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Root traits and rhizosphere characteristics determining potassium acquisition from soils

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► **To cite this version:**

Philippe Hinsinger, Michael Bell, Philip J. White. Root traits and rhizosphere characteristics determining potassium acquisition from soils. *Frontiers of Potassium*, Jan 2017, Rome, Italy. 2017. hal-01604222

HAL Id: hal-01604222

<https://hal.science/hal-01604222v1>

Submitted on 2 Jun 2020

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Root and rhizosphere-related traits determining **K** acquisition efficiency and placement decisions

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SCIENCE & IMPACT
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→ **acknowledgements – co-authors / sponsor**



- **Michael Bell**
Brisbane – Australia



- **Philip White**
Dundee – Scotland / UK



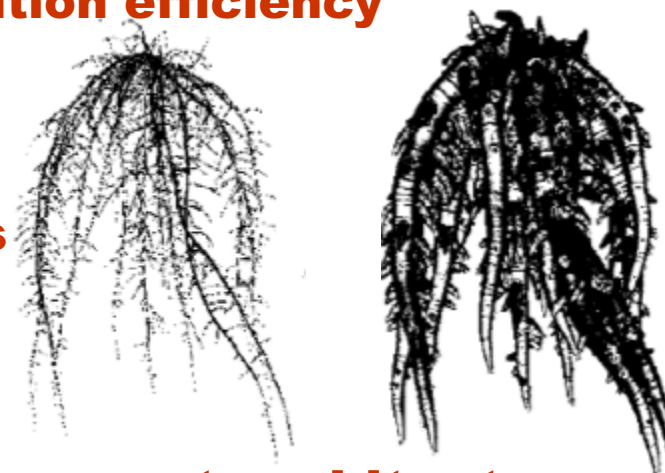
→ introduction – why/how improving soil K acquisition efficiency ?

→ **Green Revolution was based on crops responsive to high soil fertility**

→ **the second Green Revolution will be based on crops tolerant of low soil fertility**

→ **exhibiting greater nutrient acquisition efficiency**

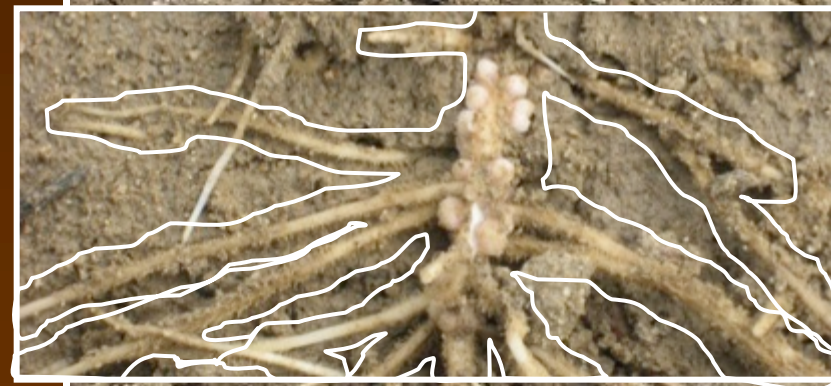
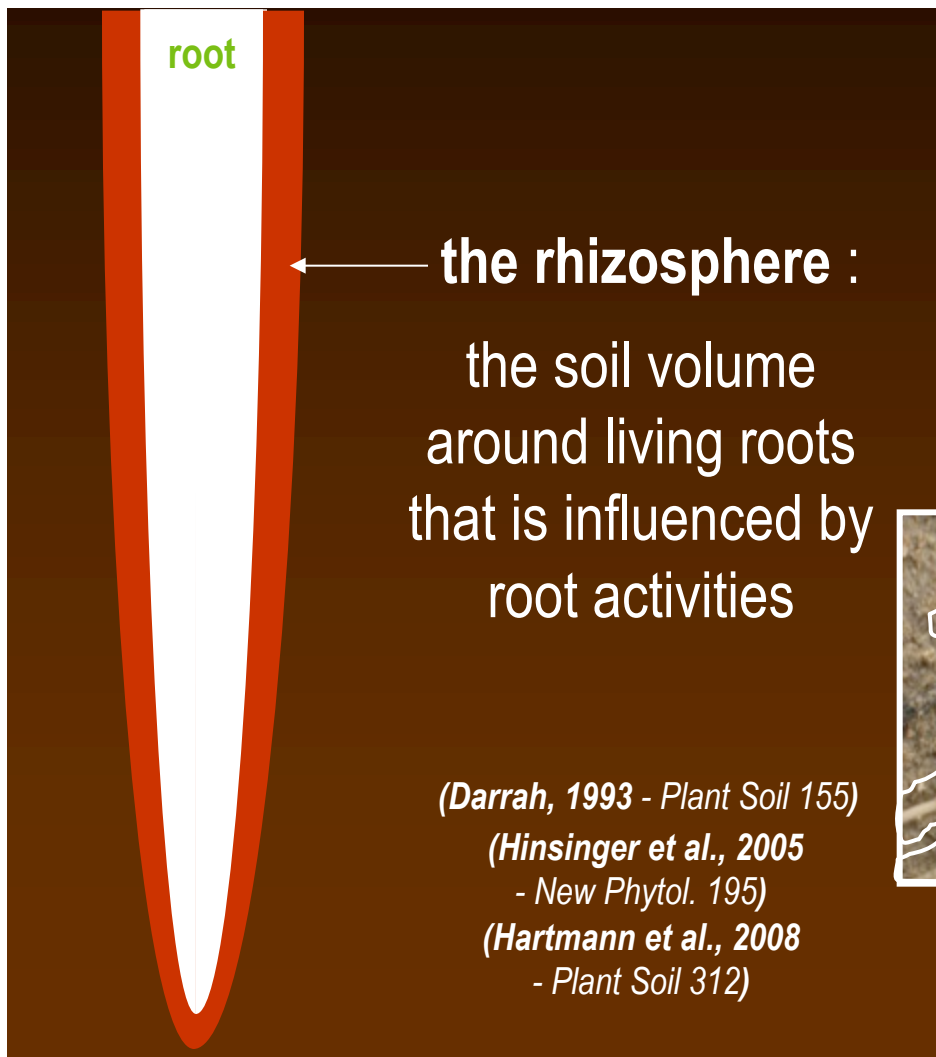
→ **via foraging / mining strategies**



→ **root architecture and rhizosphere traits**

‘Roots of the second Green Revolution’ (Lynch, 2007 – *Aust. J. Bot.* 55)

→ introduction – why/how improving soil K acquisition efficiency ?



... a unique hotspot of soil biogeochemistry determining nutrient bioavailability
(Hinsinger, Bengough, Vetterlein & Young, 2009 – *Plant Soil* 321)

→ soil properties determining the fate of K at the root-soil interface

- **K mobility : mass-flow vs diffusion in the rhizosphere**
- **K availability vs K bioavailability**
- **K distribution : topsoil vs subsoil K availability**

→ K mobility : mass-flow vs diffusion

| Nutrient | Concentration range |
|----------|----------------------------|
| <i>P</i> | 1...10 μM |
| <i>K</i> | 100...1000 μM |
| <i>N</i> | 1000...10000 μM |

→ due to strong interactions with soil solid phases (adsorption/desorption)

→ range of typical K^+ ions concentrations in soil solutions is 10-fold greater than phosphate and 10-fold smaller than nitrate

= a major constraint for K acquisition

(Hinsinger et al. 2011 – Plant Soil / Marschner Review)

→ **K mobility : mass-flow vs diffusion**

Least mobile



Most mobile

| Nutrient | Mass-flow | Diffusion |
|-----------------|-----------------|------------|
| P | 7% | 93% |
| K | 18% | 82% |
| N | 79% | 21% |
| Ca or Mg | >100% | - |
| S | >100% | - |

Respective contributions of mass-flow and diffusion to nutrient acquisition by maize

(Barber 1995)

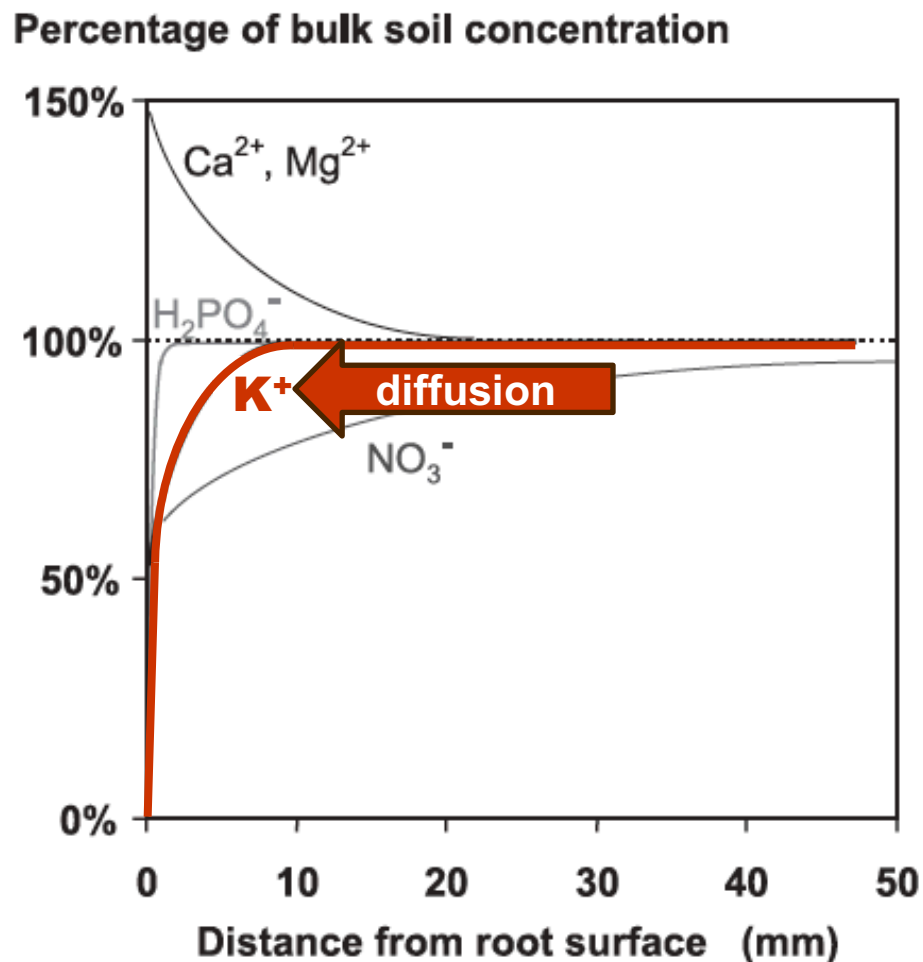
→ **K⁺ ions are poorly mobile in soils**

**more than phosphate
and much less than nitrate**

= a major constraint for K acquisition

(Hinsinger et al. 2011 – Plant Soil / Marschner Review)

→ K mobility : mass-flow vs diffusion

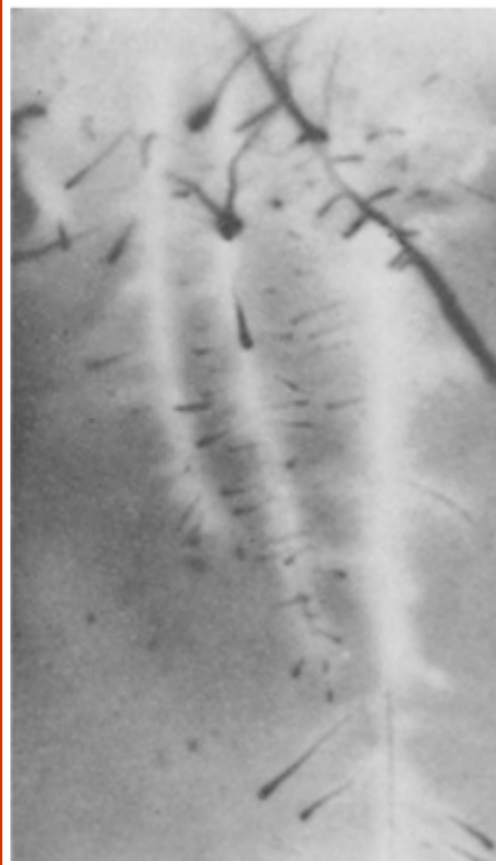


→ **steep K⁺ concentration gradient promoting K⁺ diffusion**

Depletion of K⁺ ions in the rhizosphere extends several mm

(Hinsinger 2004 – Encyclopedia of Plant and Crop Science)

→ K mobility : mass-flow vs diffusion



(Walker and Barber, 1962)

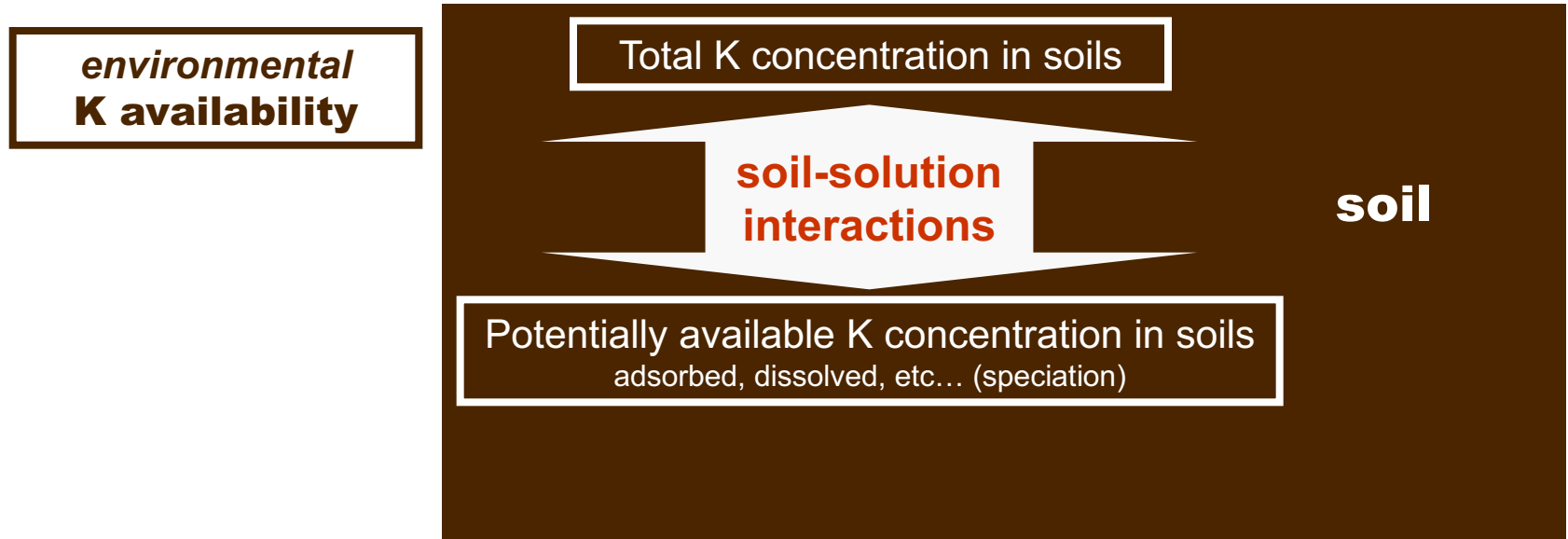
→ **Rb or K uptake by roots and rhizosphere depletion occur over a small volume of soil due to poor mobility of Rb⁺ or K⁺ ions in soils**
= a major constraint for K acquisition

(Hinsinger et al. 2011 – Plant Soil / Marschner Review)

Rhizosphere depletion of ⁸⁶Rb due to ion uptake by 13-day old maize roots

(Walker and Barber 1962 – Plant Soil 17)

→ K availability vs K bioavailability

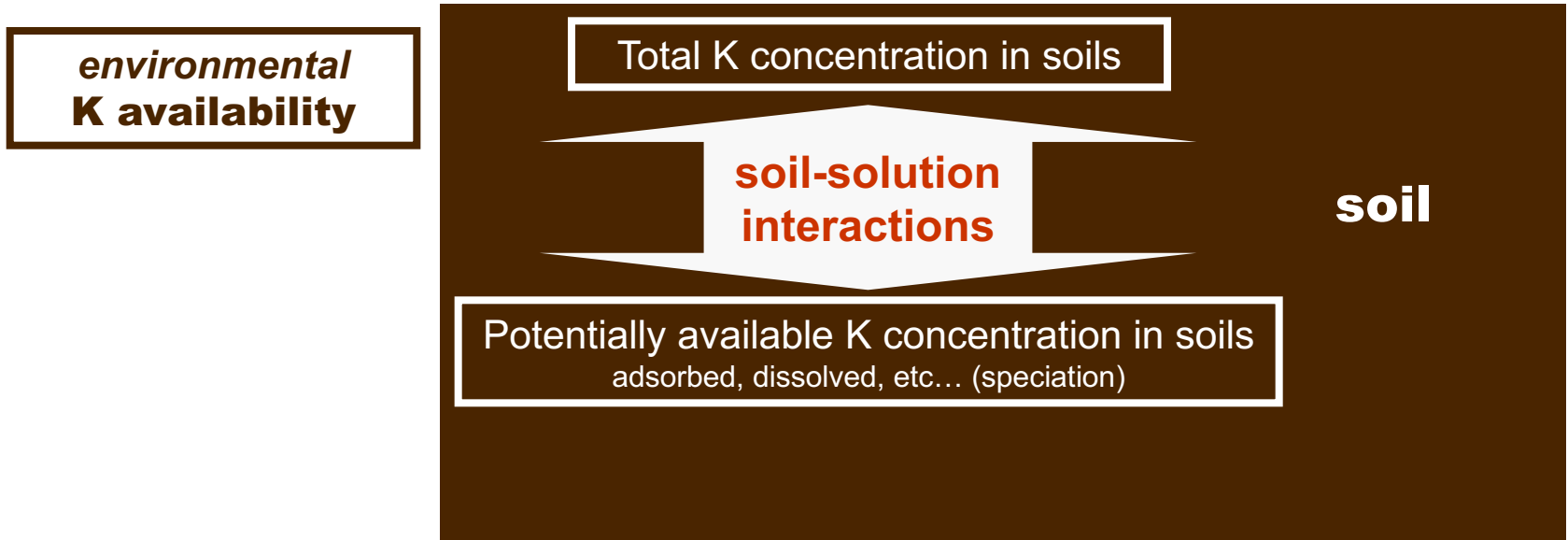


only a small fraction of total soil K is actually readily available

towards a unified concept of bioavailability → ISO/DIS 17402 (ISO, 2006)

(Harmsen et al., 2005 – Land Contam. Reclam. 13 ; Harmsen, 2007 – J. Environ. Qual. 36)

→ K availability vs K bioavailability



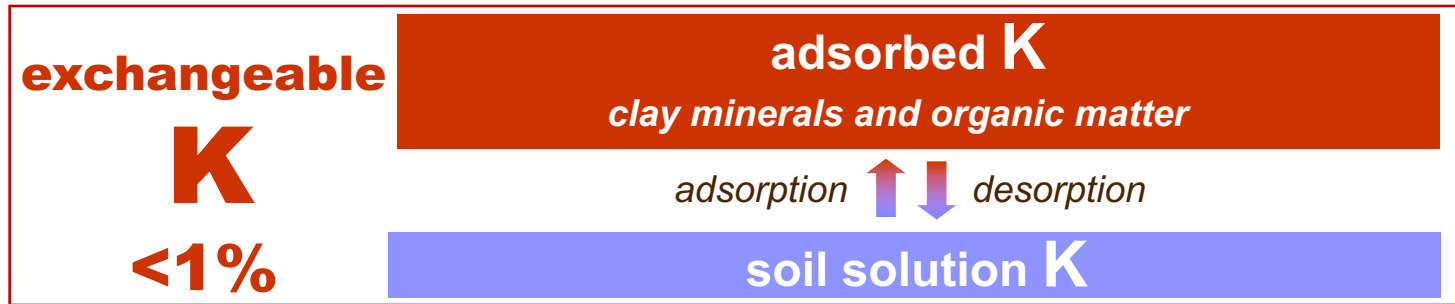
only a small fraction of total soil K is actually readily available

→ often assumed to correspond to the exchangeable pool of K in soils

towards a unified concept of bioavailability → ISO/DIS 17402 (ISO, 2006)

(Harmsen et al., 2005 – Land Contam. Reclam. 13 ; Harmsen, 2007 – J. Environ. Qual. 36)

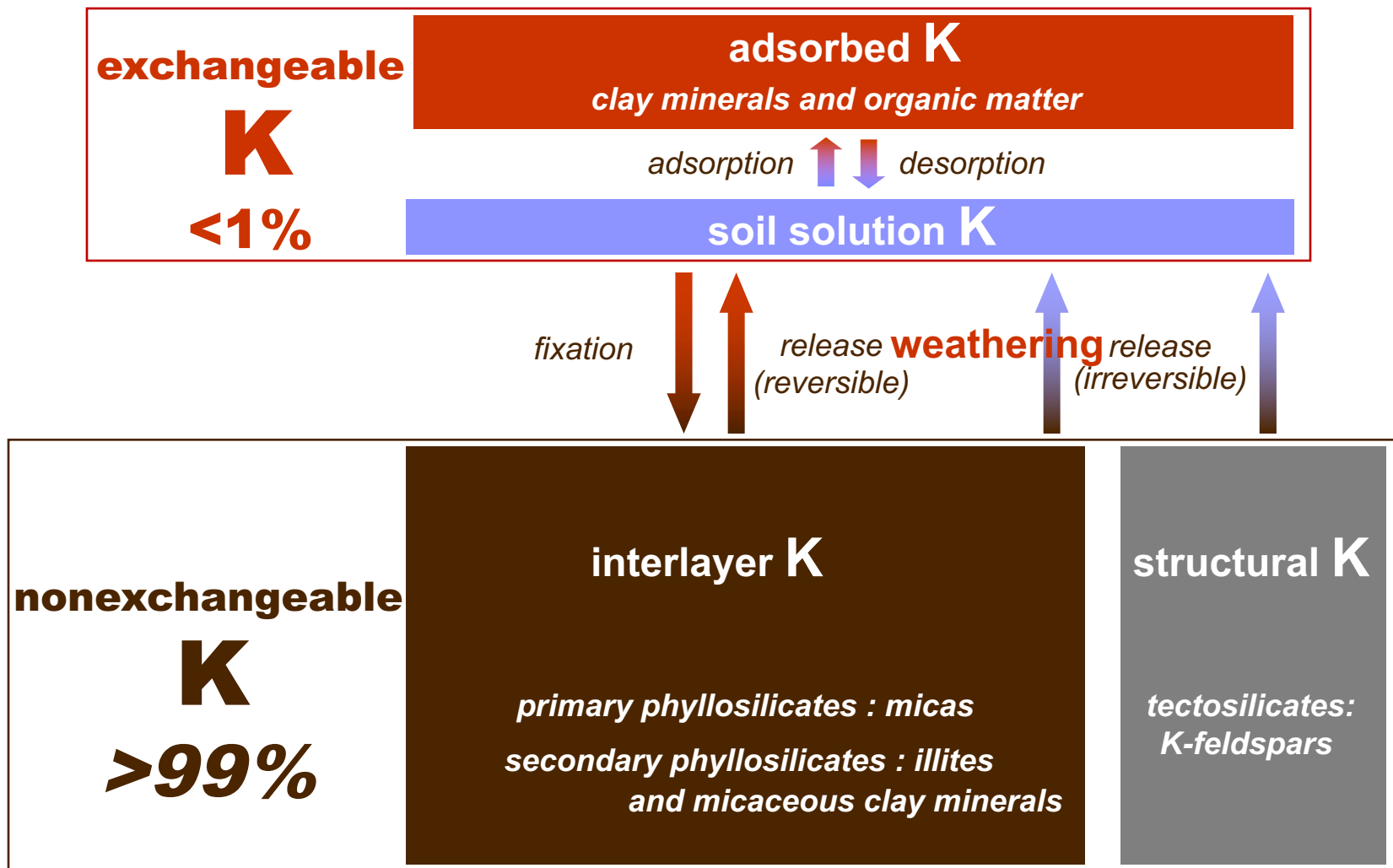
→ K availability vs K bioavailability



Pools of K and processes determining K availability in soils

(Hinsinger, 2006 – Encycl. Soil Science 2nd Ed.)

→ K availability vs K bioavailability

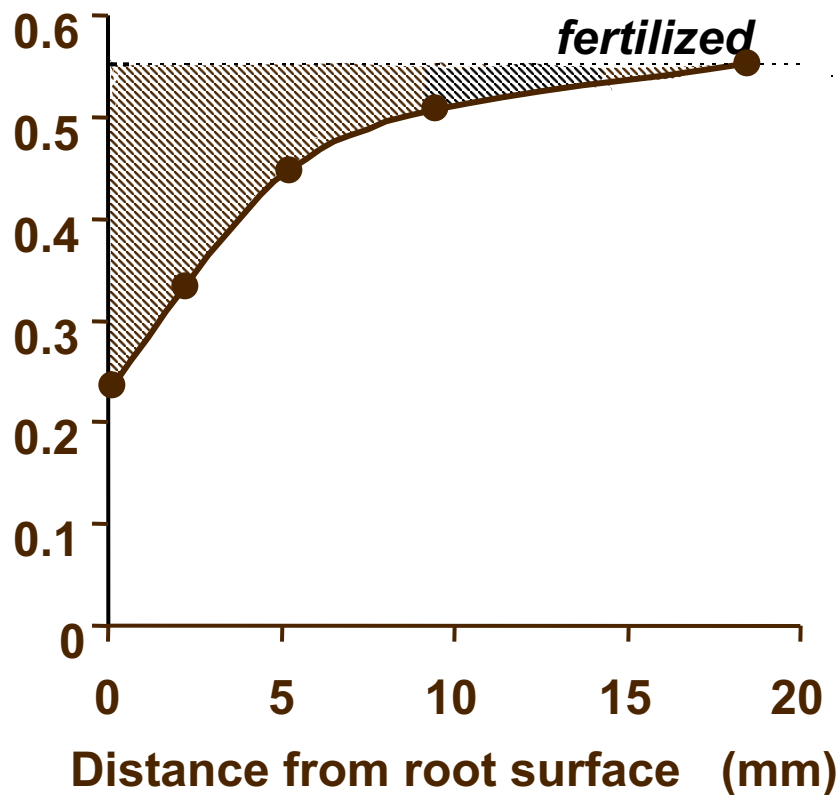


Pools of K and processes determining K availability in soils

(Hinsinger, 2006 – Encycl. Soil Science 2nd Ed.)

→ K availability vs K bioavailability

Exchangeable K (cmol kg⁻¹)

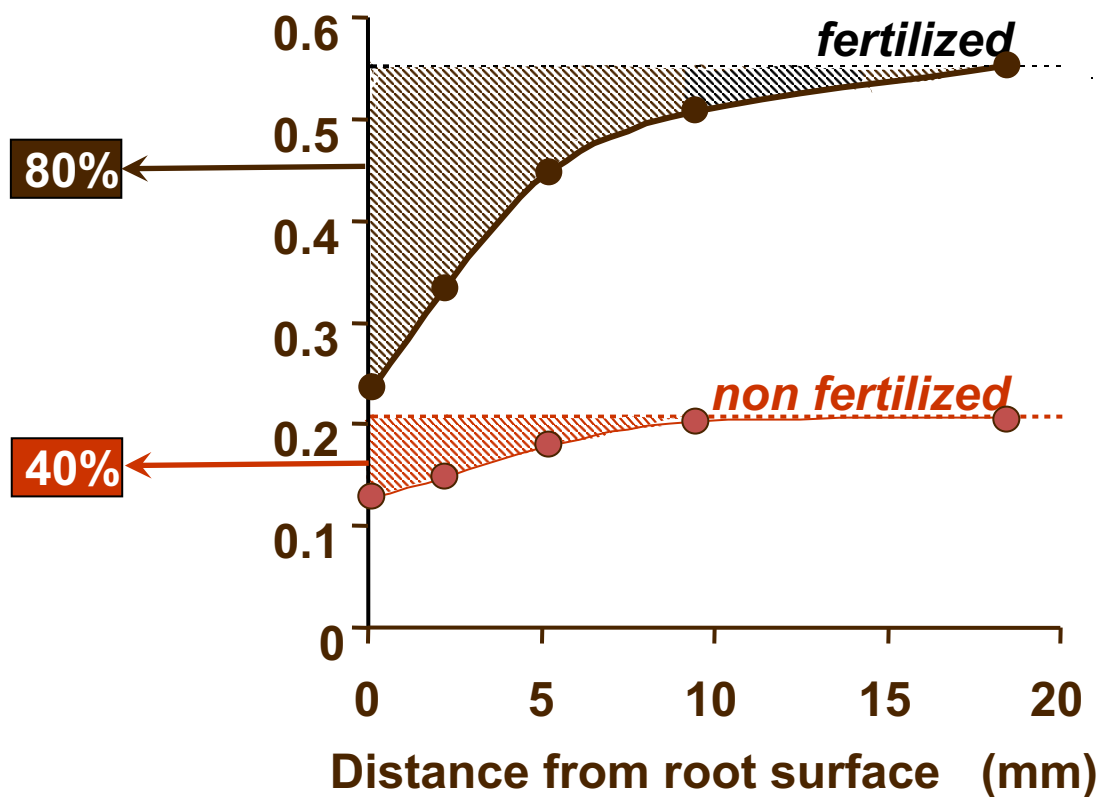


Large depletion of exchangeable K in the rhizosphere
within 4 days of plant growth

- long-term K fertilizer trial of Gembloux, Belgium -
(Hinsinger 2004 – Encyclop. Plant Crop Science)

→ K availability vs K bioavailability

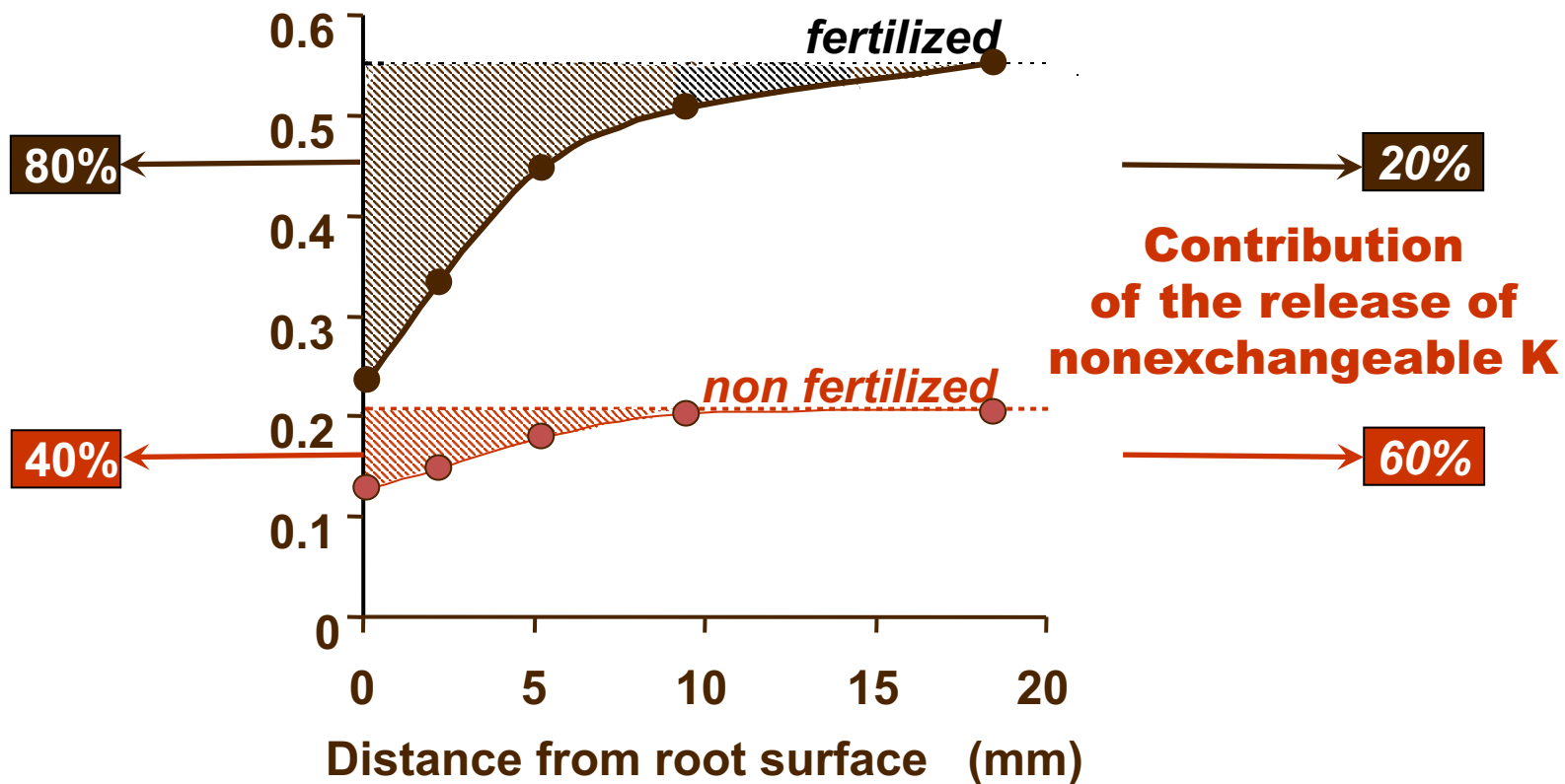
Exchangeable K (cmol kg⁻¹)



Large depletion of exchangeable K in the rhizosphere within 4 days of plant growth contributing 40-80% of K acquisition by oilseed rape - long-term K fertilizer trial of Gembloux, Belgium - (Hinsinger 2004 – *Encyclop. Plant Crop Science*)

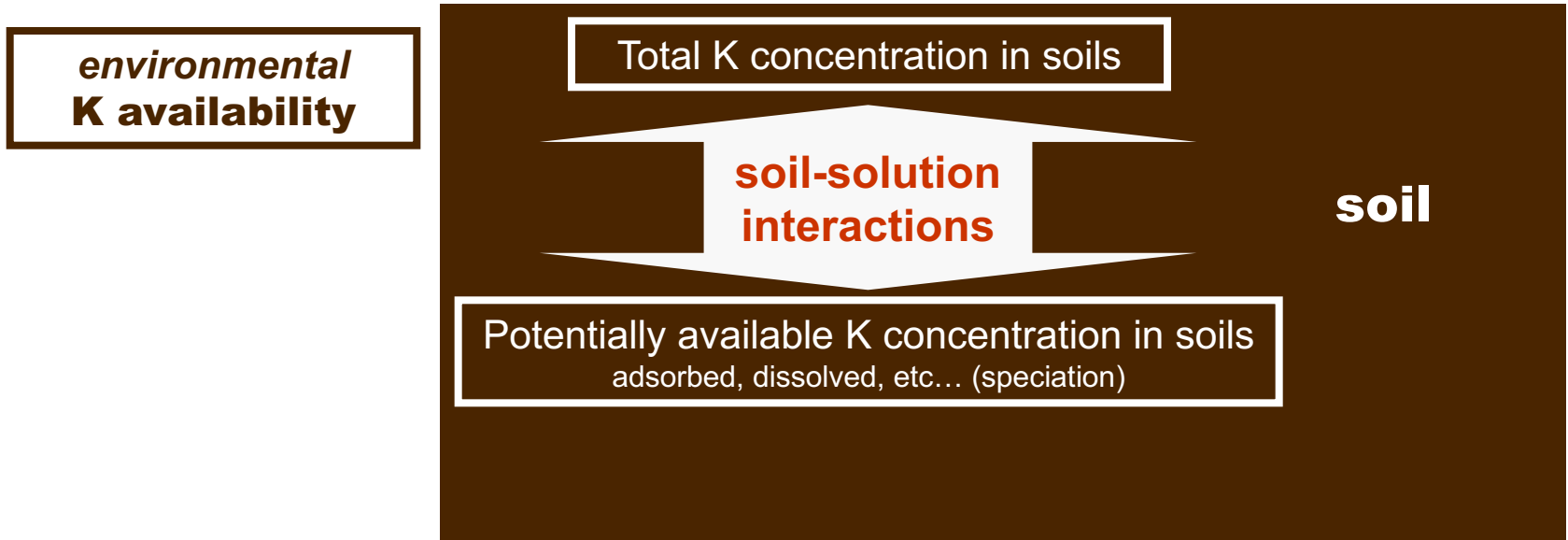
→ K availability vs K bioavailability

Exchangeable K (cmol kg⁻¹)



Large depletion of exchangeable K in the rhizosphere
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→ K availability vs K bioavailability



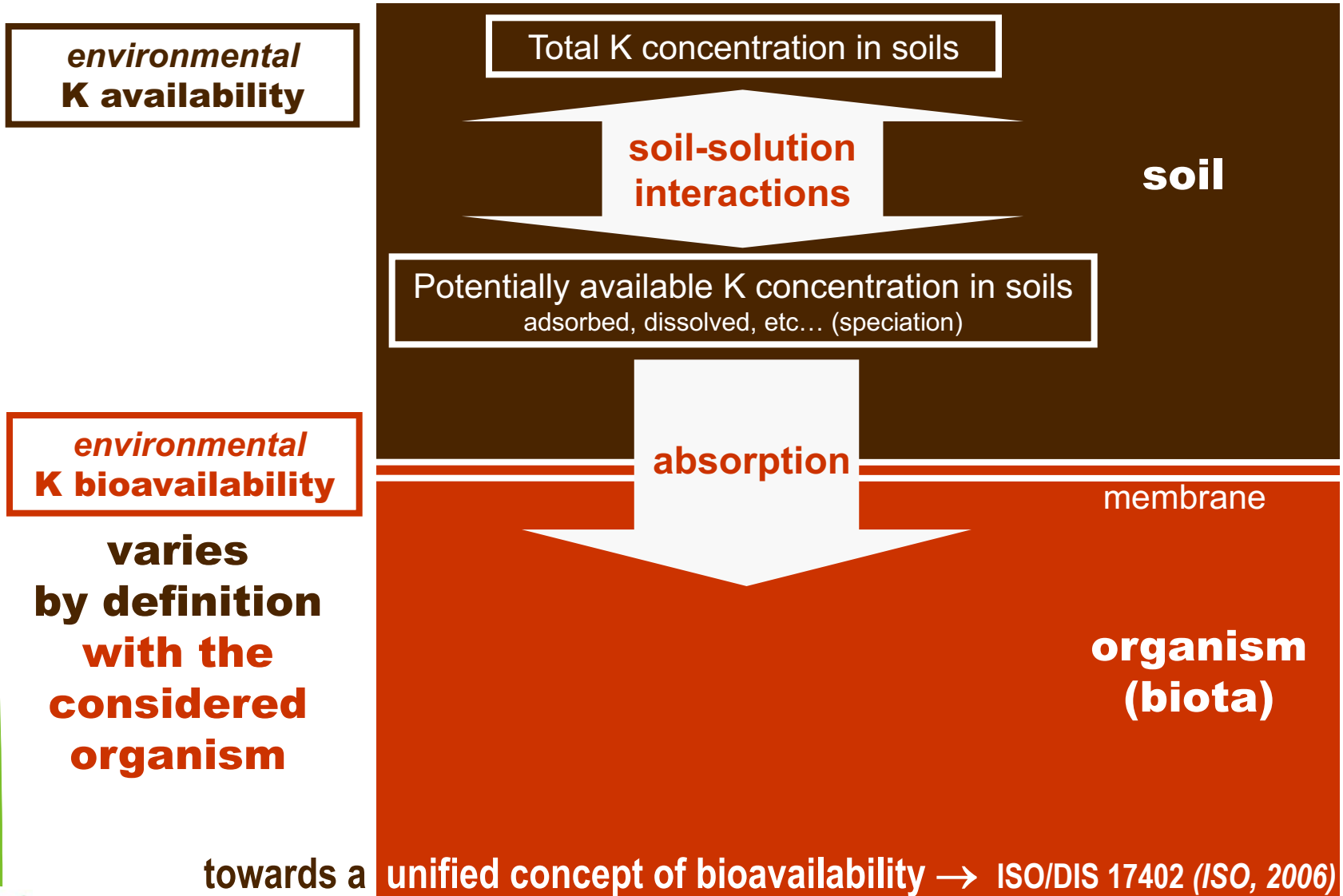
only a small fraction of total soil K is actually readily available

soil K availability is a poor surrogate of soil K bioavailability as measured by soil testing methods and thus independently of the targeted organism

towards a unified concept of bioavailability → ISO/DIS 17402 (ISO, 2006)

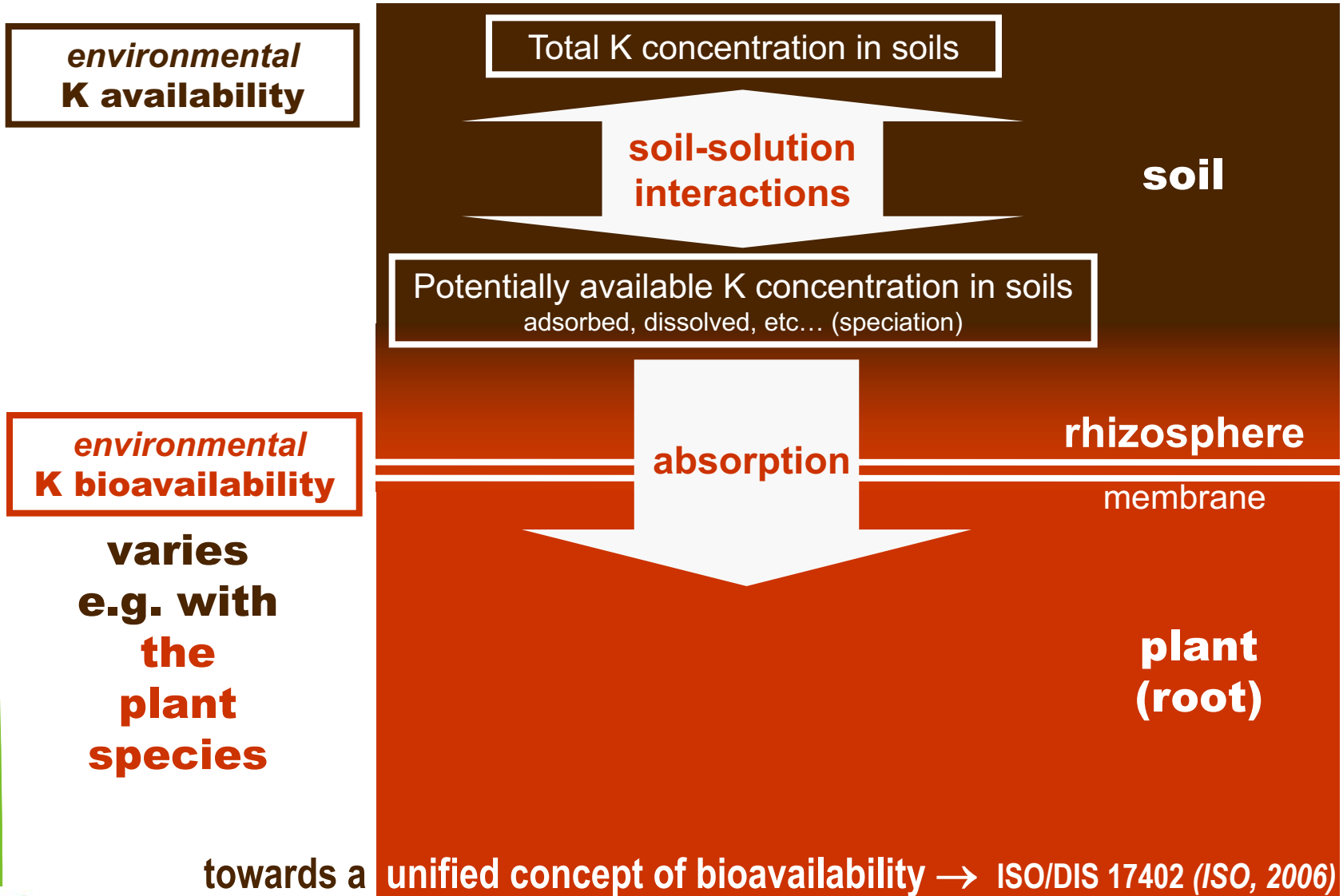
(Harmsen et al., 2005 – Land Contam. Reclam. 13 ; Harmsen, 2007 – J. Environ. Qual. 36)

→ K availability vs K bioavailability



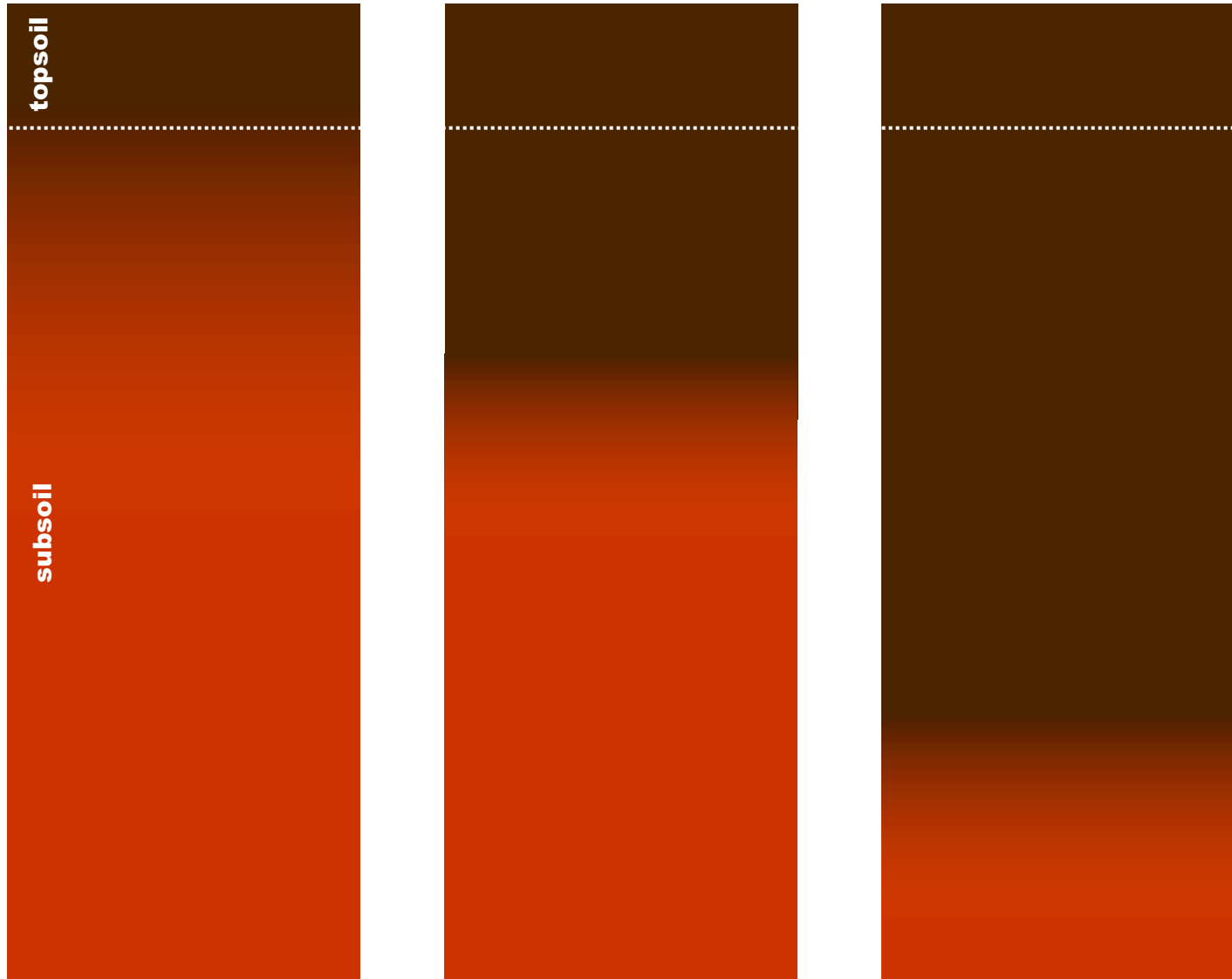
(Harmsen et al., 2005 – Land Contam. Reclam. 13 ; Harmsen, 2007 – J. Environ. Qual. 36)

→ K availability vs K bioavailability



(Harmsen et al., 2005 – Land Contam. Reclam. 13 ; Harmsen, 2007 – J. Environ. Qual. 36)

→ K distribution : topsoil vs subsoil K availability

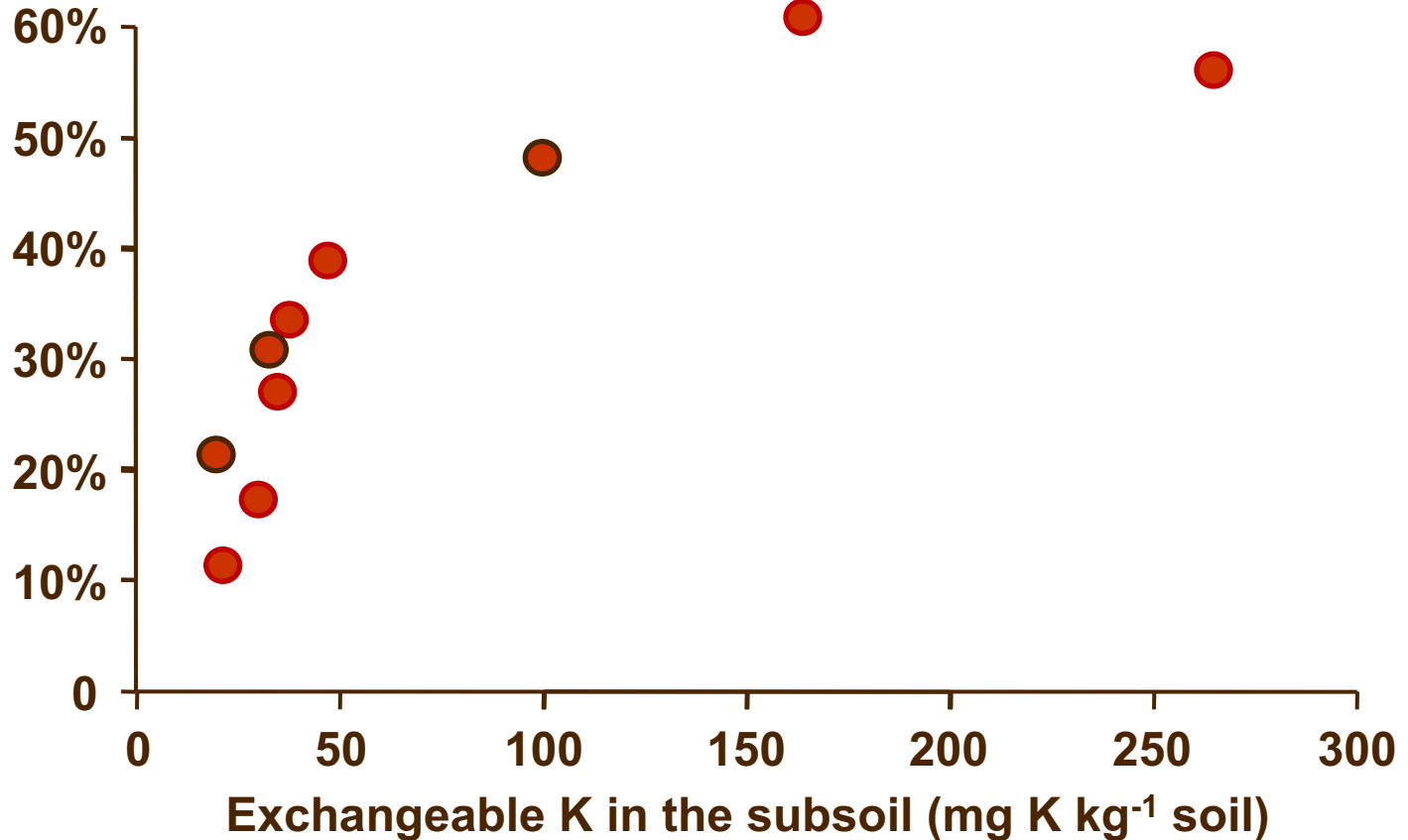


→ some soils can exhibit strong vertical gradients while others show more even distribution of K with depth

→ **K distribution : topsoil vs subsoil K availability**

→ **large contribution of subsoil K, depending on its K content**

% uptake from subsoil K



K uptake from the subsoil in a loess soil with topsoil $\text{exch. K} = 90 \text{ mg K kg}^{-1} \text{ soil}$ in 10 plots cropped with spring wheat in Germany (for two years)

(Kuhlmann 1990 – Plant Soil 127)

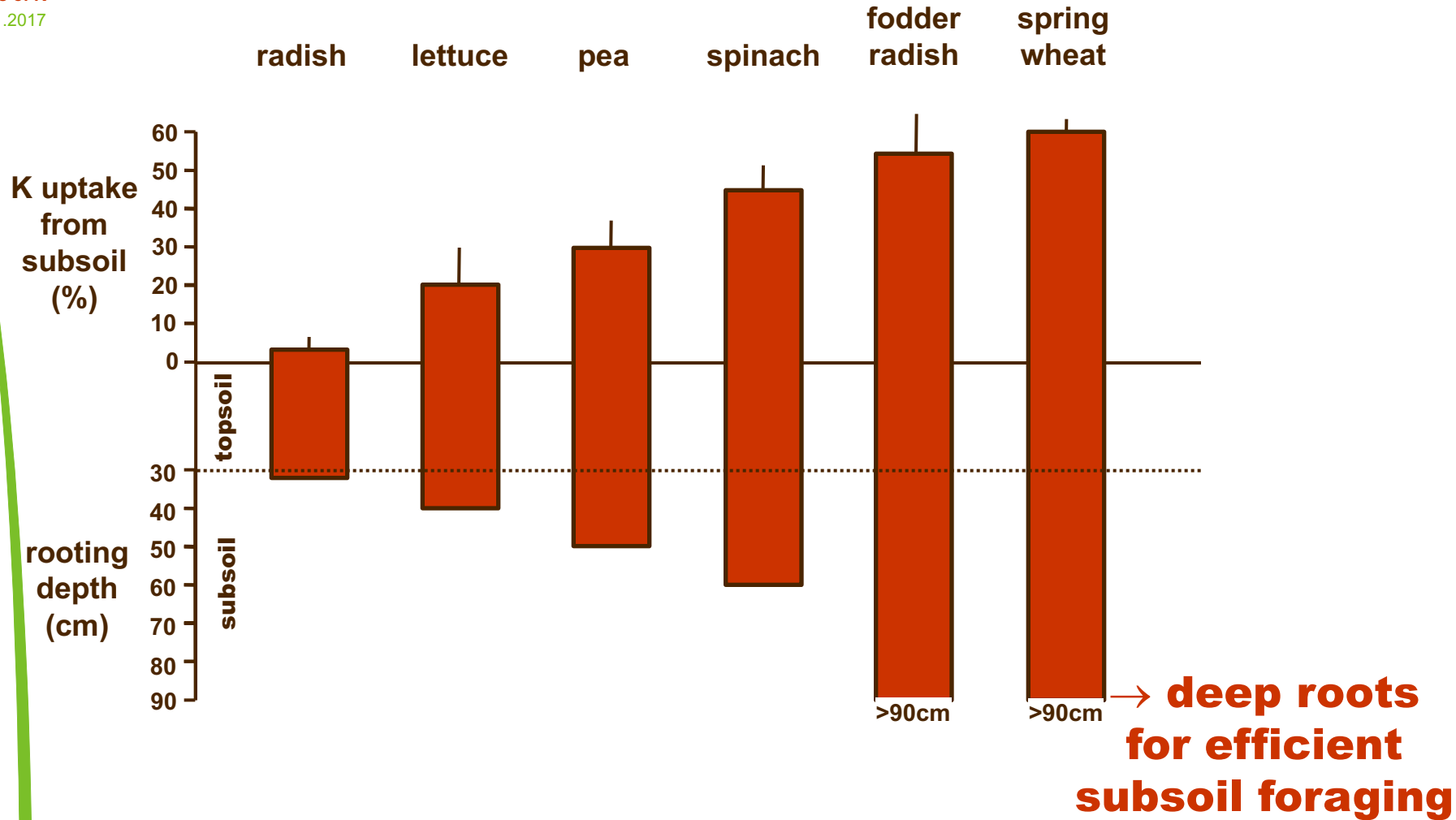
→ **root morphological traits determining the K foraging capacity of plants**

→ **root system architecture and plasticity**

→ **root length and growth**

→ **root hairs and mycorrhiza**

→ root system architecture and plasticity

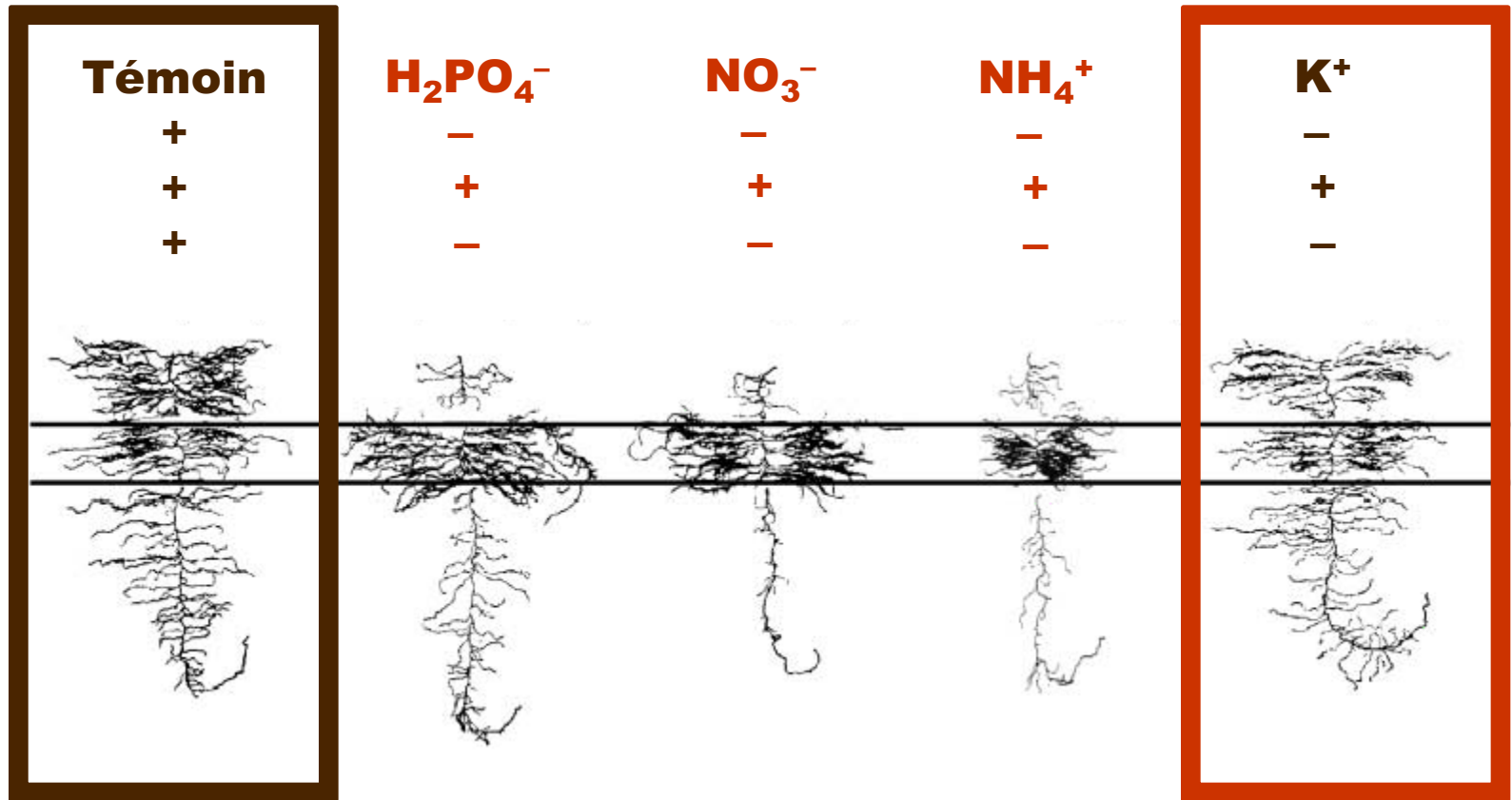


K uptake from the subsoil in a loess soil with topsoil exch. K = 90 mg K kg⁻¹ soil as related to rooting depth of different crop species

(Kuhlmann 1990 – Plant Soil 127)

→ root system architecture and plasticity

→ no plasticity for K acquisition, as for P or N



Root proliferation (foraging) in the central compartment (100-fold enriched) in hydroponically-grown barley : **does not occur for K**

(Drew, 1975 – *New Phytol.* 75)

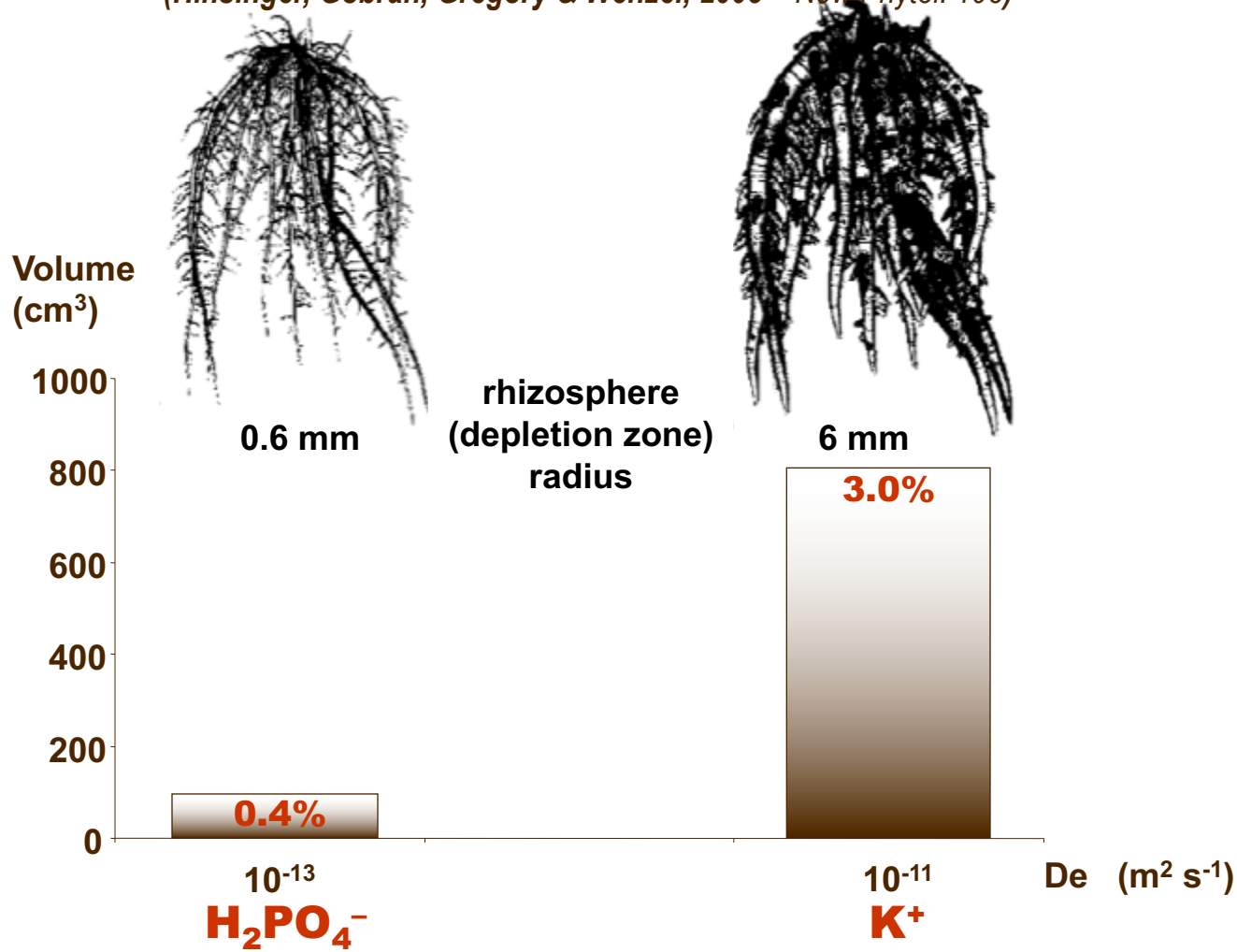
→ root system architecture and plasticity

→ **rhizosphere = small fraction of whole soil**

(Hinsinger, Gobran, Gregory & Wenzel, 2005 – *New Phytol.* 195)



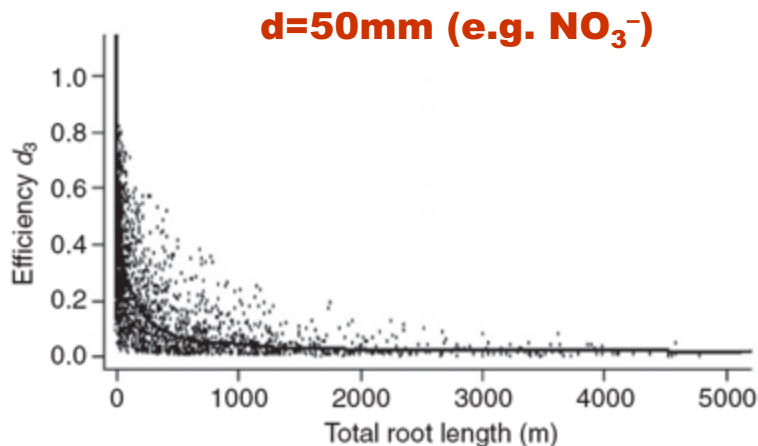
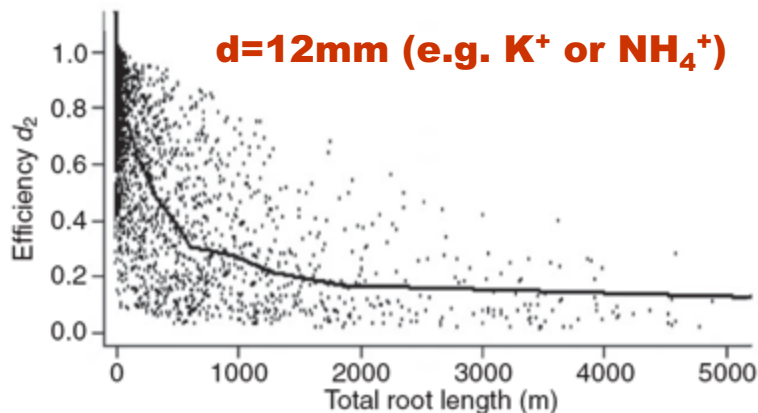
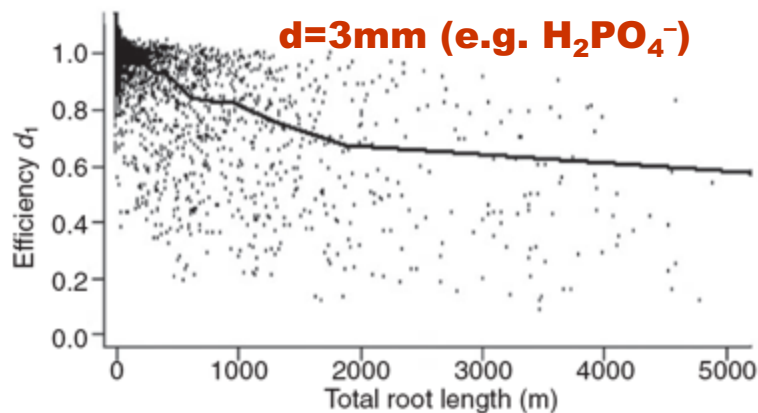
root architecture



Simulation of the volume of depletion zones for poorly-mobile nutrients exhibiting different diffusion coefficients (De) in 13-day old common bean

(Ge, Rubio & Lynch, 2000 – *Plant Soil* 218)

→ **root length and growth**



Relation between efficiency* and total length of the root system (4096 simulations)

(Pagès, 2011 – Plant Cell Environ. 34)

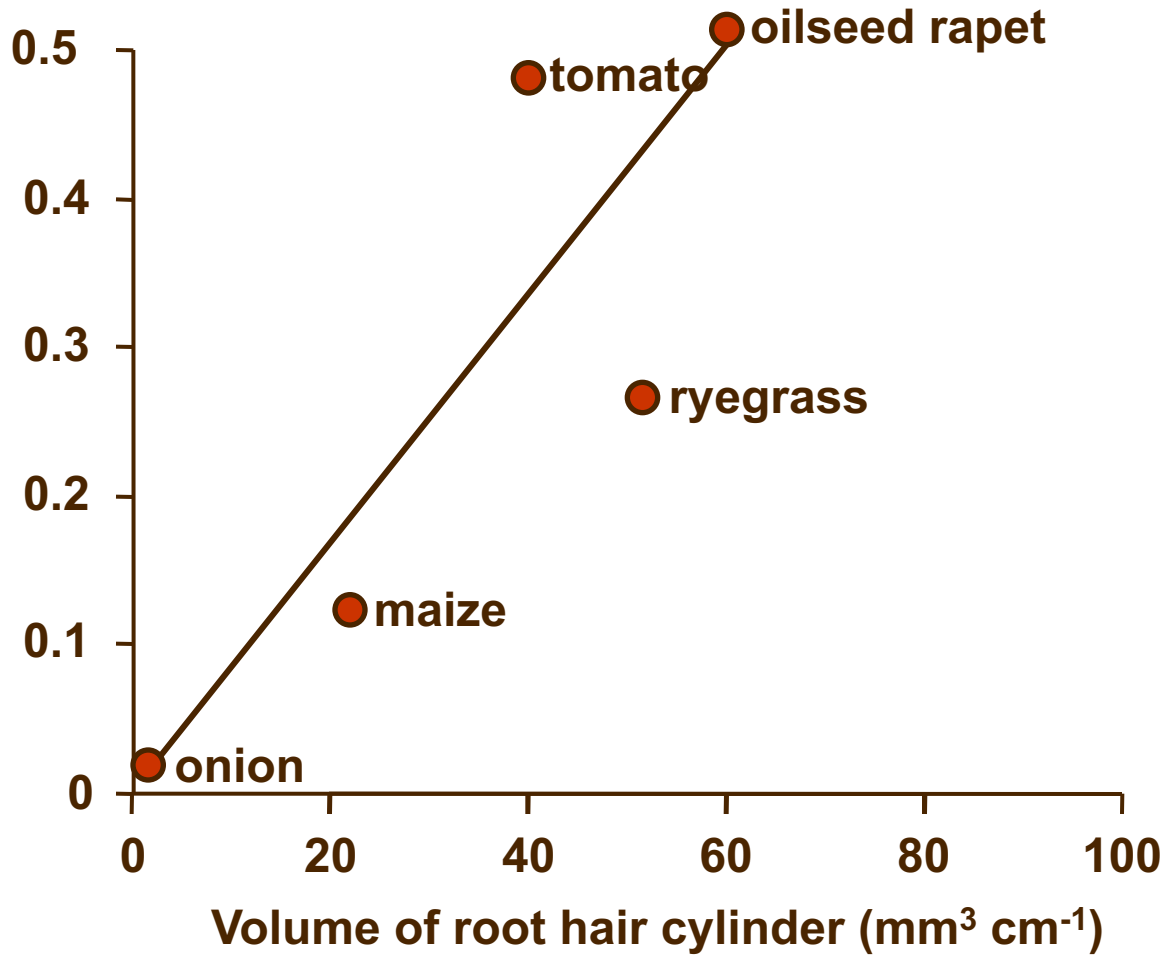
* the ratio of the colonized volume to the volume of a virtual cylinder with the same length as the whole root system

$$e = EV / (\pi * TL * d_i^2)$$

→ increasing root length is less necessary for K than for phosphate, but more so than for nitrate

→ **root hairs and mycorrhiza**

K uptake rate
($\text{pmol cm}^{-1} \text{s}^{-1}$)

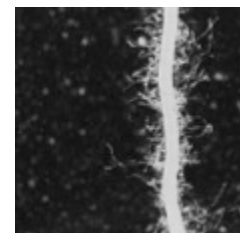
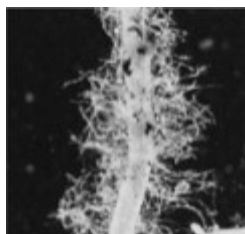


→ **a key role of root hairs in K acquisition**

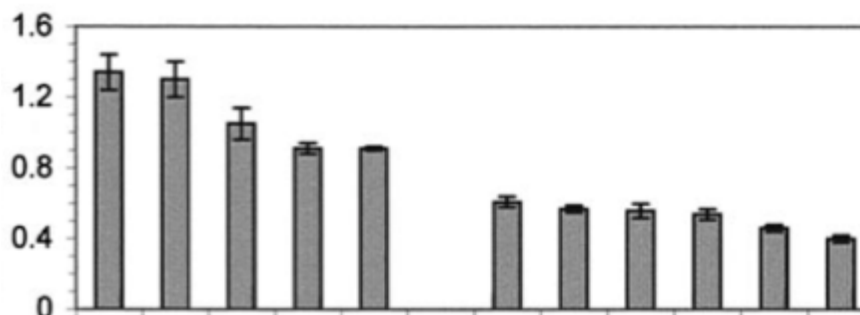
K acquisition vs root hair length, and hence volume of the rhizosphere

(Claassen & Jungk 1984 – *Z. Pflanzenern. Bodenkd.* 147 ; Jungk 2001 – *J. Plant Nutr. Soil Sci.* 164)

→ root hairs and mycorrhiza



Root hair length
(mm)



→ **substantial variation within a given crop species**

Genotypic variation of root hair length in barley
(and thus volume of soil explored)

(Gahoonia & Nielsen, 1995 – Plant Soil 262)

→ **root hairs and mycorrhiza**



→ **while mycorrhizal hyphae can considerably increase the actual volume of the rhizosphere / depletion zone (extending up to several centimeters from root surface),**

(Jakobsen, Abbott & Robson, 1992 – New Phytol. 120; Thonar, Schnepf, Frossard, Roose & Jansa, 2011 – Plant Soil 339)

their quantitative contribution to K acquisition is little documented, compared with P acquisition

→ **root physiological traits determining the K mining capacity of plants**

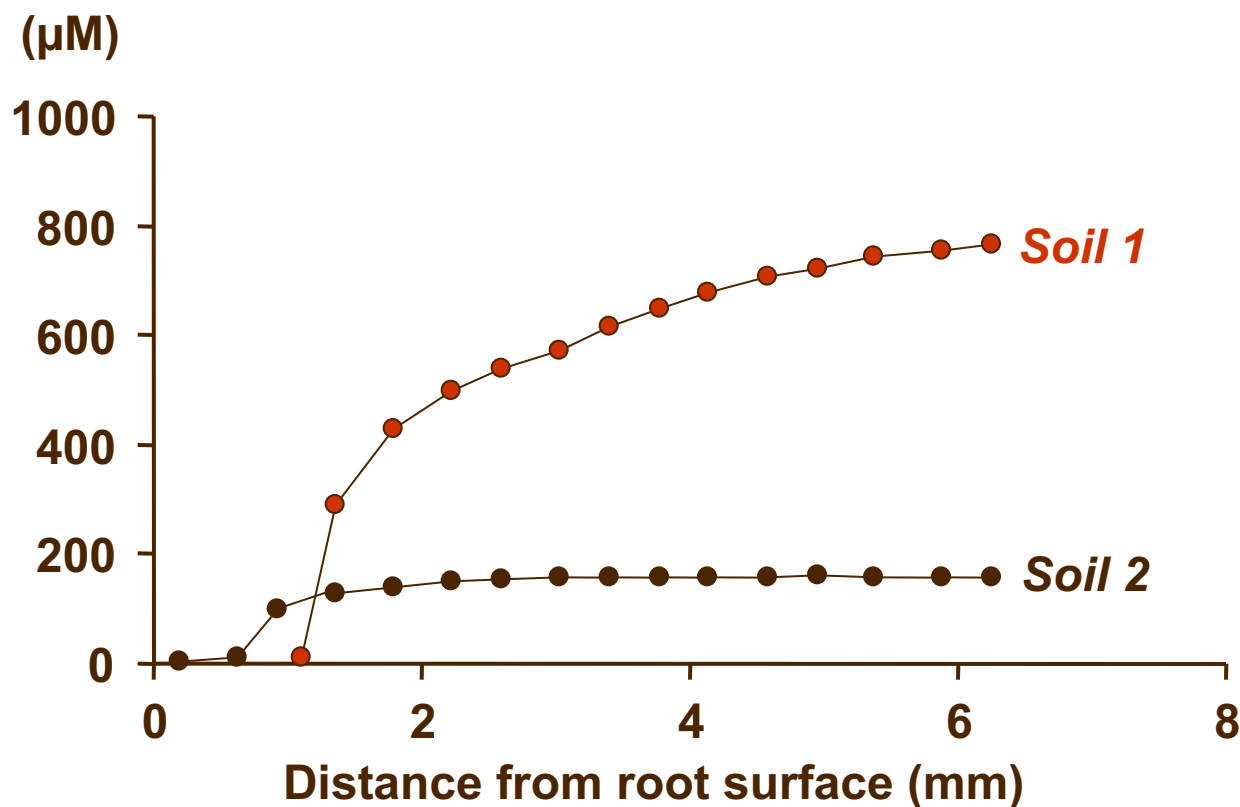
→ **K uptake and depletion in the rhizosphere**

→ **pH modification in the rhizosphere**

→ **exudation in the rhizosphere**

→ K uptake and depletion in the rhizosphere

Soil solution K concentration



→ **steep depletion: rhizosphere K concentration \approx 2-3 μ M**

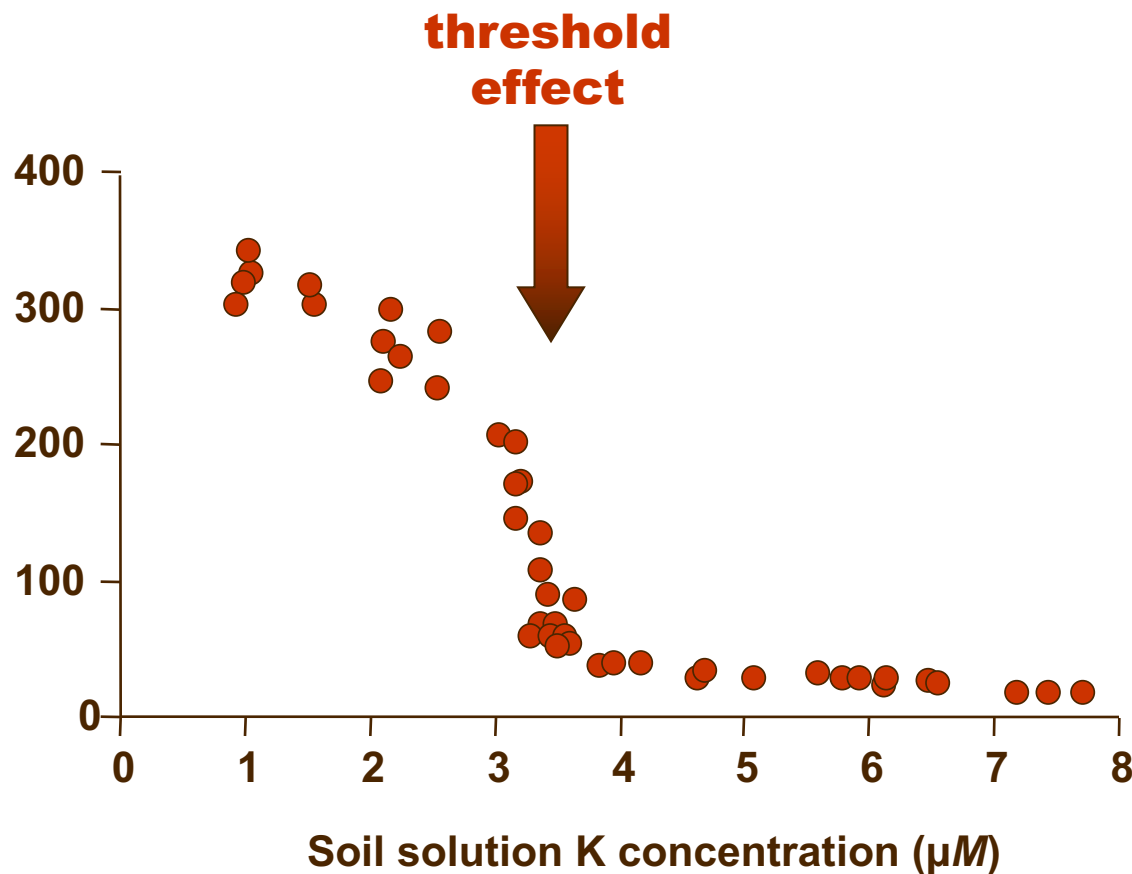
→ **driving force for root-induced release of interlayer K**

Depletion of K in the rhizosphere of maize in two different soils

(Claassen & Jungk 1982 - Z. Pflanzenernaehr. Bodenkd. 145)

→ K uptake and depletion in the rhizosphere

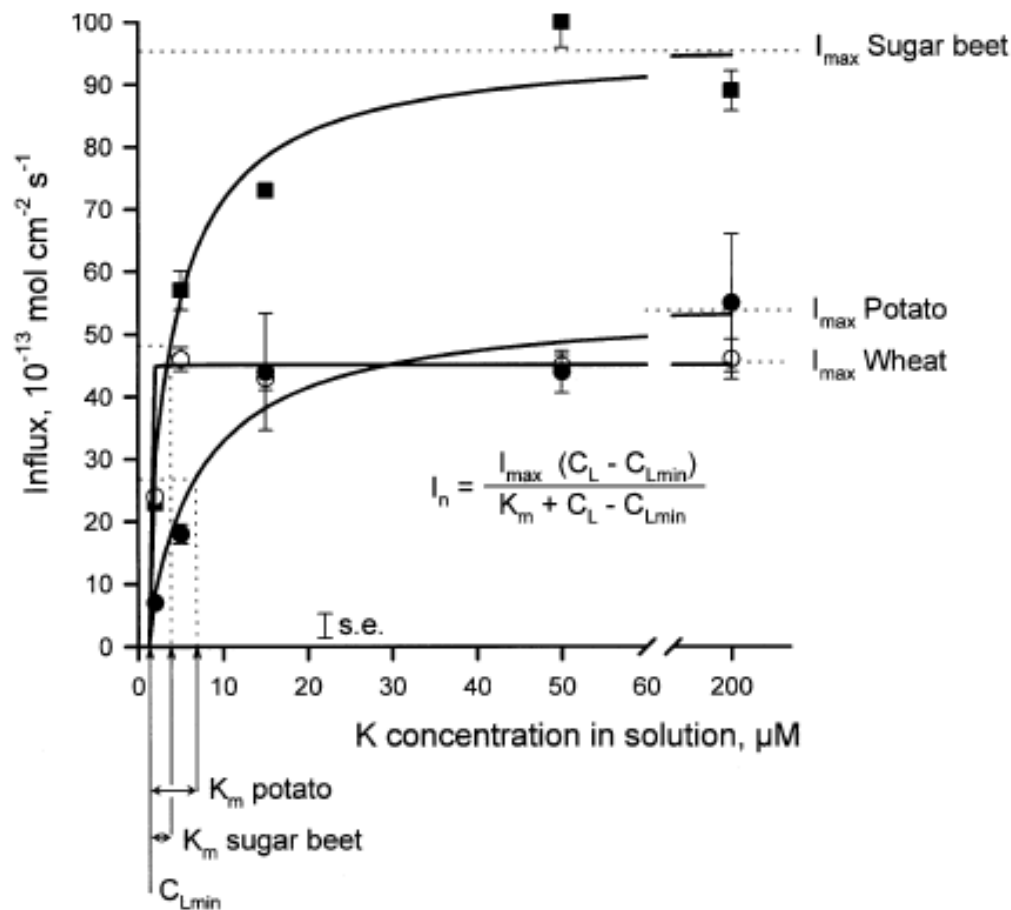
Rate of release of nonexchangeable K ($\mu\text{mol K kg}^{-1} \text{ day}^{-1}$)



Low K concentration in the soil solution (below a threshold value of 3-4 μM) is promoting the release of nonexchangeable K in soils

(Springob & Richter, 1998 – *J. Plant Nutr. Soil Sci.* 161)

→ K uptake and depletion in the rhizosphere



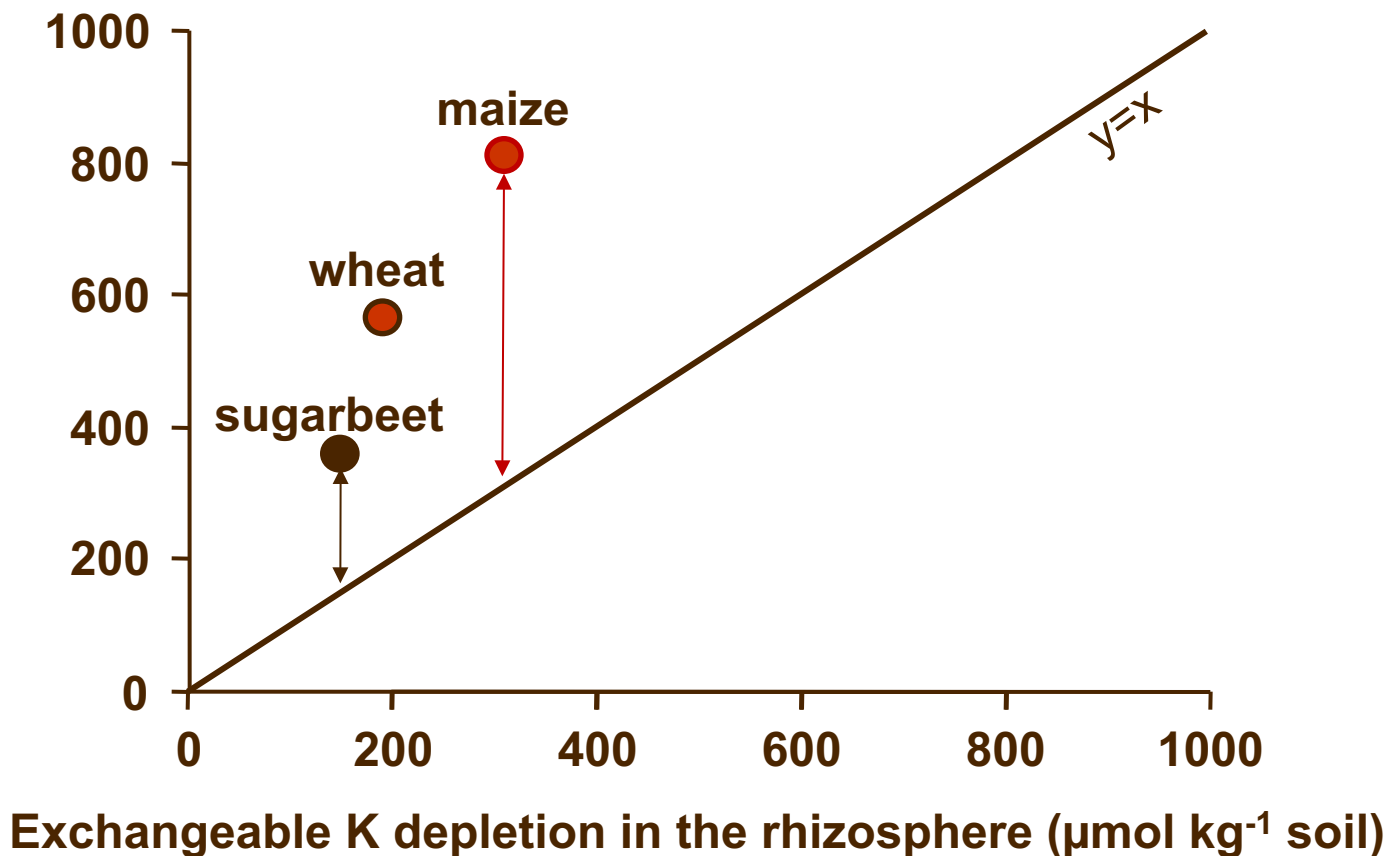
→ **wheat and sugar beet can take up more K than potato at low concentrations**

K uptake kinetics of three crop species, showing that poor K acquisition efficiency of potato is related to its lesser uptake capacity (higher K_m)

(Steingrobe & Claassen, 2000 – J. Plant Nutr. Soil Sci. 163)

→ K uptake and depletion in the rhizosphere

Bioavailable K ($\mu\text{mol kg}^{-1}$ soil)



→ **large contribution of nonexchangeable K release**
sugarbeet < wheat < maize

K acquisition (= bioavailable K) vs exchangeable K depletion in the rhizosphere of three crop species in a low K soil (unfertilized)

(Samal, Kovar, Steingrobe, Sadana, Bhadoria & Claassen 2010 – Plant Soil 332)

→ mining strategies of K acquisition

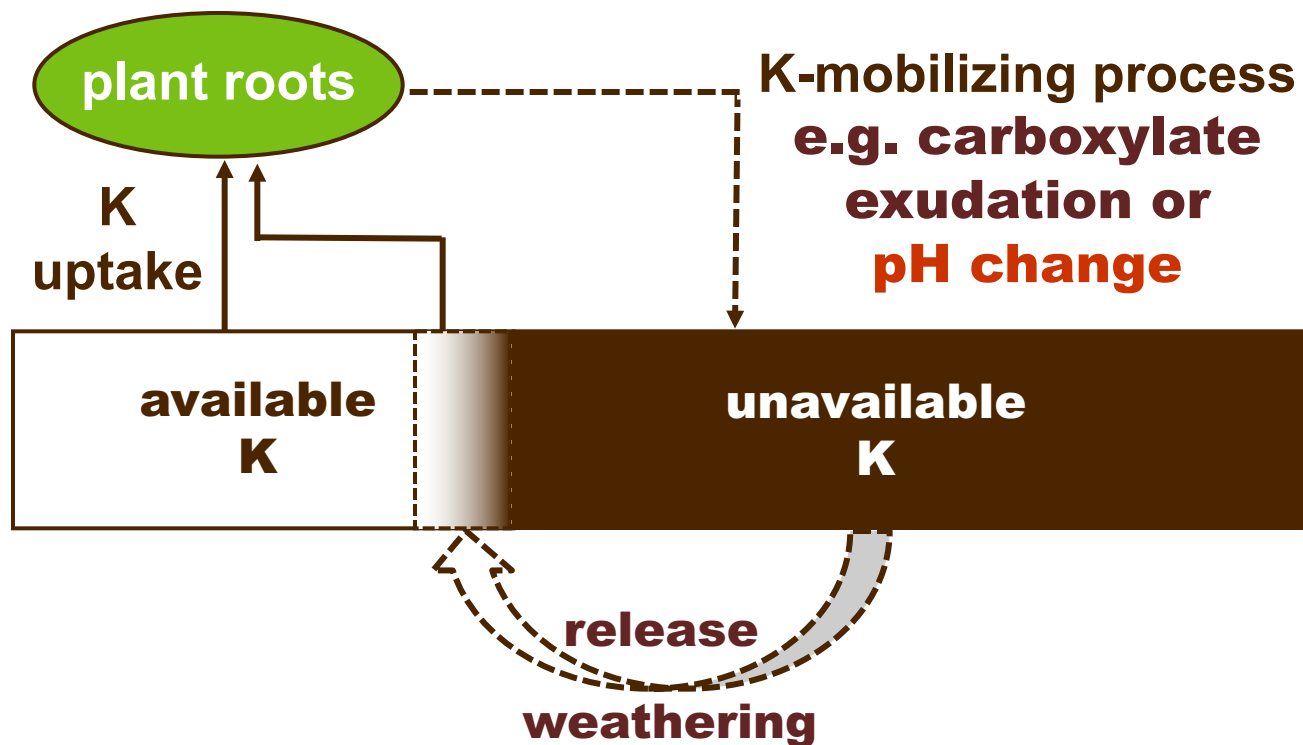


Rhizosphere processes possibly contributing to
the mining strategy of plant roots

(Hinsinger et al. 2011 – Plant Soil / Marschner Review)

→ mining strategies of K acquisition

→ **root mining strategy**
resulting in increased rhizosphere K availability

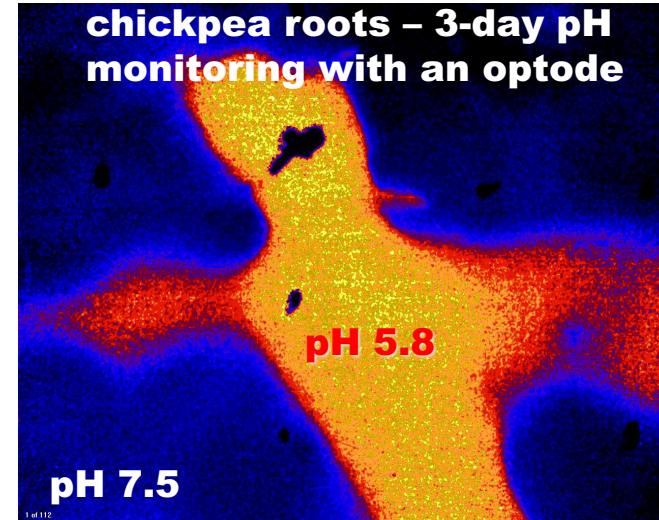
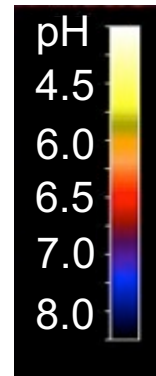


Rhizosphere processes possibly contributing to
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(Hinsinger et al. 2011 – Plant Soil / Marschner Review)

→ mining strategies of K acquisition

→ root mining strategy
resulting in increased rhizosphere K availability



→ pH modification in the rhizosphere
considerable: up to +/- 2-3 pH units

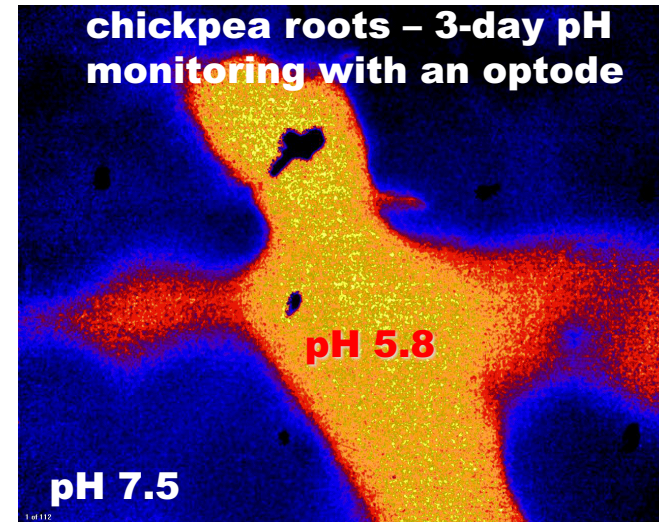
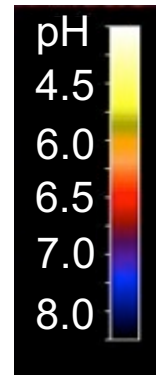
(Blossfeld, Schreiber, Liebsch, Kuhn
& Hinsinger 2013 – Ann. Bot. 112)

(Hinsinger, Plassard, Tang & Jaillard, 2003 - Plant Soil 248)

resulting in K release from mica (Hinsinger, Elsass, Jaillard & Robert, 1993 – J. Soil Sci. 44)

→ mining strategies of K acquisition

→ **root mining strategy**
resulting in increased rhizosphere K availability



→ **pH modification in the rhizosphere**
considerable: up to +/- 2-3 pH units

(Hinsinger, Plassard, Tang & Jaillard, 2003 - Plant Soil 248)

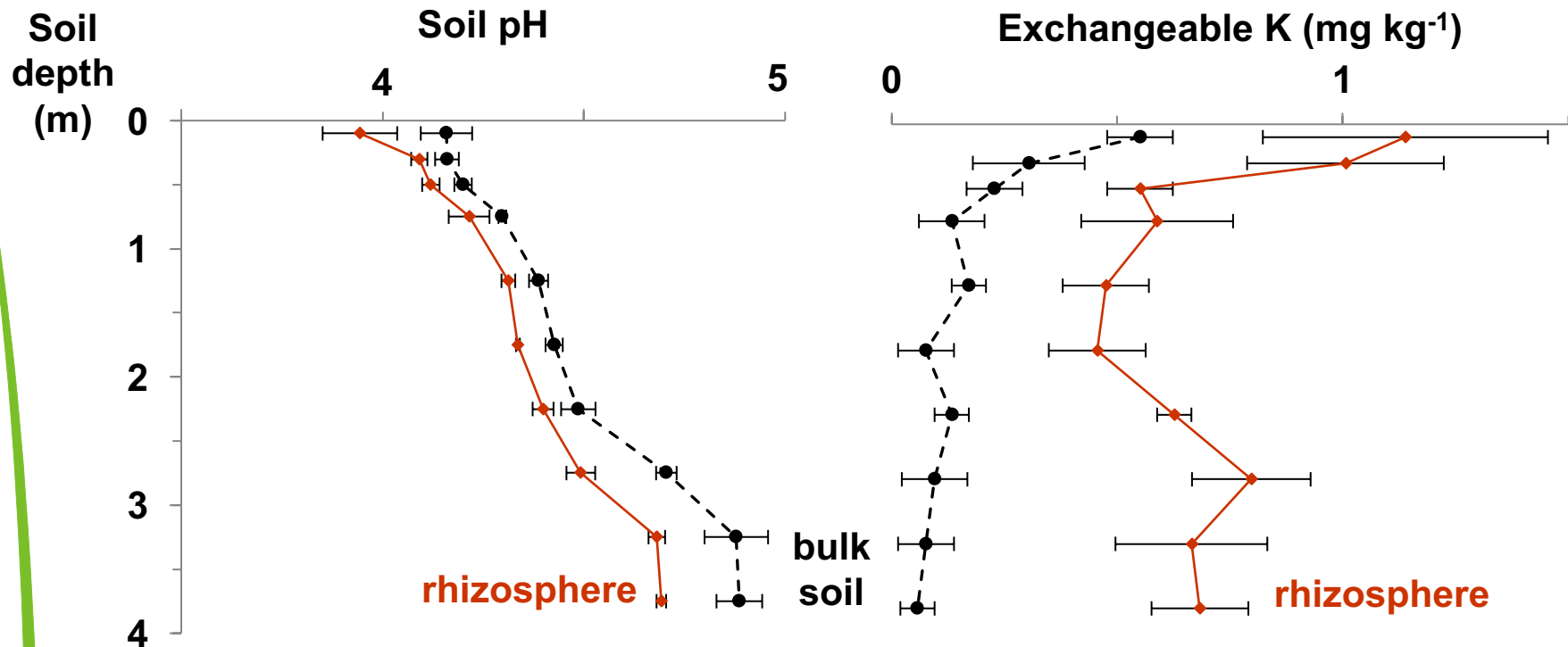
resulting in K release from mica *(Hinsinger, Elsass, Jaillard & Robert, 1993 – J. Soil Sci. 44)*

(Blossfeld, Schreiber, Liebsch, Kuhn & Hinsinger 2013 – Ann. Bot. 112)

→ **exudation in the rhizosphere:**
role of complexing carboxylates such as citrate, oxalate ?

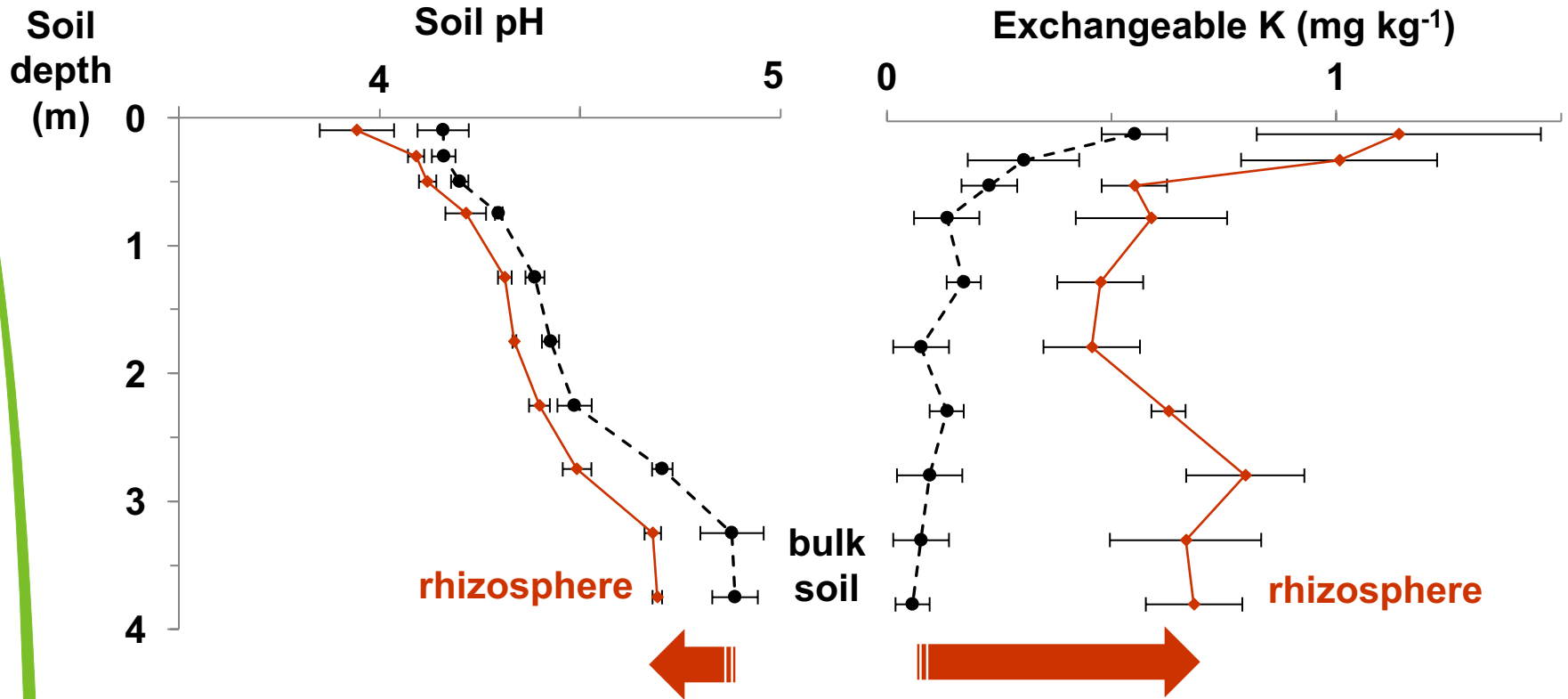
...little direct evidence except for **ectomycorrhizal roots of trees**

resulting in K release from mica / feldspar *(Wallander & Wickman, 1999 – Mycorrhiza 9)*



Root-induced acidification and increase of available K at depth in the rhizosphere of eucalypts in a deep, poor oxisol in Brazil
 (Pradier, Hinsinger, Laclau, Bouillet, Guerrini, Gonçalves, Asensio, Abreu-Junior & Jourdan 2017
 – Plant Soil in press)

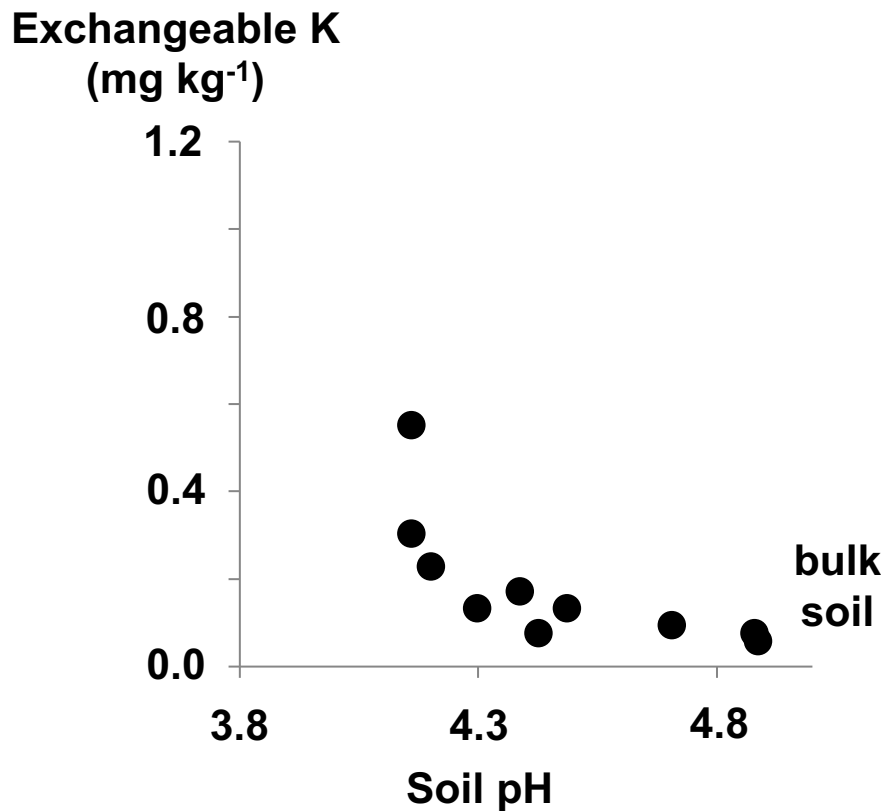
→ mining strategies of K acquisition



→ **acidification & weathering of K-silicates in the rhizosphere ?**

Root-induced acidification and increase of available K at depth in the rhizosphere of eucalypts in a deep, poor oxisol in Brazil
 (Pradier, Hinsinger, Laclau, Bouillet, Guerrini, Gonçalves, Asensio, Abreu-Junior & Jourdan 2017
 – Plant Soil in press)

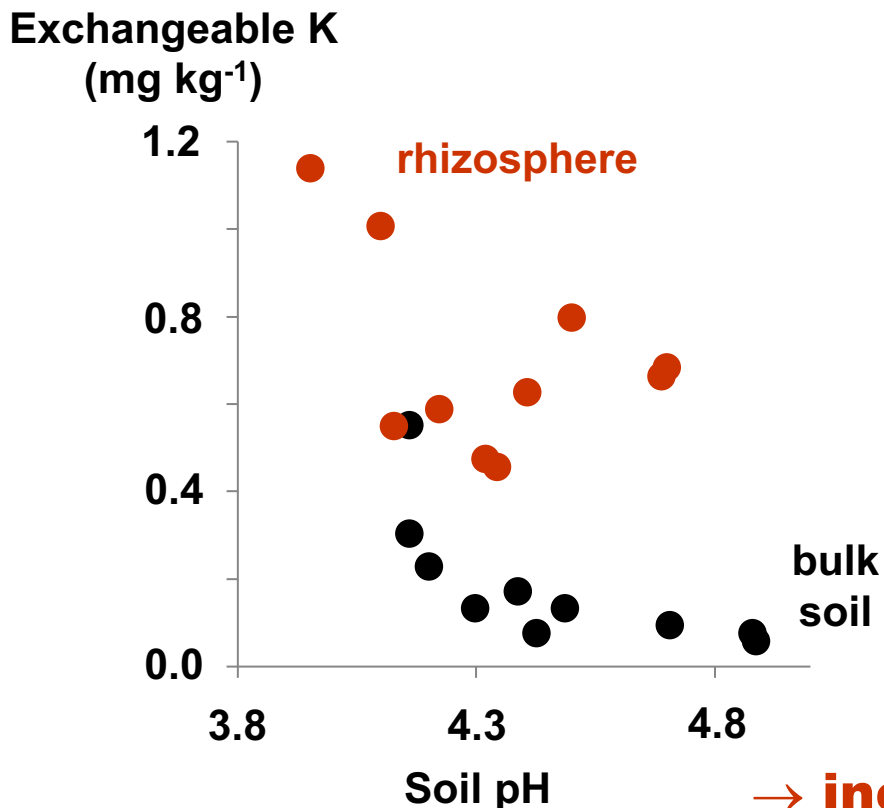
→ mining strategies of K acquisition



Relationship between pH and available K across soil depths
in the bulk soil in a deep, poor oxisol in Brazil

(Pradier, Hinsinger, Laclau, Bouillet, Guerrini, Gonçalves, Asensio, Abreu-Junior & Jourdan 2017
– Plant Soil in press)

→ mining strategies of K acquisition



→ **increased K availability in the rhizosphere is only partly due to root-induced acidification...
... role of exudates ???**

Relationship between pH and available K across soil depths in the bulk soil / rhizosphere of eucalypts in a deep, poor oxisol in Brazil
(Pradier, Hinsinger, Laclau, Bouillet, Guerrini, Gonçalves, Asensio, Abreu-Junior & Jourdan 2017
– Plant Soil in press)



**Manipulating either root traits
or microbial communities**

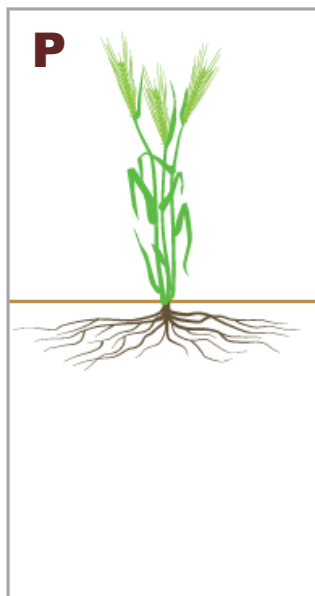
→ **root and
rhizosphere
strategies**

for an ecological intensification
of agroecosystems

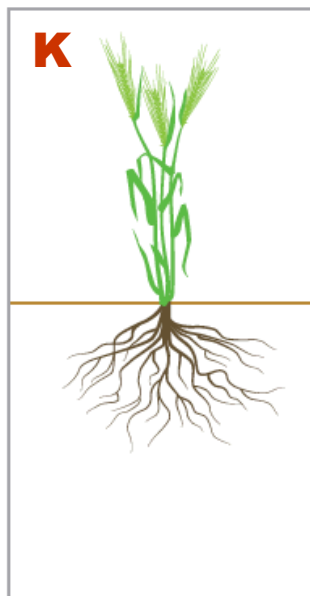
(Bakker, Manter, Sheflin, Weir & Vivanco, 2012 – Plant Soil)

- **Root foraging strategies**
 - **Root architecture**
 - **Root length and growth**
 - **Root hairs**
 - ***Mycorrhizal symbiosis***
+ *PGPR-induced promotion*
- **Root mining strategies**
 - **Rhizosphere K depletion**
 - **Rhizosphere acidification**
 - **Organic C exudation**
 - ***Microbial activity stimulation***

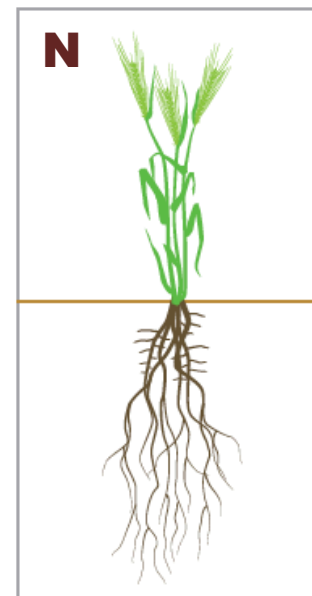
→ conclusions : root traits for nutrient acquisition



Topsoil foraging for P
 Early root vigour
 Large root biomass or root/shoot ratio
 More cortical aerenchyma
 Large root surface area (lateral rooting, root hairs) in topsoil
 High root length density
 Proliferation in patches of high P phytoavailability
 Mycorrhizal associations
 Greater exudation of H⁺ and organic compounds
 Greater exudation of phosphatases
 Greater phosphate uptake capacity of root cells



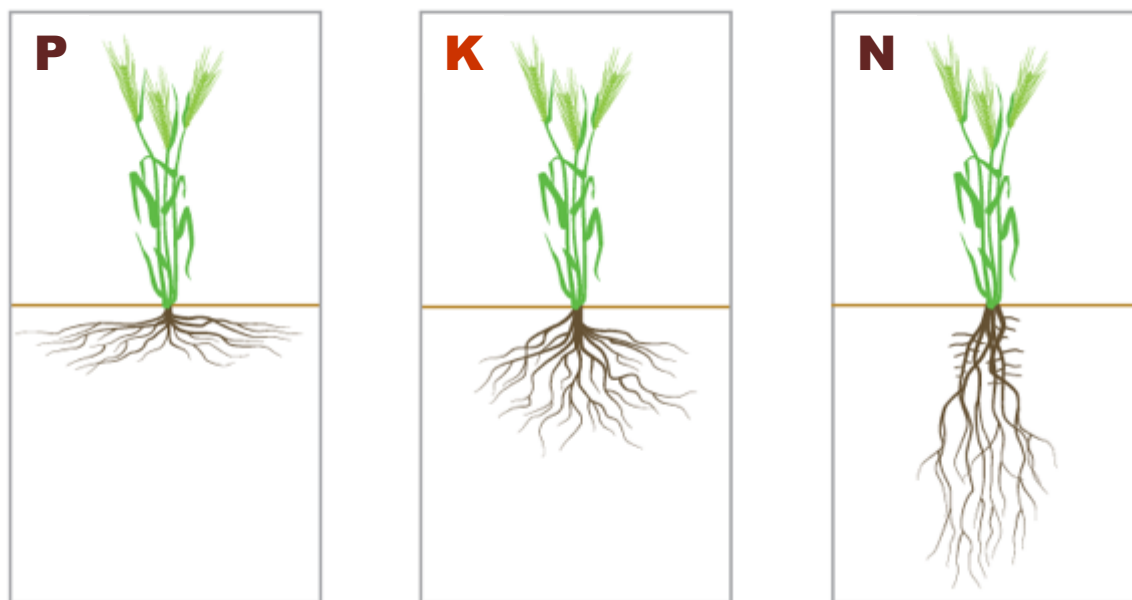
Intermediate response for K
 Early root vigour
 Large root biomass or root/shoot ratio
 More cortical aerenchyma
 Large root surface area (lateral rooting, root hairs)
 High root length density
 Proliferation in patches of high K phytoavailability
 Greater exudation of H⁺ and organic compounds
 Greater K⁺ uptake capacity of root cells
 Greater water uptake through transpiration



Steep, cheap and deep for N
 Early root vigour
 Large root biomass or root/shoot ratio
 More cortical aerenchyma
 Initial roots with shallow growth angles
 Later roots with steep root growth angles
 Large root surface area (lateral rooting, root hairs)
 High root length density
 Greater N-uptake capacity of root cells
 Greater water uptake through transpiration
 Greater exudation of Biological Nitrification Inhibitors
 Greater association with organisms fixing N₂

(White, George, Gregory, Bengough, Hallett & McKenzie 2013 – Ann. Bot.112)

→ **conclusions : root traits for nutrient acquisition**



topsoil foraging

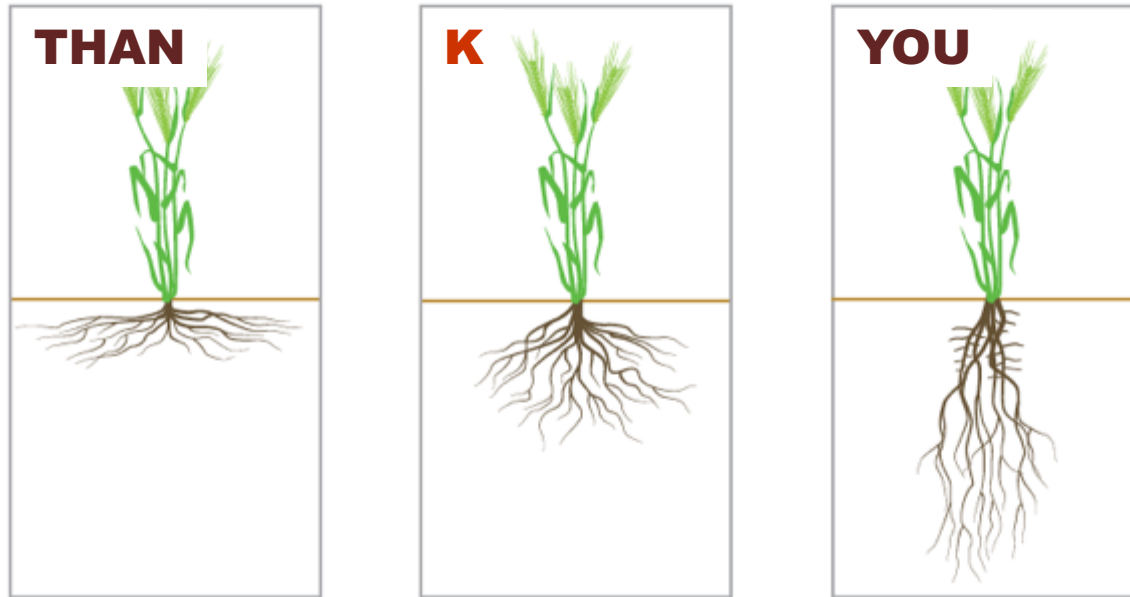
intermediate response

steep, cheap and deep

→ **a matter of trade-offs when aiming for improving simultaneously P, K and N (or water) acquisition efficiency**

(White, George, Gregory, Bengough, Hallett & McKenzie 2013 – Ann. Bot. 112)

→ **conclusions : root traits for nutrient acquisition**

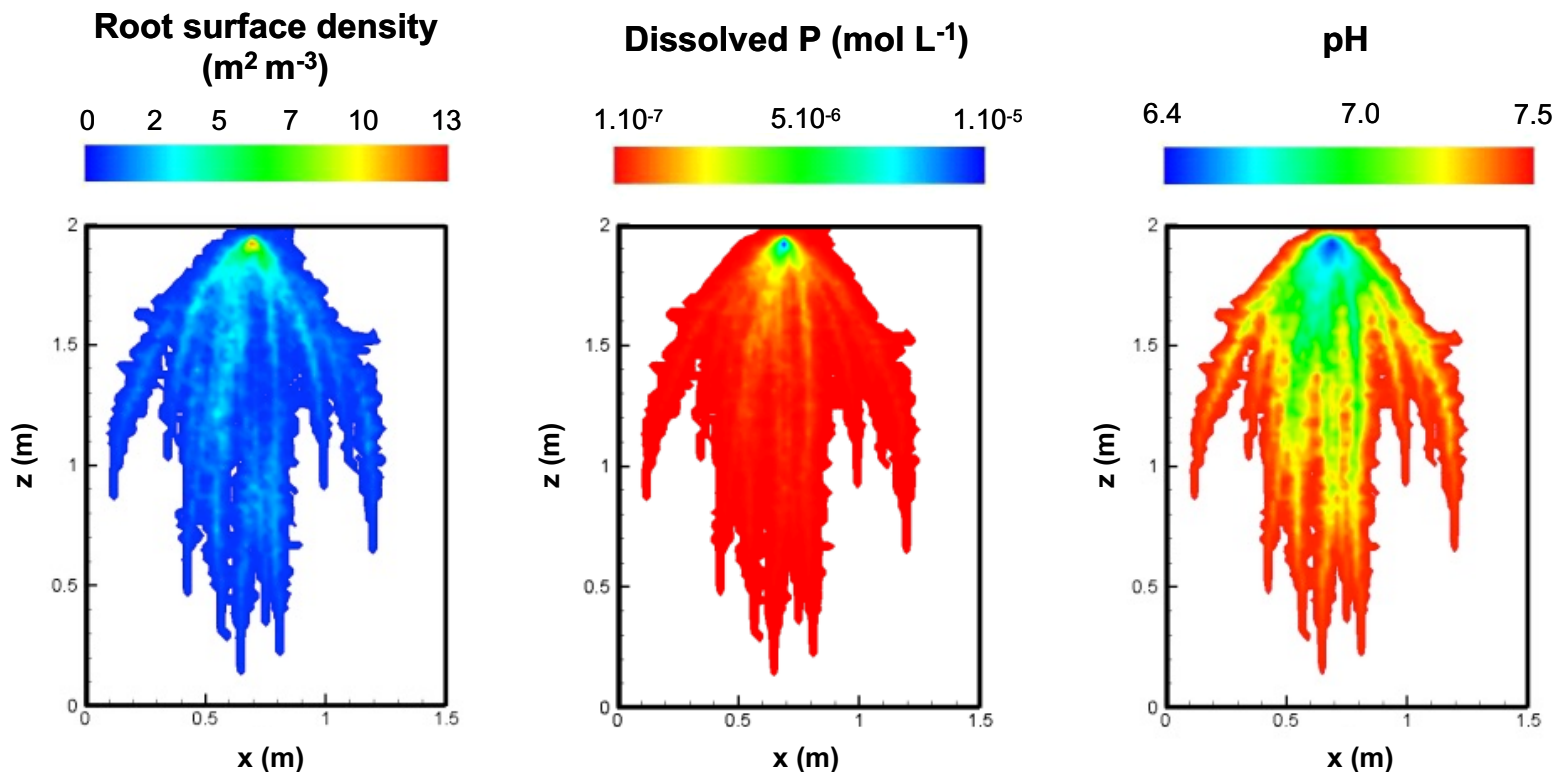


→ **any questions ?**



→ root strategies for improving P efficiency

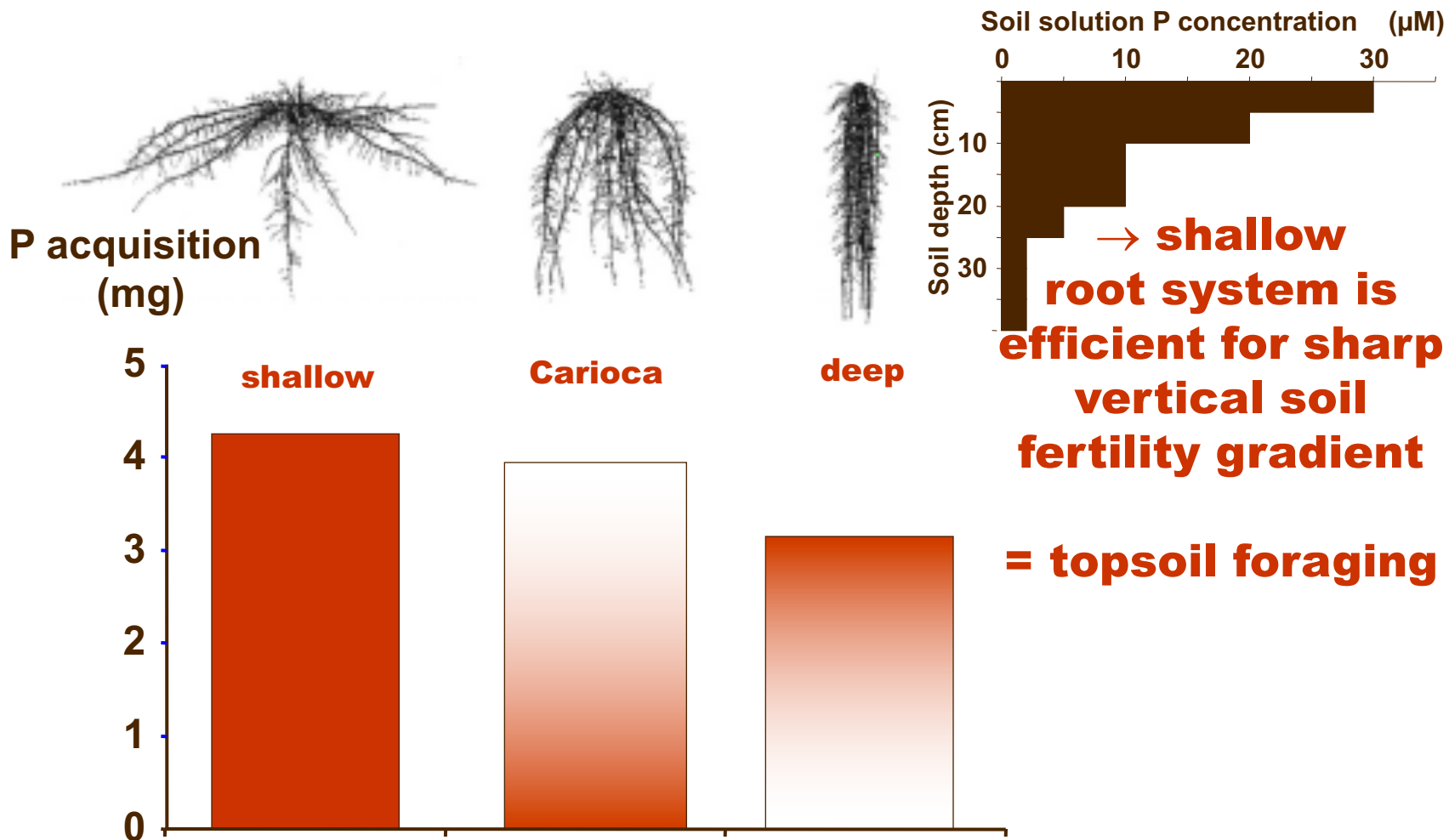
→ Pyramiding the foraging and mining strategies of P acquisition – numerical modelling to find novel ideotypes



Coupling the ArchiSimple and MIN3P models in a cereal (e.g. maize) –
Rhizosphere acidification is solubilising more P where root density is greatest

(Gérard, Blitz, Hinsinger & Pagès 2016 – Plant Soil)

→ root system architecture and plasticity



Simulated P acquisition as a function of root architecture in common bean grown in a soil exhibiting a strong P availability gradient in the topsoil
(Ge, Rubio & Lynch, 2000 – Plant Soil 218)