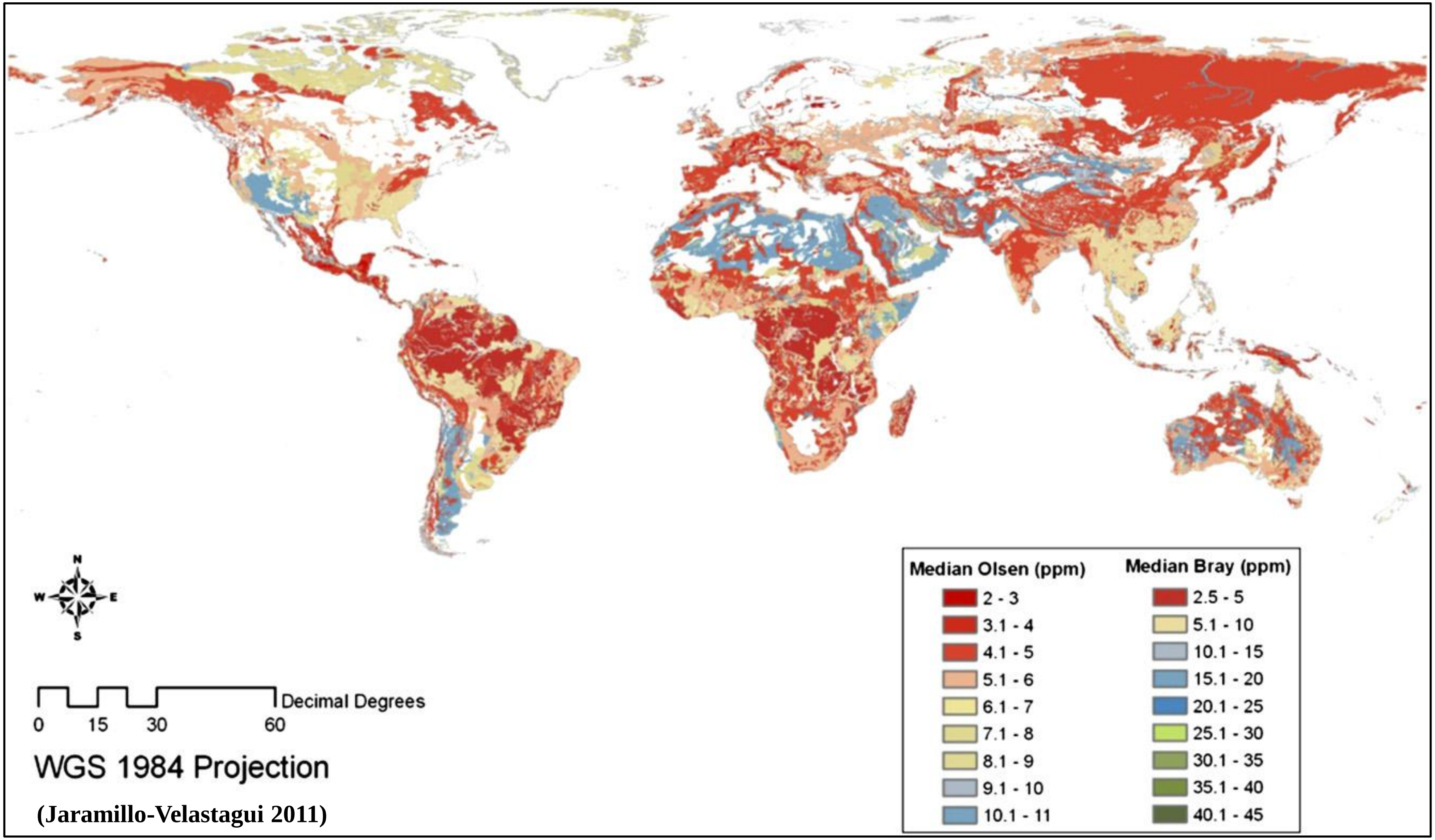
http://www.usf.uni-kassel.de/cesr

Climate change projections for the Pannonian Basin

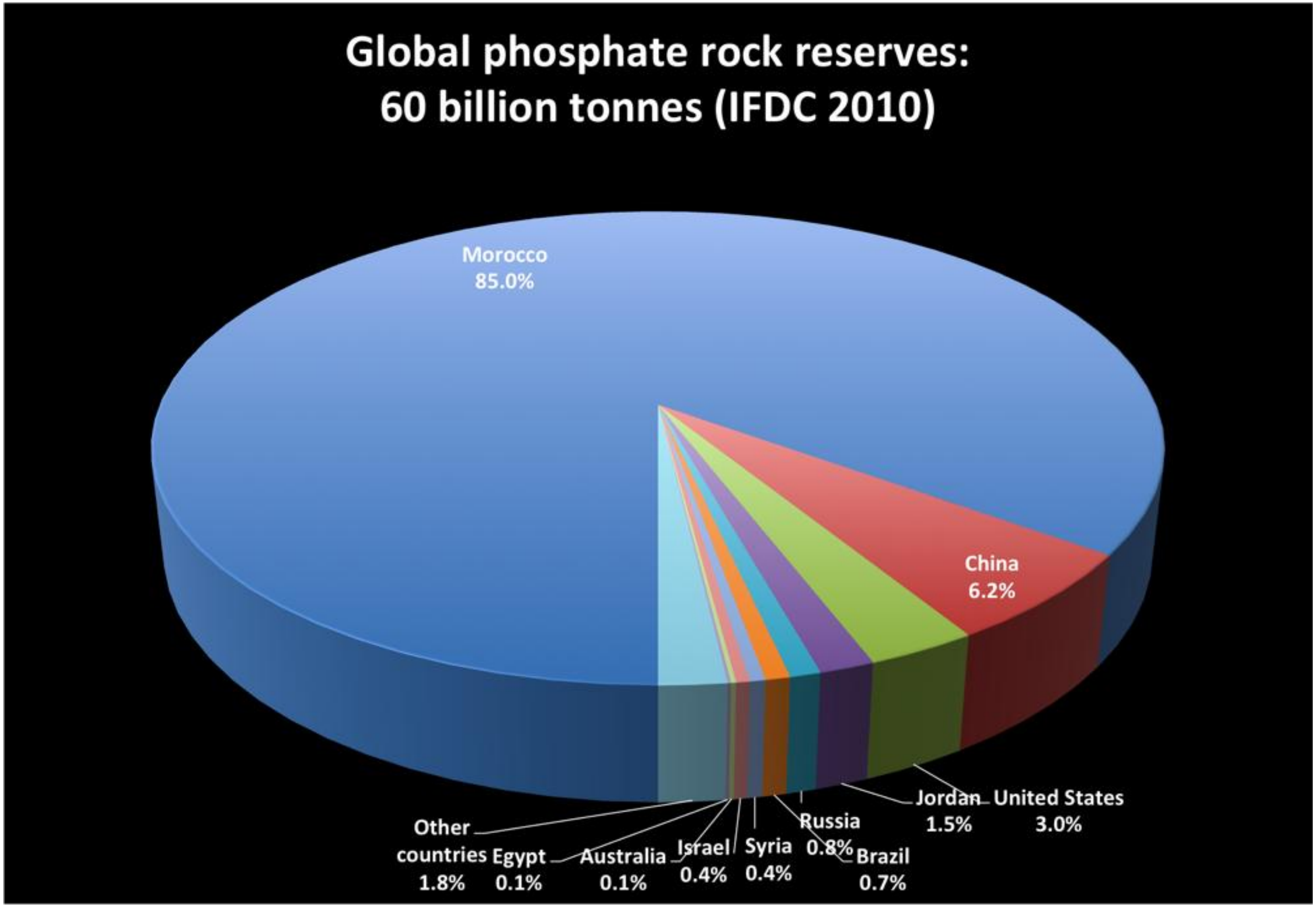
(*Trnka et al. 2010. Is rainfed crop production in central Europe at risk? Using a regional climate model to produce high resolution agroclimatic information for decision makers. Journal of Agricultural Science 148: 639-656.*)

- Increase in incident global radiation and air temperatures →
- Increased saturation deficits →
- Higher rates of ET →
- More severe water deficit during the critical period April – June →
- Large areas of Austria, the Czech Republic, Slovenia, Hungary and Slovakia in need of measures for increasing agricultural water use efficiency
- Higher inter-annual yield variability due to increase in extreme weather events, e.g. heat waves and dry spells

Global P availability in soils



(Jaramillo-Velastagui 2011)



At current production rates, these reserves would last for 300 – 400 years

Global P fertilizer consumption

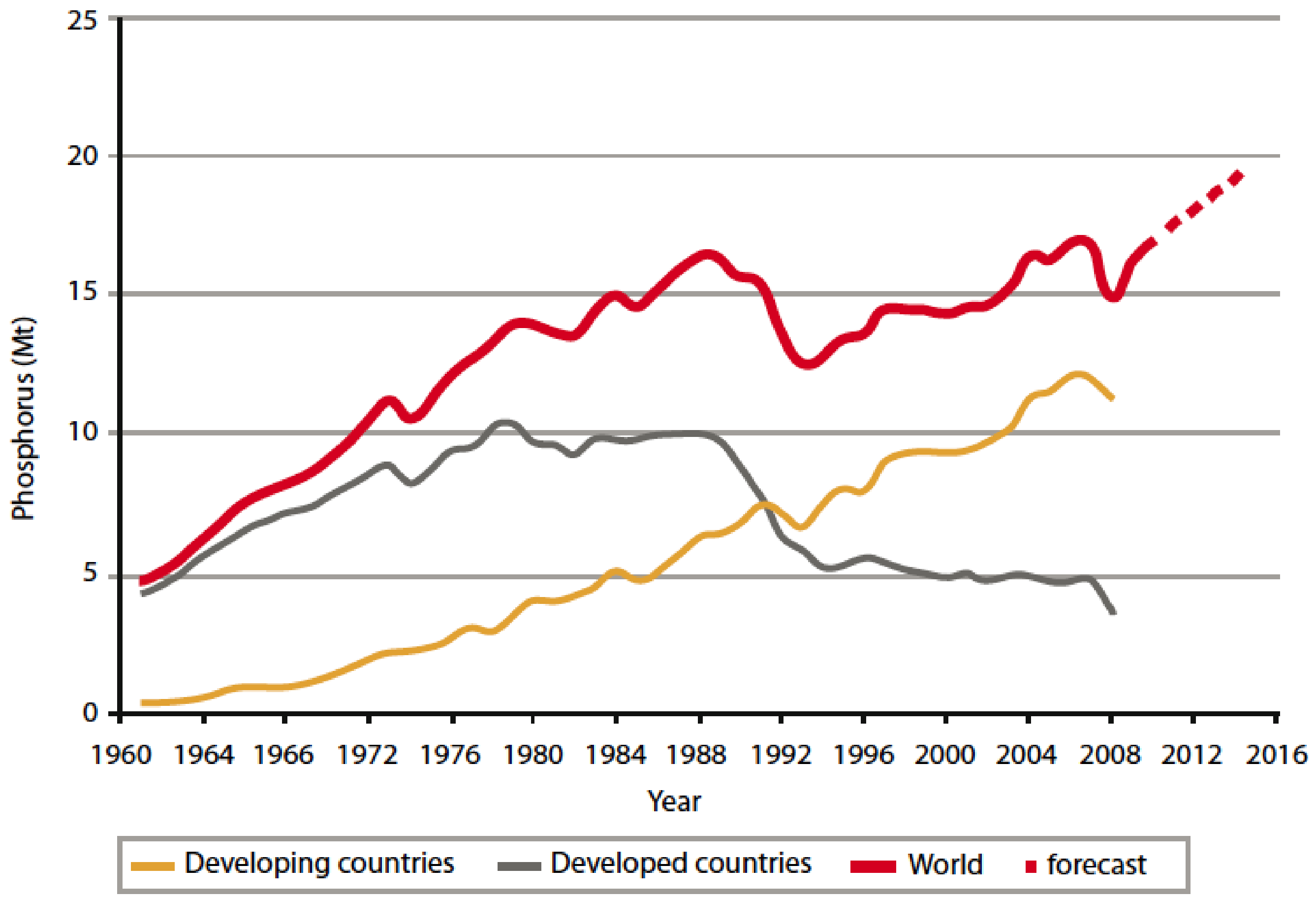


Figure 4: Global phosphorus fertilizer consumption. Demand in developed countries reached a plateau and then declined around 1990. It has continued to increase steadily in developing countries. *Source: Heffer and Prud'homme (2010)*

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Roots – the hidden half

No-tillage sugar beet, 24th June 2013, Wullersdorf

Rooting depth and **density** are key traits for improving water and nutrient uptake efficiency.

Management of root growth via agronomy or plant breeding is desired.

Clear strategies are difficult to define due to multiple interactions between root and soil.

Roots of dicots vs.monocots

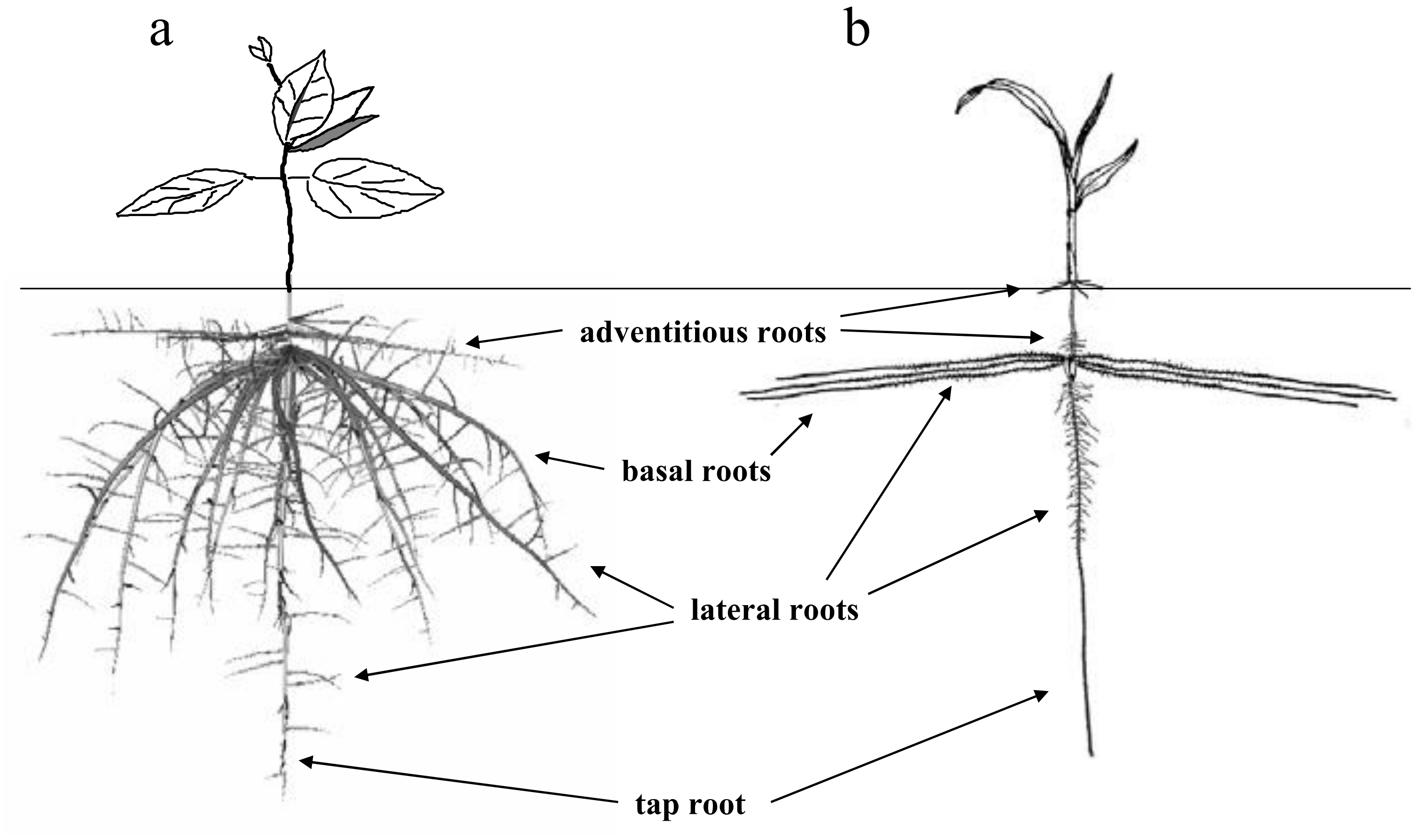
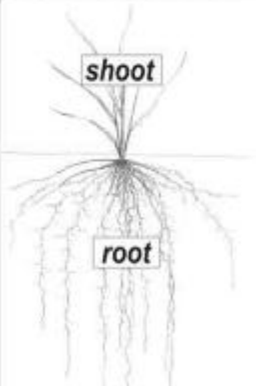


Fig. 7.4a, b. Herbaceous root systems, typified by common bean, a dicot (**a**), and maize, a monocot (**b**)

(Lynch 2005)

Classification categories of root system types

1. Whole plant allometry



Root dominated
Root : shoot ratio > 1

High system size
Root : shoot ratio 0.5-1.0

Intermediate system size
Root : shoot ratio 0.3-0.5

Low system size
Root : shoot ratio 0.1-0.3

Shoot dominated
Root : shoot ratio < 0.1

2. System shape

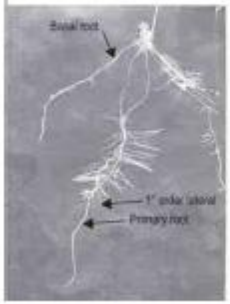
Inverted cone shape
Near surface horizontal extension, low branching tap root in depth

Cylindrical shape
Homgeneous lateral and vertical extension

Restiform shape
Dominant vertical extension of tap root with narrow lateral branching

Discoidal shape
Dominant surface near lateral extension

3. Developmental type

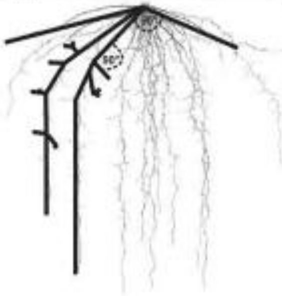


Primary root system - low order
Dominant primary root with few lateral branches

Primary root system - high order
Pimary root with intense lateral branching

Shoot born axes dominated system
Dominance of shoot born root axes, primary and basal roots subordinated or non/functional

4. Branching type



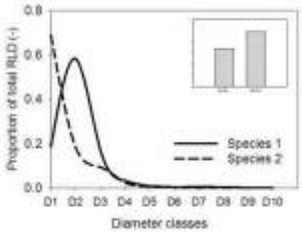
Herringbone system
Topology index near a

Dichotomous system
Topology index near b

Gravitropic type
Narrow angle between primary and first order laterals

Exotropic type
Near right angle between primary and first order laterals

5. Axes morphology

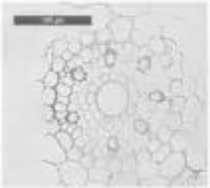


Tap root type
Strong secondary thickening of tap root (e.g. storage root)

Fine root dominance
Highest root length in fine root class (r < 0.2 mm), high specific root length

Even root type
Low decrease in diameter among root axes of different order

6. Anatomy and physiology



High flow system
Large xylem vessels and low radial resistance via suberization/lignification

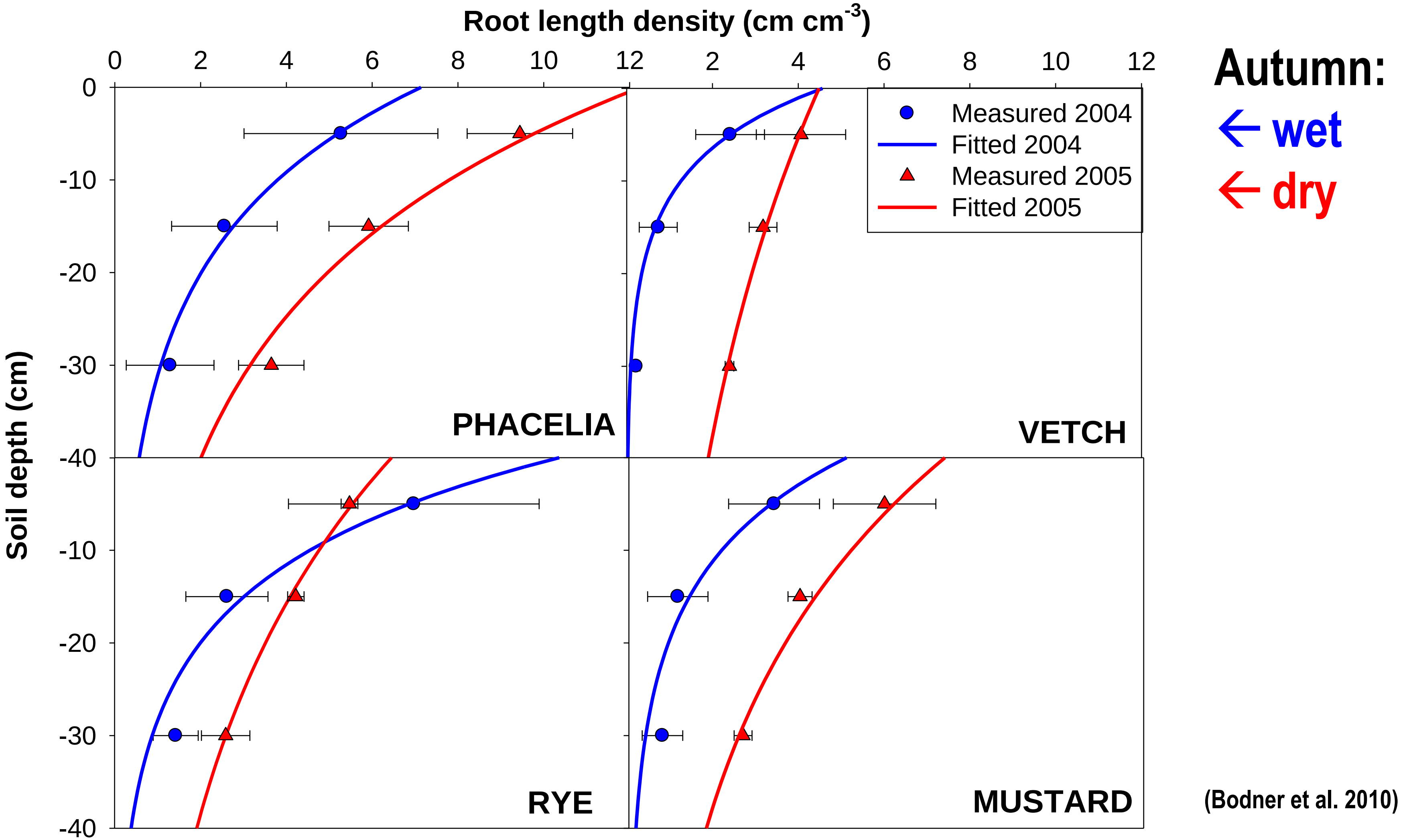
Isolating system
Strong lignificatin and suberization

Penetration system
High diameter, strong exudation

Aearation system
Cortex with Aerenchyma

(Bodner et al. 2013)

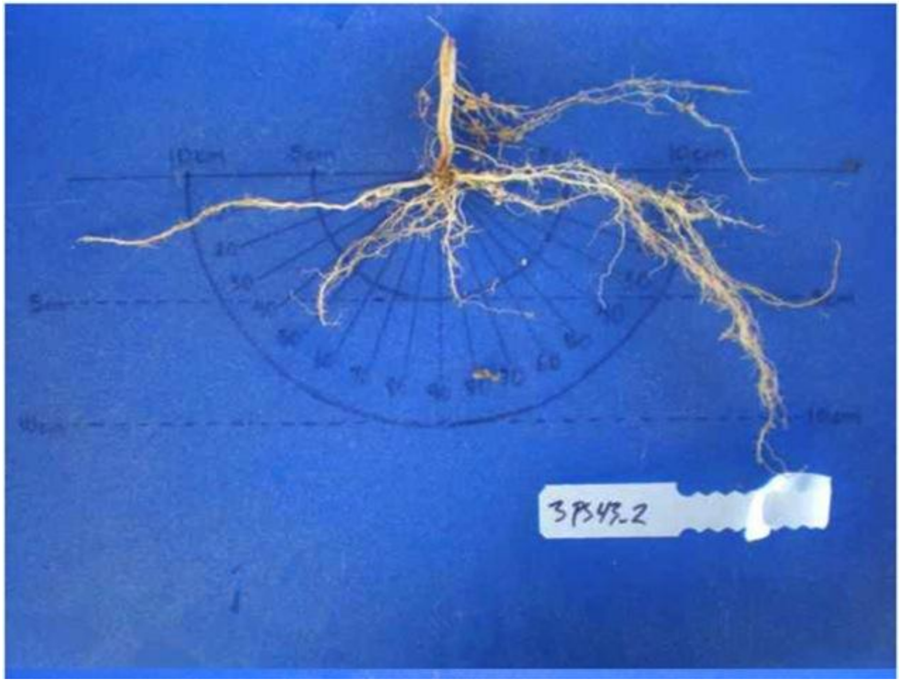
Root distribution in depth of cover crops

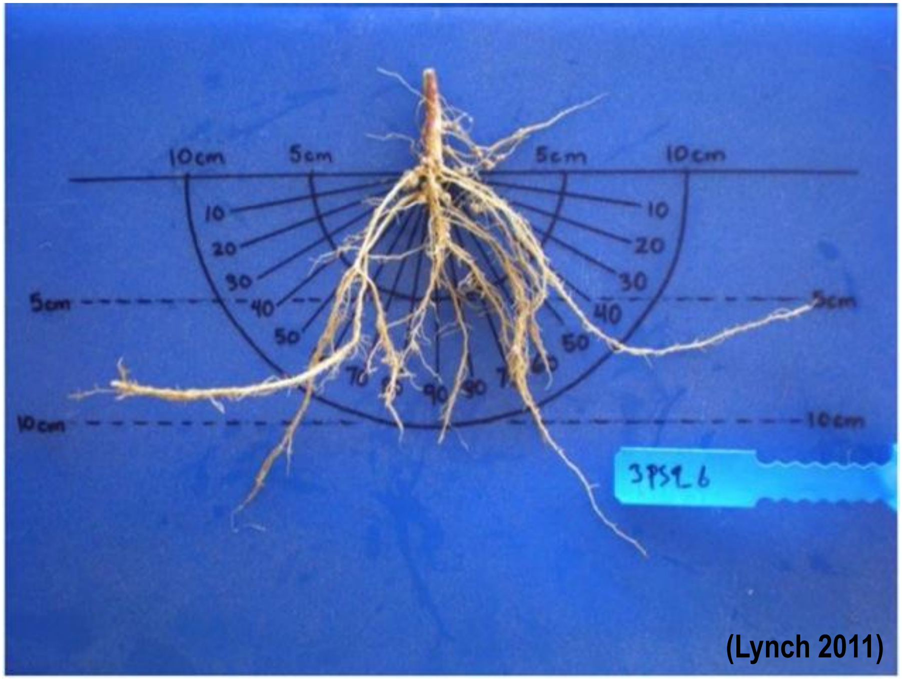


(Bodner et al. 2010)

Root distribution is sensitive to soil moisture

Root growth angle (RGA) of common bean genotypes grown in the field

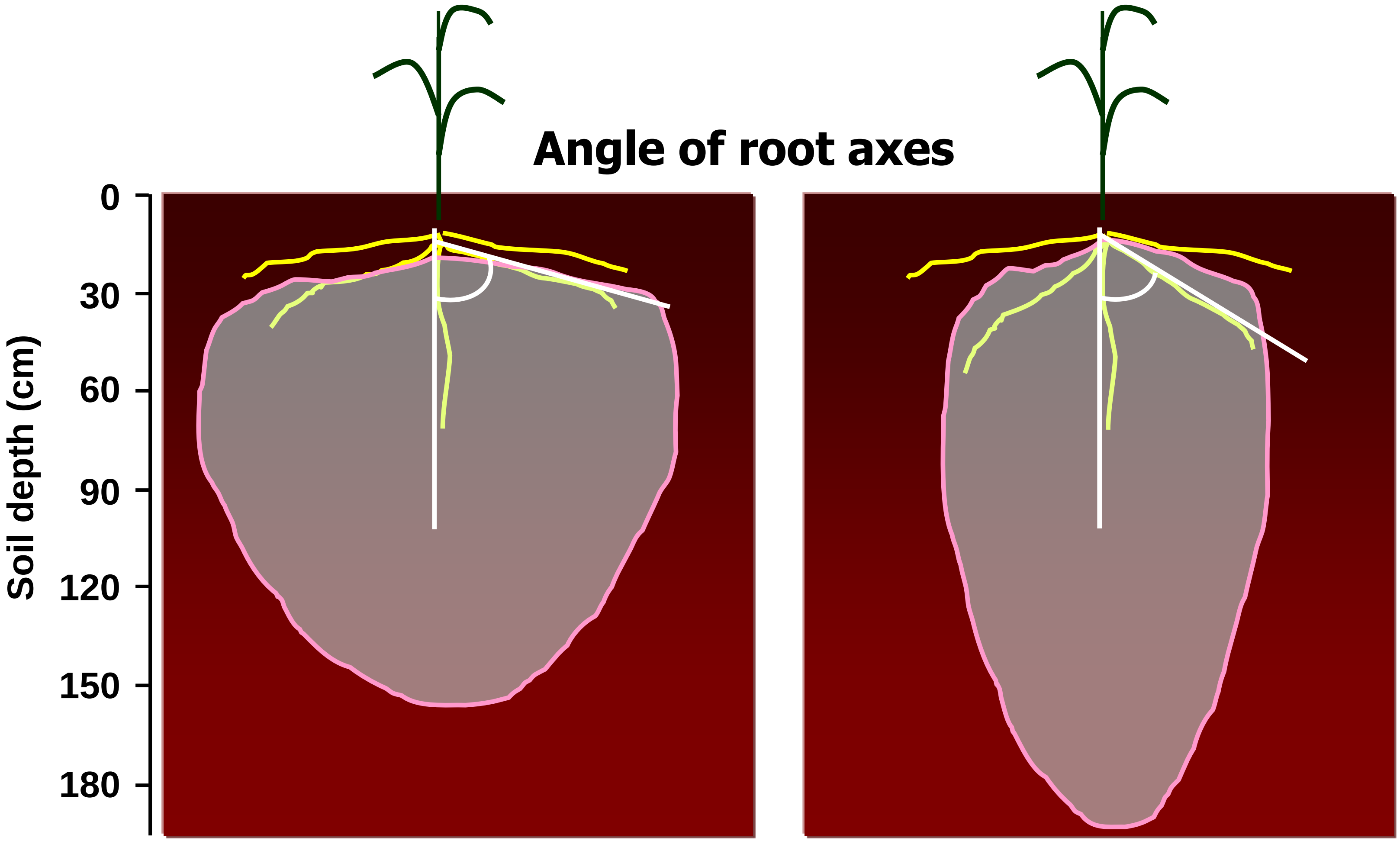


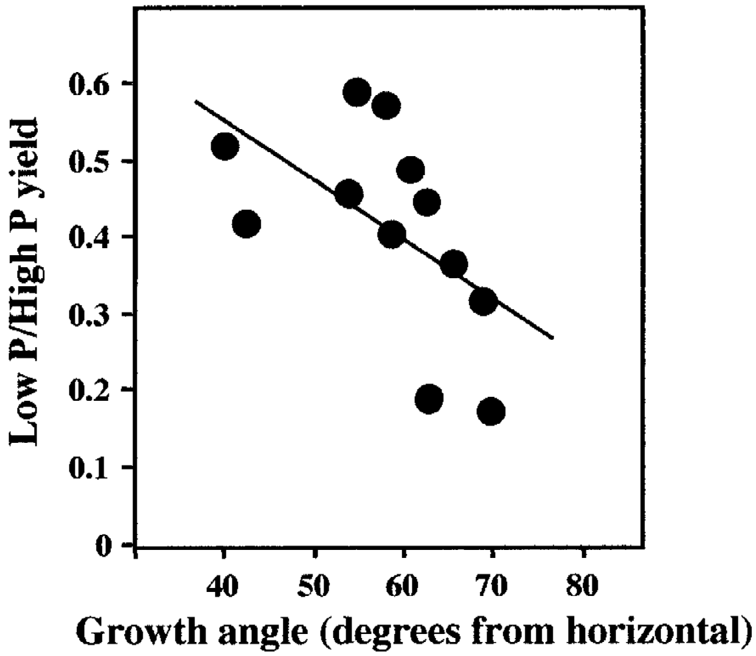


(Lynch 2011)

Shallower RGA increases P acquisition (*topsoil foraging*)
(basal in legumes; seminal & crown roots in maize)

Growth angle of seminal roots shapes root architecture





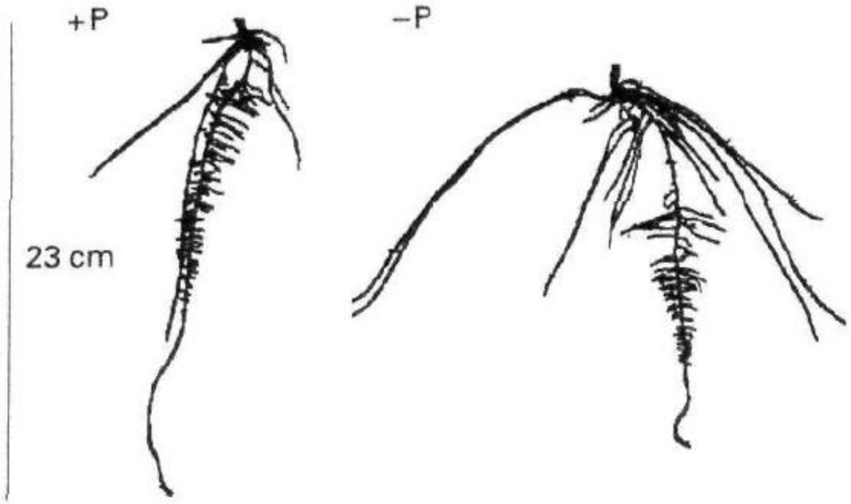


Figure 2. Comparison of two representative root systems of bean cv. G 19833 5 d after basal root emergence with 1·0 mM P and without P.

Growth angle improves yield under low P

Growth angle is sensitive to P supply

Basal root whorl number (BRWN) in legumes

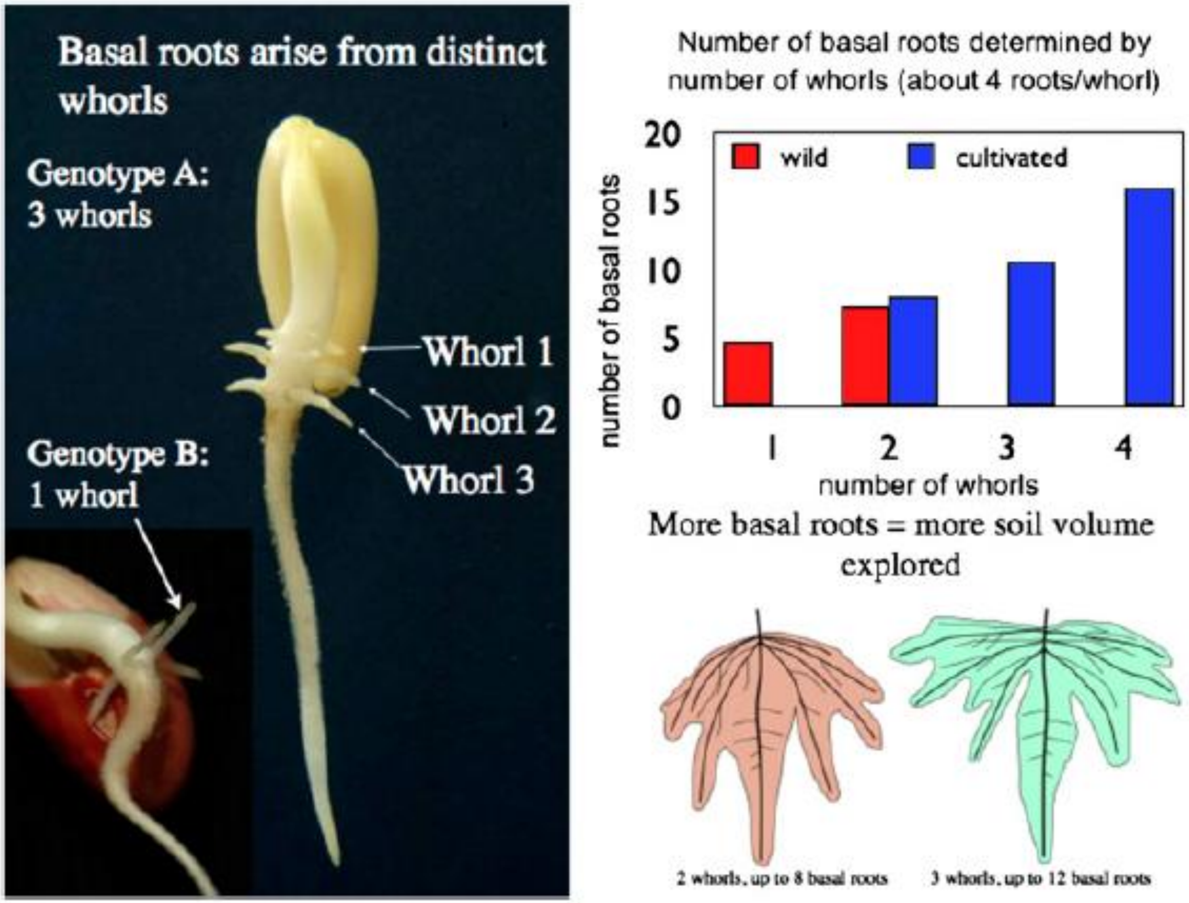
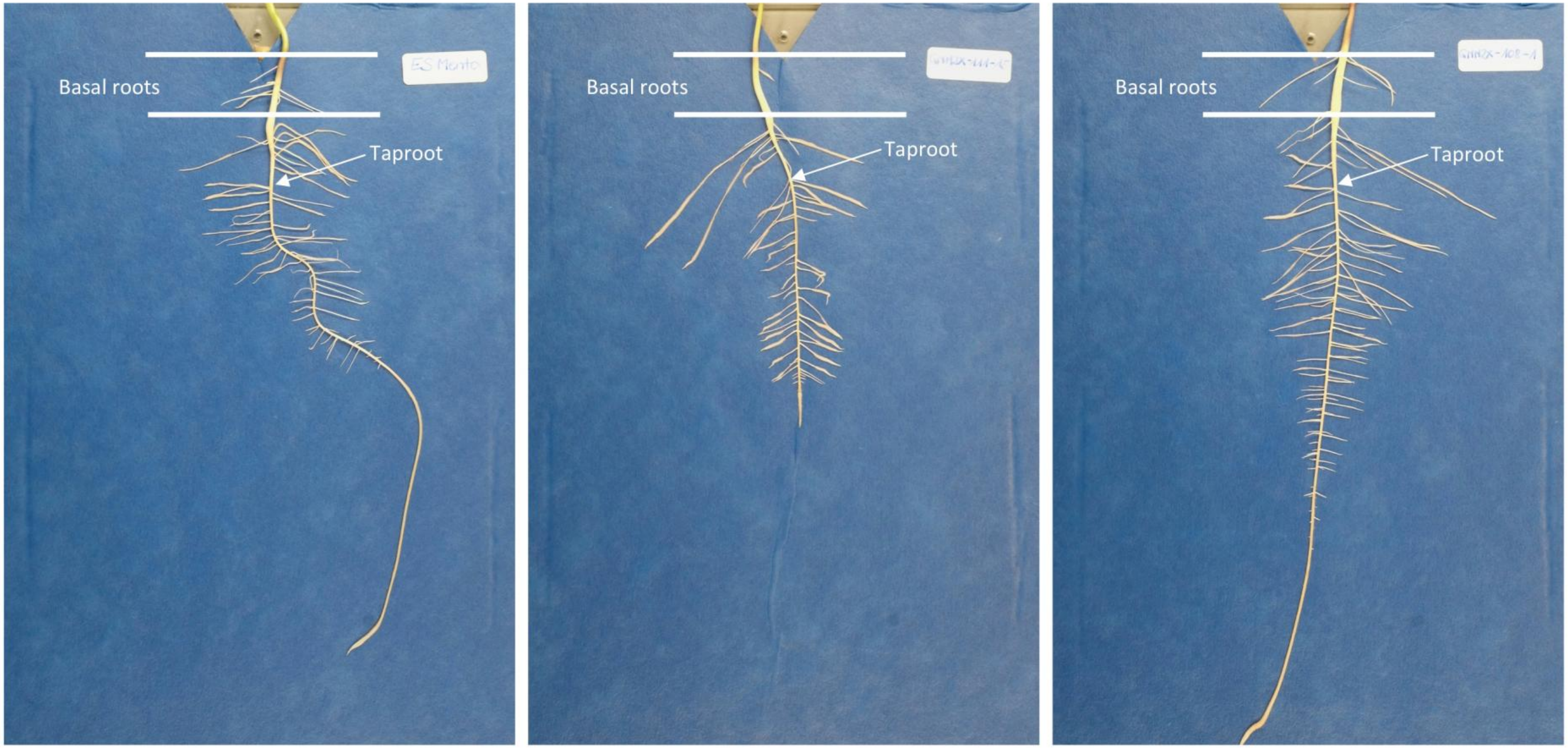


Figure 4. Variation in BRWN in common bean is related to the number of basal roots produced and therefore soil exploration.

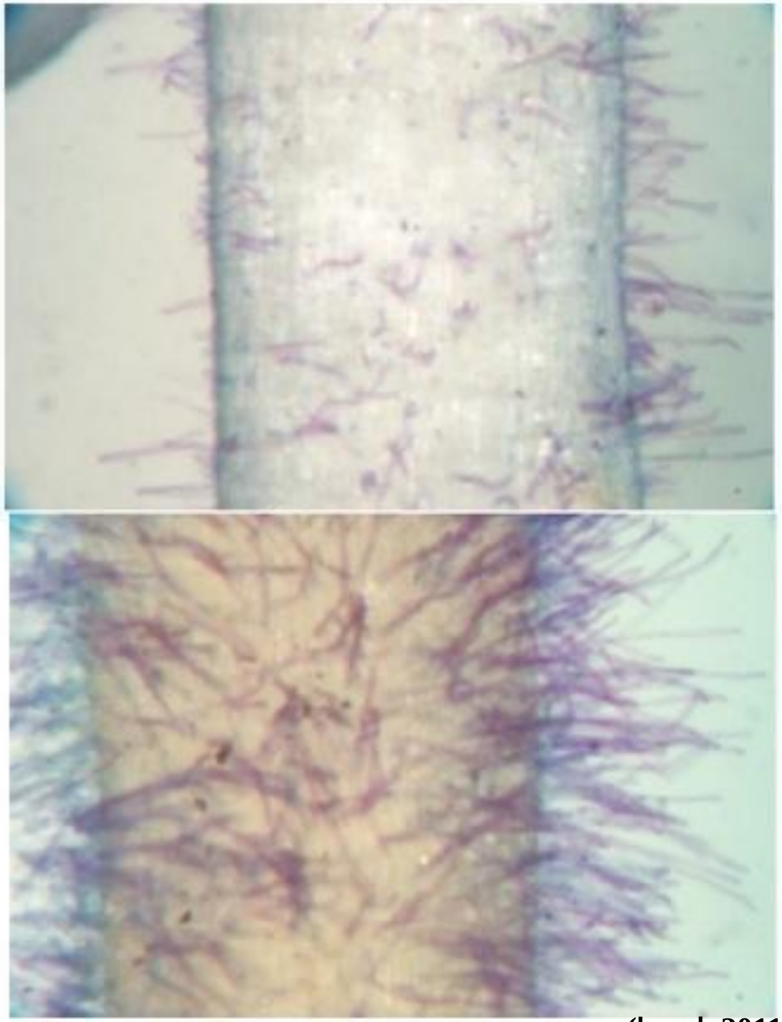
(Lynch 2011)

Genotypic variation in number and growth angle of basal roots and taproot length and branching



7-day old soybean grown in a pouch-germination paper-plexiglass system (Manschadi et al. 2013, unpublished)

Root hair length and density



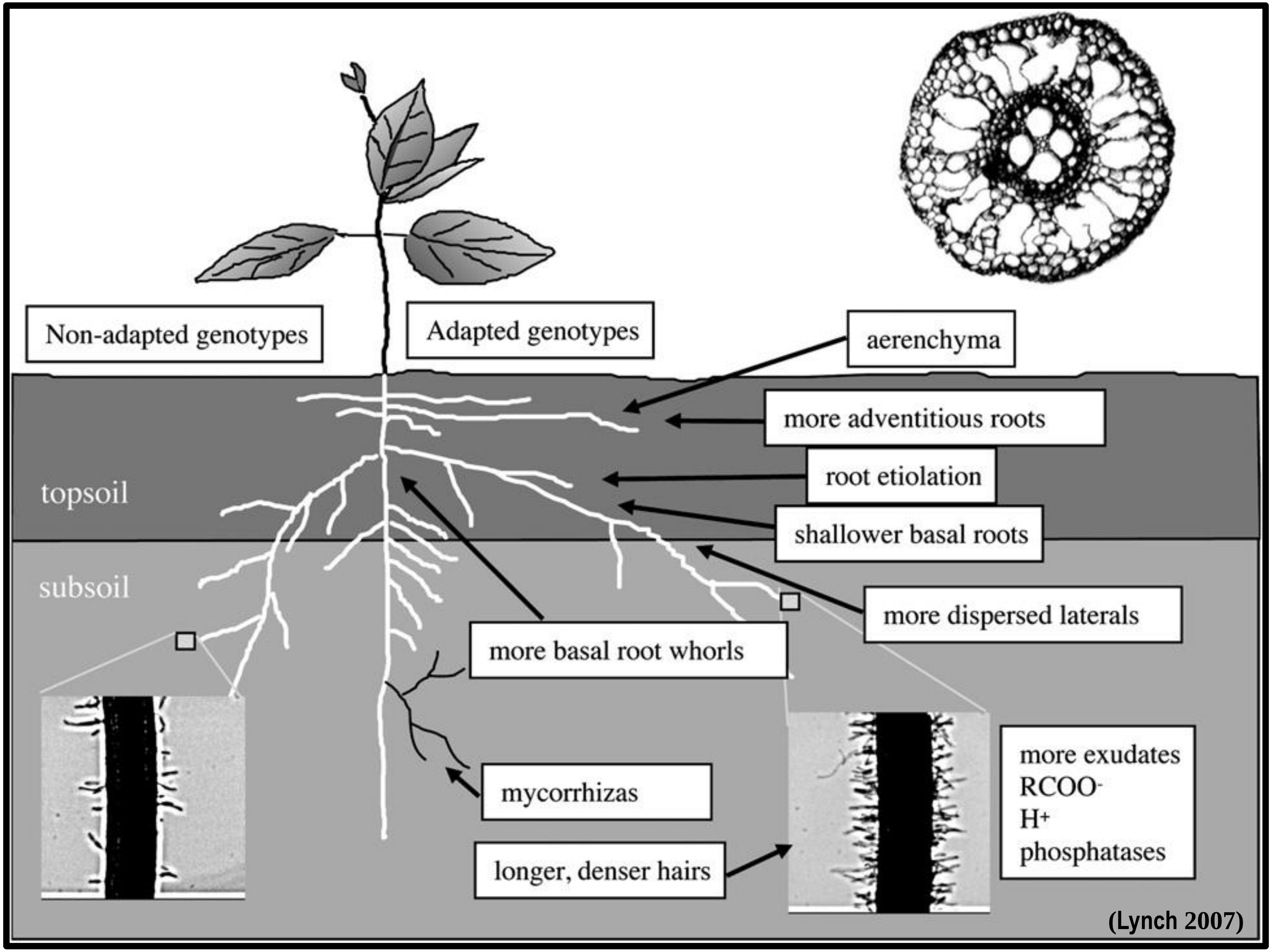
(Lynch 2011)

Common bean:

← Commercial cultivar from Central America

← Peruvian landrace

Summary: Root phenes favourable with low P



Epilogue:
Integrated crop improvement strategy

- Physiological **trait dissection** → Identification of target root phenes
- Development of appropriate **phenotyping** platforms
- Identification of sources of **genetic variation** for target traits
- Simulation **modelling**: environment characterisation; virtual evaluation of improved crop genotypes and their long-term contribution to sustainability of target agroecosystems
- Plant **breeding**: development of adapted crop varieties; possible breeding target: **dimorphic root system** with adequate root growth in both shallow and deep soil layers

Conclusions

- **Efficiencies in general** depend on numerator and denominator values.
- Agronomic **WUE** depends on yield and transpiration. Environmental factors affect water supply, crop factors affect water use and drought resistance. Maximizing water uptake is compatible with high yield (*water spenders*).
- **PUE** depends mostly on acquisition and is maximum at soil „critical P“ levels.
- Globally, water and phosphorus are both strongly **limited resources** with high importance for crop productivity.
- **Roots** are a complex plant organ, characterized by many traits. They are essential for soil resource acquisition, and soil resources affect root traits in reverse.
- Among others, **R**oot **G**rowth **A**ngle, **B**asal **R**oot **W**horl **N**umber and **root hairs** are promising breeding targets for improved water and P acquisition. In addition, **dimorphic root systems** with adequate soil exploration for different limited resources might help to improve resource acquisition.

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