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Sampling, defining, characterising and modeling the rhizosphere – The soil science tool box

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Keywords

geophysics, imaging, isotope probing, microcosms, soil solution, spectroscopy

Abstract

We review methods and models that help to assess how root activity changes soil properties and affects the fluxes of matter in the soil. Subsections discuss (i) experimental systems including plant treatments in artificial media, studying the interaction of model root and microbial exudates with soil constituents, and microcosms to distinguish between soil compartments differing in root influence, (ii) the sampling and characterization of rhizosphere soil and solution, focusing on the separation of soil at different distances from roots and the spatially resolved sampling of soil solution, (iii) cutting-edge methodologies to study chemical effects in soil, including the estimation of bioavailable element or ion contents (biosensors, diffusive gradients in thin-films), studying the ultrastructure of soil components, localizing elements and determining their chemical form (microscopy, diffractometry, spectrometry), tracing the compartmentalization of substances in soils (isotope probing, autoradiography), and imaging gradients in-situ with micro electrodes or gels or filter papers containing dye indicators, (iv) spectroscopic and geophysical methods to study the plants influence on the distribution of water in soils, and (v) the modeling of rhizosphere processes. Macroscopic models

42 with a rudimentary depiction of rhizosphere processes are used to predict water or nutrient
43 requirements by crops and forests, to estimate biogeochemical element cycles, to calculate soil water
44 transport on a profile scale, or to simulate the development of root systems. Microscopic or
45 explanatory models are based on mechanistic or empirical relations that describe processes on a single
46 root or root system scale and / or chemical reactions in soil solution.
47 We conclude that in general we have the tools at hand to assess individual processes on the microscale
48 under rather artificial conditions. Microscopic, spectroscopic and tracer methods to look at processes
49 in small „aliquots" of naturally structured soil seem to step out of their infancy and have become
50 promising tools to better understand the complex interactions between plant roots, soil and
51 microorganisms. On the field scale, while there are promising first results on using non-invasive
52 geophysical methods to assess the plant's influence on soil moisture, there are no such tools in the
53 pipeline to assess the spatial heterogeneity of chemical properties and processes in the field. Here,
54 macroscopic models have to be used, or model results on the microscopic level have to be scaled up to
55 the whole plant or plot scale. Upscaling is recognized as a major challenge.
56

57 **Introduction**

58 There are two basic questions involved with this part of rhizosphere research. (i) How are physical and
59 chemical soil properties and related functional parameters (e.g. structural stability, availability of
60 water, nutrients or toxic substances) affected by root growth, root physiological processes involved in
61 nutrient acquisition and uptake and related root-microbe interactions, and how far do these effects
62 extend from the root (Hinsinger et al. 2005)? (ii) How do these root-related processes affect the fluxes
63 of water, elements and ions in the soil, and thus biogeochemical cycles? On principle all methods for
64 the analysis and modeling of the properties of the respective soil phases apply and can be looked up in
65 standard textbooks such as Weaver et al. (1994; biochemical and isotopic methods), Sparks (1996;
66 chemical methods), Dane and Topp (2002; physical methods), Pansu and Gautheyrou (2006;
67 mineralogical and chemical methods) and Nollet (2007; water analysis with implications for soil
68 solution analysis). The critical issue, which is the red-line of this chapter, is to separate, define or
69 identify the rhizosphere. In a first section, the various degrees of simplifying real soil and
70 experimental systems to study the interaction of model root and microbial exudates with soil
71 constituents are discussed. Laboratory and field systems are presented that allow a distinction of soil
72 compartments in terms of root influence, that facilitate the sampling of rhizosphere soil or soil
73 solution, or that enable the *in-situ* analysis of the root's influence on soil properties. In the second
74 section, methods to separate rhizosphere from bulk soil and to sample rhizosphere solution and gas are
75 presented together with a brief overview of analytical methods for their characterization. Soil
76 biological methods are described by Sørensen et al. (2008). The third section is devoted to cutting-
77 edge methodologies to study chemical effects in soils. This includes techniques to assess bioavailable
78 contents, to trace the compartmentalization of organic carbon, and to map the distribution of elements
79 and species *in-situ*. In the fourth section, the prospects of spectroscopic and geophysical methods to
80 image non-invasively the plant influence on soil moisture distribution in the laboratory and field are
81 discussed. Modeling, the topic of the fifth section, is an important tool to understand and predict plant
82 influence on soil properties, and vice versa, how to manage the soil to fulfill plant water and nutrient
83 requirements. In addition, models are useful to estimate how plant activity affects terrestrial element
84 cycles, and vice versa, how plants react to climatic changes. Scaling model results up from the single-

85 root level to the whole-plant, plot or catchment level is one of the most demanding current research
86 issues. In a sixth and last section we discuss this and other challenges ahead. An alternative treatment
87 of aspects dealt with in this paper can be found in Luster and Finlay (2006).
88
89 **Experimental systems**
90 Field soil is a complex three-phase system with varying degrees of spatial and temporal heterogeneity
91 of physical and chemical properties. Soil fauna, microorganisms and growing plant roots increase this
92 heterogeneity. In particular, growing plant roots add spatial gradients in two directions (Fig. 1). Along
93 the growth direction, root segments differ in their functionality in terms of uptake (water, nutrients) or
94 exudation, causing a variability of root-induced changes in the properties of the surrounding soil. This
95 root influence decreases with increasing distance from the root surface leading to gradients from the
96 rhizosphere to the bulk soil. In addition, there is a temporal variation in root influence due to diurnal,
97 seasonal or age related changes in the physiological activity of root segments. Dead parts of the root
98 system first become local sources of organic matter, and after their degradation macropores can be
99 created which can have a strong impact on the soils transport properties. The goal of rhizosphere
100 research being to assess these plant influences, minimising the heterogeneity of the soil itself is an
101 important consideration. The degree of simplification in terms of substrate properties and / or system
102 geometry must be adequate for the problem and allow a correct interpretation of the data.
103
104 *Artificial substrates*
105 The nature of artificial growth media relates to the fact that root activity generally needs water as
106 medium. They either contain no solid phase at all (hydroponics) or employ a solid phase with low
107 chemical reactivity suspended in or irrigated with nutrient or treatment solution. Artificial solid
108 substrates are often easier to sterilize than soil material. Sterilization of soils can alter their chemical
109 and physical properties (Wolf and Skipper 1994) and it is difficult to maintain sterility during longer
110 experiments. As such artificial substrates are excellent tools to study plant physiological reactions
111 (Neumann et al. 2008), but also potential plant effects on soil solution can be investigated.

112 In hydroponic culture the composition of root exudates can be studied without adsorption losses to a
113 solid phase, whereas the effect of mechanical impedance experienced by roots growing in soil on
114 exudation is neglected (Neumann and Römheld 2001). The in- or efflux of ions from root segments
115 can be measured in hydroponics using micro electrodes (Plassard et al. 2002), or in gelatinized
116 solutions by visualizing gradients with dye indicators and quantification with videodensitometry
117 (Plassard et al. 1999). In order to add mechanical impedance to growing roots, while maintaining the
118 advantage of controlled soil solution composition, glass beads (Hodge et al. 1996) or sand mixtures
119 (Tang and Young 1982) have been used as growth media for the collection of root exudates. The
120 chemical inertness of these media, however, is limited (Sandnes and Eldhuset 2003). Volcanic glasses
121 like perlite or clays like vermiculite are excellent preculture media, but are of limited use to assess root
122 exudation or chemical gradients around roots (Heim et al. 2003).
123
124 *Testing root influence on specific soil materials*
125 An effective way of investigating the influence of root activity on the structure or reactivity of soil
126 components like clay minerals or oxides is to study their interaction with isolated root exudates or
127 model compounds (e.g., carboxylates, siderophores) in the absence of plants (Ochs et al. 1993;
128 Reichard et al. 2005). Data on sorption of organic compounds by soil materials can give clues about
129 their migration potential in soils (Jones and Brassington 1998). The compilation of Martell and Smith
130 (1974-1989) provides thermodynamic data on equilibria between exudates as ligands and dissolved
131 metal ions. The behavior of carboxylate anions in soils was reviewed by Jones (1998), that of
132 phytosiderophores by Kraemer et al. (2006). An elegant way to test the effect of individual compounds
133 on the bioavailability of nutrients was presented by Ström et al. (2002). They grew maize seedlings in
134 “rhizotubes”, added a solution with carboxylate anions to a ^{33}P labeled patch of soil, and measured the
135 ^{33}P uptake.
136 Alternatively, minerals can be mixed into an inert substrate and the effect of a growing root system
137 with or without microbial inoculation on weathering can be assessed (Leyval and Berthelin 1991). The
138 spatial extent of root exudation on weathering can be studied effectively using root mat systems as
139 described below (Hinsinger and Gilkes 1997).

140

141 *Laboratory systems to assess gradients in soil*

142 When studying root influence on soil, simplifications with respect to soil structure and root system
143 geometry are usually involved, and / or compartments with a high root density separated from root-
144 free soil. Depending on the system, destructive methods for the collection of rhizosphere soil can be
145 applied, rhizosphere soil solution can be sampled, or gradients can be assessed by non-invasive tools.
146 There is no unambiguous nomenclature for such systems. For example, rhizotrones and rhizoboxes are
147 often used for similar types of flat growth systems in which plants form quasi 2D root systems. In the
148 following we will use the term "microcosm" and differentiate between types by the way how roots
149 interact with the soil and how rhizosphere is defined.

150

151 *Microcosms in which roots are in direct contact with soil*

152 Pot and column studies belong into this category. Differences between bulk and rhizosphere soil can
153 be assessed by separating rhizosphere from bulk soil by shaking or washing (Liu et al. 2004), by resin
154 impregnation followed by microscopic or spectroscopic inspection of thin sections, or by non-invasive
155 3D tomography (Pierret et al. 2003). Both repacked soil (aggregate structure destroyed) and soil
156 monoliths can be studied.

157 Flat boxes, in which quasi 2D root systems are formed in a narrow slit filled with soil come in various
158 dimensions. The so-called "Hohenheim" box is inclined to force the root system to develop
159 preferentially along the lower cover plate (Dinkelaker and Marschner 1992). This type of microcosms
160 is usually filled with repacked soil or artificial substrates, which may be arranged in zones of different
161 properties (Hodge et al. 1999). Often the boxes are at least partly transparent to allow the visual
162 observation of root development. Rhizosphere gradients can be assessed by sampling the soil in
163 different distances from the root. More importantly, such microcosms are ideal for the application of
164 non-invasive methods for *in-situ* characterization of gradients. Soil solution can be sampled in defined
165 distances from given root segments as described below. The advantage of having roots in direct
166 contact with soil is contrasted by the difficulties of detecting small effects by individual roots.

167

168 *Microcosms in which membranes are used to separate compartments or root mats*

169 Membranes, usually made of poly-amide, are used to separate microcosms into different
170 compartments. Membranes with a mesh size of 20-30 µm can be penetrated by fungal hyphae and root
171 hairs, but not roots. Membranes with a mesh size of 0.45 µm allow exchange of soil solution and gases
172 but neither hyphae nor roots can penetrate.
173 Compartment systems are devices, in which membranes are used to separate “root zone”, “fungal
174 hyphae zone” and root / hyphae free soil. Often the properties of the different compartments are
175 compared as a whole. If root density in the root compartment is large, rhizosphere gradients may be
176 observed in an adjacent soil compartment (Corgié et al. 2003; Vetterlein and Jahn 2004).
177 In other systems dense root mats are formed which are in contact with the soil via the membrane (Fig.
178 2). The root mat itself can be in contact with soil or an artificial substrate (Gahoonia and Nielsen
179 1991), or it is formed in an air-filled compartment (Wenzel et al. 2001). Such systems are ideal for
180 assessing chemical rhizosphere gradients by sampling the soil or the soil solution in the root-free
181 compartment in defined distances from the membrane. The root mat approach has the advantage of
182 amplifying the root influence, and thus to enable the detection also of otherwise small effects.
183 However, the results may not be representative for field conditions with less dense root systems. Also,
184 the exchange of water and ions between root and soil can be affected by the membrane (Fitz et al.
185 2006).
186

187 *Field systems*

188 Lysimeters are large 3D, usually cylindrical, and often weighable structures to study water, element
189 and ion fluxes in larger soil volumes under field conditions (not to be confused with tension or
190 tension-free lysimeters which are soil solution collection devices). Lysimeters either contain a soil
191 monolith or are refilled with loose soil material. While refilled lysimeters allow to establish
192 experimental setups with several treatments under the same soil conditions (Luster et al. 2008),
193 monolith lysimeters provide a controlled access to naturally structured soil (Bergström and Stenström
194 1998). Rhizosphere in a microscopic sense cannot be studied unless coupled to observation tools such

195 as mini-rhizotrons (Majdi 1996). However, plant effects on soil can be studied by comparing planted
196 and plant-free lysimeters.
197 There are several designs of root windows described in the literature (Polomski and Kuhn 2002). The
198 most common type consists of glass- or plexiglass plates pressed onto a soil profile and can be
199 combined with sampling and observation methods similar to microcosms of the "flat box" type
200 (Dieffenbach and Matzner 2000).
201
202 **Sampling and characterization of rhizosphere soil and soil solution**
203 Dependent on soil texture and structure, plant species and observed parameter, root induced changes
204 of most soil properties can be observed up to a distance of a few µm to about 7 mm from the surface
205 of an active root segment or a root mat (Jungk and Claassen 1997; Jones et al. 2003). Sampling
206 procedures for rhizosphere soil and solution have to cope with this demand for spatial resolution.
207 However, rhizosphere effects may also reach beyond this range when considering highly mobile
208 compounds like water or CO_2 (Gregory 2006, Hinsinger et al. 2005) or when including the effects of
209 fungal hyphae extending from mycorrhizal root segments ("mycorrhizosphere", e.g. Agerer 2001).
210
211 *Sampling rhizosphere soil*
212 For the separation of rhizosphere soil from so-called bulk soil several procedures based on shaking or
213 washing-off soil particles adhering to roots have been proposed. First, the root system, together with
214 adhering soil is carefully removed from the soil. Then Naim (1965) obtained rhizosphere soil by
215 shaking the root system for 5 minutes in water. Turpault (2006) defined bulk soil, rhizosphere soil
216 (detaches spontaneously when drying the root system) and rhizosphere interface (falls off when
217 shaking the dried root system). Others define the soil falling off when shaking the root system as bulk
218 soil and only the soil that is removed by subsequent brushing as rhizosphere soil (Yanai et al. 2003).
219 Because soil texture and actual soil moisture strongly influence the amount adhering to the root
220 system, results from different experiments should be compared with caution.

221 Slicing techniques require root mat type microcosms. Gahoonia and Nielsen (1991) sliced the frozen
222 soil with a microtome in different distances to the root mat. Because freezing the soil may alter its
223 chemical properties, Fitz et al. (2003a) developed a device that allows thin-slicing without freezing.
224
225 *Characterization of rhizosphere soil*
226 For the characterization of separated rhizosphere soil in principle all soil analytical methods published
227 in text books (see introduction) or recommended by organizations such as Deutsches Institut für
228 Normung (www.din.de), United States Environmental Protection Agency (www.epa.gov) or United
229 Nations Economic Commission for Europe (www.unece.org) may be used.
230 There are two major groups of methods for chemical soil properties. The first deals with the total
231 analysis of the soil solid phase, which is generally of little interest to rhizosphere research. The
232 exception is total C and N analysis which is well applicable because of the small amounts of sample
233 required by modern elemental analyzers. The second group comprises a large variety of extraction
234 procedures to characterize different fractions of soil bound molecules or ions. Extractions for organic
235 compounds (root and microbial exudates, contaminants) usually aim at complete recovery. Volatile
236 organic compounds with a boiling point < 200 °C are purged from a heated soil suspension in water or
237 methanol by an inert gas and trapped on suitable sorbents, while less volatile compounds are extracted
238 using suitable solvents and applying different techniques (Sawhney 1996). By contrast, extractants for
239 elements, inorganic ions and inorganic or organometallic compounds are often chosen to obtain a
240 bioavailable fraction. An overview of commonly used extractants for this purpose is given in Table 1.
241 Note that fractions are defined mainly operationally, and thus results obtained with different methods
242 may not be easily compared. Nevertheless, depending on extractant, element and plant species there
243 may be good correlations between extractable element concentration and plant uptake (citations in
244 Sparks 1996 or Pansu and Gautheyrou 2006). A comprehensive characterization of soil-bound
245 elements can be achieved by sequential extractions. There are protocols defining several fractions for
246 organic nitrogen and carbon (Stevenson 1996; VonLützow et al. 2007), phosphorus (Psenner et al.
247 1988; Kuo 1996) and trace metals (Tessier et al. 1979; Zeien and Brümmer 1989). Since extraction
248 methods have been developed without sample volume restrictions, the often limited sample amount

249 may hamper their application in rhizosphere research, depending on analyte content in the soil and on
250 the sensitivity of the analytical method. Generally extracts can be analysed by commonly available
251 analytical equipment such as potentiometry, molecular absorption spectrometry, gas and liquid
252 chromatography, atomic absorption spectrometry (AAS) or inductively-coupled plasma optical
253 emission spectrometry (ICP-OES). Only the detection of less-abundant analytes asks for more
254 specialised equipment involving mass-spectrometric detection. Because the availability of standard
255 reference materials for extractable contents in soils is limited (www.nist.gov/srm; www.erm-crm.org),
256 most extraction methods require the use of internal references and the traceability of instrument
257 calibration to certified standards.
258 Isotopic exchange is another method for determining bioavailable contents applicable to ions of a few
259 elements with radioactive isotopes (PO_4^{3-}, SO_4^{2-}, K^+, Zn^{2+}, Cd^{2+}) (Frossard and Sinaj 1997). A small
260 amount of isotopic tracer is added to a soil suspension and the dilution of the label by homoionic
261 exchange with the non-labeled ions at the soil solid phase is characterized. Either so-called E-values
262 (contents in the soil solid phase that are exchanged within a defined incubation time), or kinetic
263 parameters of the exchange are determined.
264
265 *Collection of soil solution*
266 Göttlein et.al. (1996) presented a system for the microscale collection of soil solution based on micro
267 suction cups made of ceramic capillaries with an outer diameter of 1mm. Their system was used
268 successfully to detect gradients in the rhizosphere (Göttlein et.al. 1999). Matrices of micro suction
269 cups placed in front of a developing root system allowed to monitor the changes in soil solution
270 chemistry when the root system passed through (Fig. 3; Dieffenbach et.al. 1997). This micro suction
271 cup system was slightly modified by Dessureault-Rompré et al. (2006) to allow for localized
272 collection of carboxylate anions and by Shen and Hoffland (2007) who introduced polyethersulfone as
273 porous cup material. Puschenreiter et al. (2005a) presented a suction cup with a different geometry
274 based on a nylon membrane (diameter 3mm) suitable for sampling soil solution in a defined distance
275 to root mats. Sampling soil solution with micro suction cups faces the same problems and restrictions
276 as with ordinary suction cups, just on a smaller scale. Firstly, sampling is influenced by the contact

277 with the soil matrix, and by texture and actual moisture of the soil. Secondly, analytes may be sorbed
278 by or released from the sampling system (Rais et al. 2006), which asks for thorough testing of a
279 particular system for a given problem. Nevertheless, the method has been applied successfully to
280 assess rhizosphere gradients for major inorganic cations and anions (Wang et al. 2001), organic acid
281 anions (Dessureault-Rompré et al. 2006) and trace metals (Shen and Hoffland 2007).
282 Alternatively, soil solution can be trapped by the application of filter papers, cellulose acetate filters or
283 blotting membranes onto roots exposed in flat rhizoboxes, a method which has been used mainly for
284 the collection of root exudates or root-secretory enzymes (Neumann 2006).
285

286 *Analysis of small volumes of aqueous solution*

287 The miniaturization of sampling devices also minimizes the sample volume available for analysis. In
288 principle all common analytical methods like ICP-OES, AAS, HPLC (high performance liquid
289 chromatography), IC (ion chromatography), or colorimetry (manual or automatic as in flow-injection
290 and auto analyzers) can be used, because except for flame AAS and standard ICP applications the
291 sample amount needed for the measurement itself is not very high. The main task in adapting
292 analytical methods to small sample volumes often is to optimize the autosampling system (Table 2).
293 There are techniques available that significantly reduce the sample consumption of ICP-OES (Mermet
294 and Todoli 2004) or ICP-MS (Prabhu et al. 1993; Lofthouse et al. 1997), which is normally in the
295 range of several milliliters. Capillary electrophoresis (CE) offers the possibility to analyze samples as
296 small as one droplet. Göttlein and Blasek (1996) optimized CE for the analysis of major cations and
297 anions in soil solutions. Because CE is a true ion-analytical method it offers the possibility to detect
298 the potentially phytotoxic Al^{3+} ion, which is of particular interest for studies of acidic soils (Göttlein
299 1998). Combining the analysis of labile species by CE or miniaturized voltammetric systems (Tercier-
300 Waeber et al. 2002) with total analysis by graphite furnace AAS or micro-injection ICP methods
301 (Göttlein 2006) allows metal speciation in rhizosphere solutions. ISFET-sensors enable pH
302 measurements in one to two droplets (Göttlein and Blasek 1996), and afterwards the sample can be
303 used for other analyses, because the sensors do not contaminate the sample like standard pH
304 electrodes. Dissolved organic carbon (DOC) in small sample volumes can be measured using TC

305 analyzers with a direct sample injection option, or, taking the UV absorption as an indirect measure,
306 using an HPLC system with a UV-detector but without separation column (Göttlein and Blasek 1996).
307 Employing the microanalytical methods described above, a comprehensive characterization of soil
308 solution including metal speciation is possible with a sample volume of about 250 µl. If only pH
309 measurement and CE analysis of cations and anions are done, 30 to 50 µl are sufficient. Very small
310 liquid sample volumes may also be analyzed by scanning electron microscopy coupled with energy-
311 dispersive X-ray analysis, however after sophisticated sample preparation (Bächmann and Steigerwald
312 1993).
313 Since for small solution samples the risk of contamination or adsorption losses is particularly high, the
314 proper preconditioning and cleaning of all devices and containers that the sample comes in contact
315 with are pivotal to reliable results (for recommended methods see Nollet 2007). Furthermore,
316 evaporation losses during sampling should be minimised (Göttlein et al. 1996). Some natural water
317 standard reference materials (www.nist.gov/srm; www.erm-crm.org) can be used for total analysis.
318 For speciation, quality assurance must rely on internal references.
319
320 *Sampling and analysis of soil gases*
321 Measuring the total efflux of CO_2 *in-situ* from a given, usually circular surface area of soil using
322 infrared gas analysers is a well established and routinely used method. The contribution of rhizosphere
323 respiration has been estimated either by comparing total soil respiration with respiration measured
324 after terminating autotrophic respiration by detopping of plants (Andersen and Scagel 1997), girdling
325 (Ekberg et al. 2007) or trenching (Sulzmann et al. 2005), or by applying suitable modeling to the soil
326 respiration data (Raich and Mora 2005). Alternatively, rhizosphere respiration can be assessed by
327 coupling ^{13}C labeling of the plant shoots with sampling of the soil CO_2 efflux and analysing its $\partial^{13}C$
328 using isotope-ratio mass spectrometry (Yevdokimov et al. 2007).
329 Membrane probes allow the diffusive sampling of soil gases like CO_2, N_2O, CH_4 or H_2 at various soil
330 depths in the field or in microcosms (Rothfuss and Conrad 1994; Yu and DeLaune 2006), and are
331 sometimes coupled with on-line analysis (Panikov et al. 2007). It should be tested whether gradients in
332 the partial pressure of gases from the rhizosphere to the bulk soil can be assessed with this technique.

333 The oxygen concentration in soil can be measured with microelectrodes in high spatial resolution
334 (Rappoldt 1995).
335
336 **Cutting-edge methods for studying plant effects on rhizosphere soil**
337 *In-situ assessment of soil solution*
338 *In-situ* measurements of chemical variables in the rhizosphere involve both the characterization of the
339 solid and the solution phase. Impregnating rooted soil "profiles" in microcosms with dye indicators
340 dissolved in agarose gel has been used for assessing root induced changes in pH (Fig. 4) and the
341 exudation of aluminum complexing ligands or Fe(III) reducing agents (Engels et al. 2000; Neumann
342 2006). Root-induced Mn reduction and the excretion of acid phosphatases can be detected by applying
343 specially impregnated filter papers to the rooted soil "profiles" (Dinkelaker and Marschner 1992;
344 Dinkelaker et al. 1993). While such staining methods can be used to monitor pH changes in the
345 rhizosphere with time in artificial systems composed of agarose gel (Plassard et al. 1999), they can
346 hardly be used for a continuous monitoring in real soil. Recently, a novel non-invasive method was
347 presented by Blossfeld and Gansert (2007) for the visualisation of rhizosphere pH dynamics in
348 waterlogged soils using a pH-sensitive fluorescent indicator dye in a proton permeable polymer matrix
349 (pH planar optode). However, the applicability of this method to non-saturated soils has still to be
350 proven. In aerated soils, antimony micro-electrodes allow high resolution monitoring of root induced
351 changes of pH in the rhizosphere (Häussling et al. 1985; Fischer et al. 1989; Zhang and Pang 1999).
352 Measuring soil redox potential with Pt micro-electrodes dates back to Lemon and Erickson (1952) and
353 has seen improvements to date (Hui and Tian 1998; VanBochove et al. 2002; Cornu et al. 2006). In
354 particular, they were used in microcosms to monitor redox gradients in the rhizosphere of rice in order
355 to study the formation of iron plaque on roots (Bravin et al. 2008). Except for a single application of
356 Na^+ ion selective electrodes by Hamza and Aylmore (1991), this methodology has not been applied to
357 other chemical parameters due to the lack of suitable electrodes that can be operated reliably in soil.
358 The DGT-technique (diffusive gradients in thin-films, Zhang et al. 1998) has been developed to
359 evaluate the phytoavailable pool of metals and phosphorus. A DGT device consists of a gel-embedded
360 resin layer acting as a sink for the species of interest, overlaid by another gel layer and a filter through

361 which the molecules or ions have to diffuse to reach the resin. Element and ion contents in soil
362 extracted by DGT correlate well with contents in plants (Zhang et al. 2001). Up to now, DGT devices
363 have been applied mostly to moist pastes of separated soil samples. However, they are particularly
364 promising tools for direct application to the surface of rooted soil "profiles" in rhizoboxes (Fitz et al.
365 2003b; Nowack et al. 2004). Spatially resolved maps of DGT extractable species can be obtained by
366 slicing the resin gel prior to analysis (Zhang et al. 2001) or by measuring the metal in the resin gel by
367 laser ablation ICP-MS (Warnken et al. 2004).
368
369 *Biosensors*
370 Whole-cell bacterial biosensors are constructed by insertion of a gene coding for an autofluorescent
371 protein, the most common one being the *lux* gene for the green fluorescent protein (GFP) (Killham and
372 Yeomans 2001). Three types have been developed, differing by the physiological process the
373 expression of bioluminescence is related to. Firstly, in non-specific biosensors, bioluminescence is
374 related to the basal metabolism. They can be used to detect C rhizodeposition (strains with a broad
375 range of substrates should be chosen to account for all exudates) and rhizosphere bacterial
376 colonization. In semi-specific biosensors, luminescence is linked to a generic process such as
377 oxidative stress. In specific biosensors, lighting reports on the expression of a specific pathway such as
378 the utilisation of a particular exudate compound, the degradation of or resistance to a given
379 contaminant. A number of biosensors have been developed to estimate the bioavailability of organic
380 and inorganic contaminants (Hansen and Sørensen 2001). While the simplicity and rapidity of the
381 measurement, and the possibility to monitor *in situ* various substances over time make biosensors
382 attractive, their application to real-world environmental samples is still a challenge (Rodriguez-Mozaz
383 et al. 2006). They cannot be applied directly to soils because soil particles absorb part of the emitted
384 light, and some soil constituents are autofluorescent. Usually, either the biosensor is inoculated and
385 then extracted from the soil before analysis, or the biosensor is applied to a solution after an extraction
386 stage. Several parameters should be considered carefully during the analysis such as the colonization
387 of the medium, the survival of the organisms over time, and possible matrix effects due to the presence
388 of organic matter, other contaminants, etc. The distribution of compounds can be visualised by

389 combining biosensors with imaging by a CCD camera, as shown for root exudates in sand microcosms
390 (Paterson et al. 2006). In most cases, the measured signals are used to compare different conditions,
391 but not to determine the actual concentration of a compound.
392
393 *Characterization of ultrastructure and element mapping using microscopic, diffractometric and*
394 *spectroscopic techniques*
395 This subsection is restricted to studies of the soil solid phase, while the characterization of roots is
396 addressed in Neumann et al. (2008). Standard techniques for two-dimensional element mapping are
397 scanning electron microscopy (SEM) and transmission EM (TEM) coupled with energy dispersive X-
398 ray microanalysis (EDX). Energy filtered TEM (EFTEM) offers a higher resolution and better
399 detection limit (about 10 nm and 1-10 $\mu g\ g^{-1}$, respectively). Other tools for two-dimensional element
400 mapping include synchrotron-based micro X-ray fluorescence (µSXRF), micro-particle induced X-ray
401 emission (µPIXE), secondary ion mass spectrometry (SIMS) and laser ablation (LA)– ICP-MS. SIMS
402 and LA-ICP-MS have been coupled with stable isotope probing (SIP) to image the distribution of C
403 isotopes in the soil at a sub-µm (nanoSIMS) and sub-mm (LA-ICP-MS) resolution (Bruneau et al.
404 2002; DeRito et al. 2005). Three-dimensional images of soil porosity can be obtained non-invasively
405 by X-ray computed tomography (CT) (Mooney et al. 2006a), a method also used to study root
406 architecture *in-situ* (Hodge et al. 2008). Alternatively, Moran et al. (2000) used X-ray absorption and
407 phase contrast imaging to study the relation between roots and soil structure, and Mooney et al.
408 (2006b) investigated the relation between the structure of a mineral landfill cap and root penetration
409 by polarising microscopy.
410 The various microscopic techniques listed above can be used on any growth system (artificial,
411 microcosm or field soil) after appropriate sample preparation. This sample preparation is a critical step
412 for rhizosphere samples because they contain living and hydrated components. Classical procedures
413 involving dehydration, chemical fixation, resin embedding and staining are progressively replaced by
414 cryo fixation. The latter enables the measurement of hydrated samples with techniques such as SEM,
415 TEM, µXRF and µPIXE, thus limiting possible artefacts related to dehydration and keeping the
416 systems in a more natural state (Fomina et al. 2005). Environmental SEM (ESEM) also enables

417 observation and analysis of hydrated root and soil samples with minimal perturbation (e.g. Houghton
418 and Donald 2008), however at a limited resolution.
419 Despite recent advances in data acquisition time each analysis by a microscopic technique implies a
420 compromise between resolution and size of the sample. Therefore, the representativeness of the
421 samples should be evaluated, possibly by upscaling from high resolution to coarser observation scales.
422 Mineral weathering and formation of secondary minerals have been studied intensively by EM
423 techniques, particularly by SEM-EDX (Gadd 2007) and TEM-EDX (Hinsinger et al. 1993). Observing
424 the size and shape of minerals and estimating their composition allow to predict the nature of the
425 minerals present. X-ray diffraction (XRD) allows a direct identification of minerals. Standard powder
426 diffractometers are limited by the amount of sample required (1 g), but recent instruments require only
427 a few tens of mg. Using EM and XRD, various precipitates and products of mineral weathering were
428 detected in the vicinity of fungi and roots (Hinsinger et al. 1993; April and Keller 2005; Gadd 2007).
429 However, the weak sensitivity of XRD for minor phases remains a major limitation. It can be partly
430 overcome by micro-XRD (µXRD) using laboratory or synchrotron X-ray sources, or by separation
431 prior to XRD analysis. Furthermore, XRD on oriented clays, which requires only a few mg of
432 particles, is suited to trace changes in clay mineralogy occurring in the rhizosphere, as shown in
433 artificial substrates (Hinsinger et al. 1993) and in soils (Kodama et al. 1994). Recently, Barré et al.
434 (2007) proposed a more quantitative approach for studying changes in the composition of the clay
435 fraction in the rhizosphere.
436 The local chemical environment of metals can be assessed by X-ray absorption spectroscopy (XAS),
437 including X-ray absorption near edge structure (XANES, also called NEXAFS for near-edge X-ray
438 absorption fine structure) and extended X-ray absorption fine structure (EXAFS) spectroscopy. Major
439 advantages of these techniques include element specificity, sensitivity to amorphous and weakly
440 crystalline species, and detection limits of 100 to 300 mg kg^{-1} depending on target element and matrix.
441 Bulk XAS provides information on major metal species. This technique was combined with µXRF
442 (Voegelin et al. 2007) and X-ray fluorescence microtomography (Hansel et al. 2001; Blute et al.
443 2004) to study the distribution and speciation of heavy metals in the root plaque of plants growing in
444 flooded environments. These studies revealed a heterogeneous composition of Fe(III) and Fe(II)

445 phases with associated trace element species including As(V) and Zn(II), whereas Pb(II) was
446 complexed by organic functional groups possibly belonging to bacterial biofilms. Micro-XAS
447 (µXAS), generally combined with bulk XAS and µXRF, provides information on the chemical form
448 of metals with a lateral resolution of a few μm^2 to a few hundreds of nm^2 (Manceau et al. 2002). These
449 tools were used to study the impacts of remediation treatments on metal speciation in contaminated
450 substrates (Fig. 5; Nachtegaal et al. 2005; Panfili et al. 2005, Manceau et al., 2008). Micro XRD,
451 available as additional tool on some spectrometers, allows the simultaneous identification of
452 crystalline metal bearing phases. These tools can be applied to any growth system (artificial,
453 microcosm or field soil) after homogenizing and grinding (for bulk XAS), or after resin impregnation
454 followed by thin sectioning (for µXRF/µXAS/µXRD). A major limitation of these synchrotron-based
455 techniques (and of state-of-the art microscopic facilities in general) is their restricted access due to the
456 small number of beamlines and microscopes worldwide.
457 The speciation of light elements including carbon, nitrogen, sulfur and phosphorus can be studied by
458 bulk XANES and by scanning transmission X-ray microscopy (STXM, including µXRF and
459 µXANES) using soft X-rays (Myneni 2002). The X-ray spot sizes are generally < 1 µm and can be as
460 small as few tens nm. Working with wet systems is also possible in some spectrometers. These
461 techniques have been used to study soil colloids (Schumacher et al. 2005) and bacterial
462 biomineralization (Benzerara et al. 2004) at the single-particle and single-cell scale, respectively.
463 Electron energy loss spectrometry (EELS) is a more exotic technique for speciating elements. Main
464 advantages are the coupling with TEM imaging and the very good lateral resolution of around 10 nm
465 (Watteau and Villemin 2001).
466 ^{13}C, ^{31}P , ^{15}N and ^{1}H solid and liquid state nuclear magnetic resonance (NMR) spectroscopies are
467 classical tools for the characterization of molecular structures and functional groups in soil organic
468 matter (SOM) and for the identification of low molecular weight molecules (Fan et al. 1997).
469 Advanced techniques such as high-resolution magic-angle spinning and 2D NMR open new
470 possibilities (Kelleher et al. 2006). The large sample size required for solid state NMR (0.5 to 1 g of
471 isolated SOM compared to a few tens of mg for liquid state NMR), limits its use for rhizosphere
472 applications. Fourier transformed infrared (FTIR) spectroscopy is another classical tool for the

473 characterization of molecular structures in SOM. Attenuated total reflectance (ATR)-FTIR allows the
474 study of wet systems, and FTIR microscopy enables 2D mapping with a resolution of a few
475 micrometers (Raab and Vogel 2004). Electron paramagnetic resonance (EPR) has been used to
476 quantify free radicals in organic molecules, and to study the interaction of paramagnetic metals with
477 SOM in terms of oxidation state, ligand types and coordination geometry (Senesi 1996). For EPR, the
478 same sample size restrictions apply as for solid state NMR.

479

480 *Labelling with and tracing / imaging of stable and radioactive isotopes*

481 Carbon fluxes in the rhizosphere can be assessed by $^{14}CO_2$ or $^{13}CO_2$ pulse-labelling the atmosphere of
482 a plant soil system, and measuring the radioactivity or the $\partial^{13}C$ value in the compartment of interest
483 (soil, isolated DOC, microbial biomass, roots, etc.) by liquid scintillation or isotope ratio mass
484 spectrometry (IRMS), respectively (Killham and Yeomans 2001, Rangel Castro et al. 2005). Gas
485 chromatography may be coupled with IRMS in order to probe a specific molecule or family of
486 molecules (Derrien et al. 2005). A more exotic method is the labelling with ^{11}C (Minchin and
487 McNaughton 1984).

488 Laterally resolved information on the distribution of an isotope can be obtained in different ways.
489 Gradients around roots can be determined using microcosms of the root mat type and analyzing slices
490 of soil at various distances from the root mat (Kuzyakov et al. 2003). Microcosms of the "Hohenheim"
491 type allowed to assess the equilibration of stable isotope labels for Mg, K and Ca between rhizosphere
492 soil and solution (Göttlein et al. 2005). Autoradiography on flat microcosms provides non-invasive 2D
493 imaging of the distribution of radioactive isotopes. Images were classically obtained on films or
494 photographic emulsions, then on phosphor storage screens, and more recently by electronic
495 autoradiography (Fig. 6; Rosling et al. 2004). Apart from following C fluxes, this versatile method can
496 be used to characterize the spatial distribution and its change over time of added radioactive P
497 (Hendriks et al. 1981; Hübel and Beck 1992; Lindahl et al. 2001), SO_4^{2-} (Jungk and Claassen 1997) or
498 Zn and Cd (Whiting et al. 2000).

499 The use of stable isotope probing (SIP) to assess microbial activity in the rhizosphere is treated by
500 Sørensen et al. (2008).

501

502 **Mapping the plants influence on soil moisture**

503 Using micro-tensiometers and small time-domain reflectometry sensors installed in rhizoboxes and
504 compartment systems, one-dimensional rhizosphere gradients in soil moisture and differences between
505 root and root-free compartments could be shown (Göttlein et al. 1996; Vetterlein and Jahn 2004).
506 Recently, microorganisms have been genetically altered to indicate changes in soil moisture by
507 varying the expression of the green fluorescent protein as detected by epifluorescence microscopy
508 (Cardon and Cage 2006).
509 Some of the methods to image root systems in microcosms are sensitive also to differences in
510 substrate moisture and can therefore be used to assess the plants influence on soil moisture
511 distribution. Light transmission imaging (Garrigues et al. 2006) is a rather inexpensive method with
512 which large quasi 2D microcosms (e.g. 1000 x 500 x 4 mm) can be studied at a resolution of ≥1500
513 µm. With magnetic resonance imaging (MRI; Chudek and Hunter 1997; Herrmann et al. 2002), which
514 depends on the accessibility to a medical imager or an NMR spectrometer with a suitable accessory,
515 3D images can be obtained from boxes (up to 70 x 70 x 20 mm) or cylinders (diameters up to 60 mm
516 and heights up to 200 mm) at a resolution between 10 and several hundred µm. Considering the high
517 spatial resolution, these methods are able to assess plant effects on soil moisture on the scale of a
518 single-root. However, their applicability to real soil is limited by inherent incompatibilities. Light-
519 transmission is restricted to translucent sand with addition of small amounts of clay and MRI to soils
520 with low iron contents. By contrast, X-ray computed tomography allows to map root effects on
521 structure and moisture distribution in real soils at a resolution of 100 µm to 1 mm for typically
522 cylindrical samples with a diameter of a few cm (Hamza and Aylmore 1992; Gregory and Hinsinger
523 1999). The sensitivity to soil water content, however, is comparatively weak. Recently, Oswald et al.
524 (2008) demonstrated the high sensitivity of Neutron radiography to differences in soil water content
525 and could show variable water uptake by different parts of root systems growing in flat microcosms
526 (170 x 150 x 13 mm) made of aluminum at a spatial resolution of ≥ 100 µm. Although the contrast is
527 highest in quartz sand, the method can also be applied to natural soil (Menon et al. 2007).
528 Electrical resistivity tomography (ERT) and ground penetrating radar (GPR) are non-invasive

529 geophysical methods increasingly used in hydrological studies of the vadose zone. ERT is a
530 comparatively inexpensive method exploiting the spatial variability in the electrical conductivity of
531 the soil (Benderitter and Schott 1999). Among other applications the method can be used to monitor
532 changes in soil water content in the field indirectly via inverse modelling of resistivity and the use of
533 petrophysical relationships. Large stone contents make application of ERT difficult and spatial
534 resolution for true non-invasive surface applications decreases strongly with soil depth. GPR velocity
535 tomography can be used for the same purpose, because the water content influences the soils
536 permittivity to radar waves (Annan 2005). The method, however, is ineffective in soils with clay. A
537 few studies have made the attempt to use ERT and / or GPR tomography to examine spatial variability
538 or temporal changes in soil moisture content caused by plant water uptake on the scale of the whole
539 root system (Fig. 7; Michot et al. 2003; AlHagrey 2007). Theoretically, depending on the electrode
540 spacing or the antenna frequency, the spatial resolution of ERT and GPR can be increased to the cm
541 range. However, feasability and applicability to map root-soil water interactions in the field on a
542 smaller scale than the whole root system remain to be shown.
543

544 **Rhizosphere Modeling**

545 The nature of concentration gradients in the soil caused by plant activity depends mainly on two sets
546 of factors that modeling needs to take into account. These are (i) physical and biological factors such
547 as geometry, morphology and symbiotic status of the root system, rates of growth, uptake and
548 exudation by roots, and diffusion properties of the soil around roots, and (ii) chemical factors such as
549 the distribution and speciation of chemical elements in the soil.
550 There are two main approaches to model rhizosphere processes. The first category of models follows a
551 macroscopic, empirical approach and operates on a whole plant or even field scale. Here the root
552 system is treated as a single unit without considering the effect of individual roots. The second
553 category deals with a single root or a root system and follows a microscopic approach. Table 3 gives
554 an overview of the categories and the scales discussed in this chapter.
555

556 *Macroscopic models*

557 Macroscopic models are descriptive and explanatory and help to understand the dynamic and complex
558 interactions occuring adjacent to roots (Darrah et al. 2006). These models can have several layers of
559 complexity, ranging from simple single-root models to sophisticated whole-root system models.
560 *Crop / forest models*: Although many models predicting the flow of nutrients between soil and plants
561 have been developed, few of these deal in detail with root processes. Such models often use a
562 simplified approximation of rhizosphere processes and verification is at scales larger than the
563 individual plant. Such models have been used intensively as a tool to analyze the performance of
564 cropping systems under variable climate (Wang and Smith 2004) or forest growth affected by different
565 environmental variables (Pinjuv et al. 2006). They typically involve many subprocesses and
566 satisfactory verification does not guarantee that the rhizosphere subprocesses have been modeled
567 accurately (Darrah et al. 2006). Root water uptake is normally treated in a highly simplified submodel,
568 usually with the root system acting as a zero-sink for nutrients, with uptake controlled by soil water
569 potential and transpiration rate or by diffusion flux rate (Darrah 1993). These models can be used to
570 investigate the relative impact of integrated rhizosphere processes on plant and crop scales. They
571 normally incorporate numerical schemes for deducing nutrient concentrations at root surfaces from
572 bulk soil parameters, but do not represent the rhizosphere as a volume of soil with properties different
573 from the bulk soil (Dunbabin et al. 2006). Some models also incorporate the influence of exudation or
574 microorganisms on uptake (Siegel et al. 2003).
575 *Biogeochemical ecosystem models:* These models are used to identify the governing parameters in
576 ecosystems in order to understand element or nutrient cycles or to predict ecosystem dynamics.
577 Examples include the DNDC model which simulates soil carbon and nitrogen biogeochemistry (Li et
578 al. 1994). A plant growth submodel is used to calculate root respiration, N uptake and plant growth
579 and these processes are linked to climate and soil status. Biogeochemical models pay more attention to
580 soil processes than crop models. Complexation, cation exchange, precipitation, and adsorption can be
581 included in various degrees of complexity (Cosby et al. 1985; Alewell and Manderscheid 1998).
582 *Soil profile scale:* Soil physical models describing water transport in soils also include a root water
583 uptake term, usually a pressure head dependant sink term that is introduced into the soil water balance
584 (Hopmans and Bristow 2002). There has been a tendency to describe the root water uptake analogous

585 to Darcy's equation, assuming that the rate of uptake is proportional to soil hydraulic conductivity and
586 the difference between the total pressure head at the root-soil interface and the corresponding pressure
587 head in the soil. This approach is useful to understand the root water extraction process, but it is
588 difficult to use for the interpretation of field data. Water transport models have been extended to
589 include solute uptake. In one example a three-dimensional solute transport model including passive
590 and active nutrient uptake by roots has been linked to a three-dimensional transient model for soil
591 water flow and root growth (Somma et al. 1998).
592 *Whole root system scale:* Several root architecture models are available that simulate the growth of
593 whole root systems at high spatial resolution to generate two or three-dimensional representations of
594 root systems, e.g. ROOTMAP (Diggle 1988), SimRoot (Lynch et al. 1997) or Root Typ (Pagès et al.
595 2004). An example of a modeled root system is shown in Fig. 8a. Doussan et al. (2006) extended a
596 whole root-system model to include water transport in soils with full coupling of water transport in the
597 root system and the influence of aging on the hydraulic conductivity of root segments and thus on
598 water uptake. The linking of such models to the underlying biology is not yet strongly advanced
599 (Darrah et al. 2006). However, several models have been developed that take into account interactions
600 between root systems, water and nutrients in the environment (Dunbabin et al. 2002). Wu et al. (2007)
601 recently presented a dynamic simulation model that is multi-dimensional, operates on a field scale, is
602 weather driven and models C and N cycling between plants, soil and microbes.
603
604 *Microscopic models*
605 Microscopic models, also called explanatory models, help to understand the complex and dynamic
606 interactions in the rhizosphere and are based as far as possible on mechanistic relations derived from
607 the laws of chemistry and physics and empirical relations (Kirk 2002). These models can be divided
608 into two subgroups, the molecular and the semi-empirical models. The molecular models are based on
609 the description of chemical processes by a suite of single reactions, e.g. speciation in solution or
610 surface complexation. The semi-empirical models use a more simplified description of molecular
611 processes, e.g. a buffer power to describe adsorption, desorption or precipitation/dissolution.

612 *Semi-empirical models on the single root scale:* Semi-empirical root models simulate the uptake of
613 nutrients by an isolated root segment. The classical rhizosphere model is that of Nye and Tinker
614 (1977) and (Barber 1995). It supposes a cylindrical root surrounded by an infinite amount of soil, with
615 convection and diffusion of nutrients through the soil and uptake through Michaelis-Menten type
616 kinetics at the root surface. The non-linearity of the model requires a numerical solution but recently
617 an analytical solution of the equations was obtained (Roose et al. 2001). This model has also been
618 extended to describe P or metal uptake in microcosms of the root mat type (Kirk 1999; Puschenreiter
619 et al. 2005b). Most of these models are based on a rather simplified description of soil chemistry and
620 the effects of plant roots. The actions exerted by roots on their rhizosphere are generally limited to
621 element uptake, and the chemical interactions between dissolved elements and the soil are reduced to a
622 buffer power or Freundlich adsorption isotherm (Barber 1995; Kirk 1999). Fig. 8b shows as an
623 example the influence of citrate exudation on phosphate solubilization. The effect of exudation has
624 been incorporated into the basic modeling concept, and conditional models parameterized for different
625 soils have been formulated, e.g. to model the effect of organic acid exudation on phosphate
626 mobilization (Gerke et al. 2000ab). The application of certain rhizosphere models requires to write a
627 new computer program or to change existing software. Schnepf et al. (2002) have shown that pde-
628 solvers are useful in rhizosphere modeling because they make it easy to create, reproduce or link
629 models from the known constituting equations.
630 *Semi-empirical models on the root system scale:* An upscaling of single root models to the whole root
631 system allows to predict plant uptake by integrating the flux on a unit segment basis over the total root
632 length. The approach of Roose et al. (2001) allowed the direct incorporation of root branching
633 structures and whole roots into plant uptake models, based on a mechanistic description of root uptake
634 and soil processes (Roose and Fowler 2004ab).
635 *Molecular soil solution models:* In hydrogeochemistry, sophisticated computational tools have been
636 developed to describe acid-base and redox reactions, complexation, ion exchange, adsorption and
637 desorption, dissolution and precipitation of chemical species in soil environments using
638 thermodynamic and kinetic relationships. Examples are PHREEQC (Parkhurst and Appelo 1999),
639 ECOSAT (Keizer and VanRiemsdijk 1995) and ORCHESTRA (Meeussen 2003). Additionally there

640 are computer codes that are specialized in modeling three-dimensional transport in variably saturated
641 media that include geo-chemical modeling, e.g. MIN3P (Mayer et al. 2002). Applications of some of
642 these models to rhizosphere research is described in the forthcoming paragraphs.
643 In some of the semi-empirical models mentioned above, soil solution speciation was included as input
644 parameter. Calba et al. (2004) modeled the effect of protons, solid phase dissolution and adsorption on
645 aluminum speciation in the rhizosphere, and Puschenreiter et al. (2005b) considered Ni speciation in
646 soil solution when looking at Ni uptake by a hyperaccumulator. Zhao et al. (2007) used speciation
647 modeling to elucidate the effect of plant roots on metal mobilization and speciation in soils. However,
648 in these last two examples speciation was considered static and not to be affected by root activity. In
649 particular the feedback loops between exudation, soil and element uptake are not considered implicitly
650 in single root models, although many authors have demonstrated their importance in the plant
651 availability of mineral elements (Parker and Pedler 1997).
652 *Molecular models at the single root scale:* The full coupling of single-root models with speciation
653 calculations is still in its infancy. An example of the inclusion of solution and surface speciation into
654 rhizosphere models is the modeling of the effect of citrate exudation on phosphate uptake (Geelhoed et
655 al. 1999). The model calculations showed that citrate exudation from roots increases the plant
656 availability of sorbed phosphate (Fig. 8c). Recently a simple rhizosphere model was described in
657 which the uptake into a single root was linked to three geochemical computational tools
658 (ORCHESTRA, MIN3P, and PHREEQC) (Nowack et al. 2006). The first step in this approach was an
659 accuracy analysis of the different solution strategies by comparing the numerical results to the
660 analytical solution of solute uptake by a single cylindrical root. All models were able to reproduce the
661 concentration profiles as well as the uptake flux. The strength of this new approach is that it can also
662 be used to investigate more complex and coupled biogeochemical processes in the rhizosphere. This
663 was shown exemplarily with simulations involving both exudation and the simultaneous uptake of
664 solute and water.
665 *Molecular models at the soil profile scale:* The coupling of root uptake, speciation modeling and water
666 transport in soils is even less advanced than on the single root scale. In order to describe metal uptake
667 in the presence of ligands, Seuntjens et al. (2004) developed a model coupling processes under steady-

668 state flow conditions with rhizosphere processes and speciation modeling. The simulations showed
669 that exudation of ligands does not necessarily increase the solubility and bioavailability of metals, but
670 that bioavailability may actually be reduced by formation of ternary surface complexes or reduction of
671 the free metal concentration. The model can be easily extended to include further processes.

672

673 **Challenges ahead**

674 Our review on current methodology to study the effects of root and microbial activity on soil
675 properties in the rhizosphere has shown that – although there is a need for improvements in certain
676 aspects as outlined below - in general we have the tools at hand to assess individual processes on the
677 microscale under rather artificial conditions. This is true mainly for looking at soil chemical properties
678 and processes, while due to still large methodological limitations our understanding of the biophysics
679 of the rhizosphere is comparatively limited (Gregory and Hinsinger 1999), despite major recent
680 advances (Pierret et al. 2007, Hinsinger et al. 2008). Microscopic, spectroscopic and tracer methods to
681 look at individual and coupled chemical processes in small „aliquots" of naturally structured soil seem
682 to step out of their infancy and have become promising tools to better understand the complex
683 interactions between roots, soil and microorganisms. On the field scale, however, while there are
684 promising first results on using non-invasive geophysical methods to assess the plant's influence on
685 soil moisture, there are no tools in the pipeline to assess the spatial heterogeneity of chemical
686 properties and processes in the field. For the time being, the use of macroscopic models or the
687 upscaling of model results from the single root to the whole plant or plot scale is the only solution to
688 this problem. However, upscaling itself is a major issue as outlined below. An optimal feedback
689 between different developments requires a good communication between the various disciplines
690 involved in rhizosphere research, in particular between experimental and modeling works. Both, early
691 incorporation of new insights gained experimentally at the micro scale into explanatory models and
692 involving models in experimental design could accelerate progress.

693

694 *Methodological improvements for investigations at the micro scale*

695 While most studies on root and microbial exudation limit their analysis to more abundant substances
696 like sugars, carboxylates, amino acids and siderophores, the fate and role of many compounds like
697 sterols or lactones that are exuded for signalling or as allelochemicals (Bertin et al. 2003) still need to
698 be evaluated. Coupling of advanced chromatographic or electrophoretic separation methods with mass
699 spectrometry allows to identify such compounds, e.g. in extracts of bacterial isolates (Frommberger et
700 al. 2004). However, they cannot be detected in real soil solution with current methodologies.
701 Another challenge is to identify the source of a particular compound measured in soil solution, i.e.
702 whether is has been exuded by plant roots, fungal hyphae or bacteria, or is the product of SOM
703 degradation. Further advancements in compound specific isotopic analysis are needed in order to be
704 able to trace ^{13}C labels to individual compounds. Currently, isotopic ratios can be determined for total
705 DOC in small volumes of soil solution (Glaser 2005), while for individual compounds, even for more
706 abundant ones, this will require drastic improvements in the detection limit of the coupled
707 chromatography – IRMS instrumentation.
708 Considering the large potential of biosensors to assess the spatial heterogeneity of bioavailable
709 molecules or ions, their *in-situ* application to microcosms containing real soil would be highly
710 desirable. The difficulty to discriminate between the signals from biosensors and autofluorescent soil
711 components must be overcome, and good correction factors for the reabsorption of the biosensor
712 signal by soil particles must be determined. Furthermore, the development of multi-reporter gene
713 biosensors, or the combined use of several biosensors in a given system, might help to control the
714 influence of external factors (nutrient conditions, competition, inhibition factors, etc.), and thus to get
715 more quantitative results in soils.
716 There have been great efforts to use microscopic and spectroscopic methods to assess the properties of
717 soil and their components on the microscopic and molecular scale. The techniques are slowly getting
718 sufficiently spatially resolved to separate components that are intimately associated. Apart from
719 improving the capabilities of the instruments (flux and size of the incident beam, efficiency of detector
720 systems) to get better sensitivity and resolution, efforts should focus on limiting the perturbation of the
721 systems, e.g. by preserving their hydrated state, and better assessing or controlling the radiation

722 damages by X-ray, electron or particle beams. Another challenge is to link the molecular- and
723 microscopic-scale information obtained by these techniques to information obtained at higher scale.
724

725 *Upscaling*

726 On the microscale, plant physiology and soil microbiology have developed a detailed understanding of
727 plant water and nutrient uptake, root respiration, root release of organic carbon and interactions
728 between roots and soil microorganisms. However, there is a lack of understanding as to how the
729 multiple complex interactions in the rhizosphere affect ecosystem functions on the macroscale (soil
730 profile, plot, catchment). There is an urgent need to improve the mechanistic bases of models aimed at
731 crop growth, forest production or biogeochemical element cycling by including rhizosphere processes.
732 Closing the gaps between the different scales, or in other words making explanatory or predictive
733 models on the macro scale more process-based, is a major challenge in biogeochemical research. At
734 present, most of the available upscaling approaches for soil water processes ignore the effects of
735 vegetation or use an extremely simplified approach. There is a need to develop upscaling approaches
736 that explicitly account for the effects of growing plants under field conditions (Vereecken et al. 2007).
737 A step into this direction is BIOCHEM-ORCHESTRA, a modeling tool that integrates
738 ecotoxicological transfer functions with speciation and transport modeling (Vink and Meeussen 2007).
739 The plant module, however, is still very simple and uses only empirical parameters such as the
740 relevant rooting zone and a time-dependent uptake behavior. Root architecture models such as Root
741 Typ (Pagès et al. 2004) have a great potential to be linked with other model approaches and could thus
742 contribute significantly to the integration at higher scales.
743 On the opposite end of the scale spectrum, there is an urgent need for new modeling approaches that
744 combine the molecular description of chemical processes in soils with pore-scale transport and root
745 uptake. Up to now, molecular scale analytical tools and modeling approaches have developed rather
746 independently. The coupling of 3-dimensional root growth modeling, root uptake, speciation modeling
747 and water transport in soils presents challenges both on the computational and on the conceptual level.
748 An example of a first step into this direction is the modeling of the effects of phospholipid surfactants
749 on nutrient and water uptake by whole root systems (Dunbabin et al. 2006).

750 One key problem in the upscaling of rhizosphere processes is to assess correctly the distribution of
751 active root segments in the soil. Non-invasive methods like X-ray computed tomography and MRI
752 can, under certain conditions, produce well-resolved 3D images of the root system, but they are
753 restricted to small laboratory systems. First results have demonstrated the potential of ERT and GPR
754 to provide coarse images of root systems non-invasively and *in-situ* in the field via their imprint on
755 soil moisture distribution. With GPR reflection it was even possible to resolve larger single roots in a
756 silty sand (AlHagrey 2007). This warrants further exploration of geophysical methods in terms of
757 delineating response from roots and soil structural heterogeneities, of improving spatial resolution
758 (ERT), and of application to soils with higher clay contents (GPR).
759
760 **References**

761 Agerer R 2001 Exploration types of ectomycorrhizae – A proposal to classify ectomycorrhizal
762 mycelial systems according to their patterns of differentiation and putative ecological
763 importance. Mycorrhiza 11, 107-114.
764 Alewell C and Manderscheid B 1998 Use of objective criteria for the assessment of biogeochemical
765 ecosystem models. Ecol. Model. 107, 213-224.
766 AlHagrey S A 2007 Geophysical imaging of root-zone, trunk, and moisture heterogeneity. J. Exp.
767 Botany 58, 839-854.
768 Andersen C P and Scagel C F 1997 Nutrient availability alters belowground respiration of ozone-
769 exposed ponderosa pine. Tree Physiol. 17, 377-387.
770 Annan A P 2005 GPR methods for hydrogeological studies. In Hydrogeophysics. Eds. Rubin Y and
771 Hubbard S S pp. 185-213. Springer, Dordrecht.
772 April R and Keller D 2005 Mineralogy of the rhizosphere in forest soils of the eastern United States.
773 Biogeochemistry 9, 1-18.
774 Bächmann K and Steigerwald K 1993 The use of SEM for multielement analysis in small volumes and
775 low concentration. Fresenius J. Anal. Chem. 346, 410-413.
776 Barber S A 1995 Soil nutrient bioavailability: a mechanistic approach. 2nd edition. John Wiley &
777 Sons, New York.

778 Barré P, Velde B, Catel N, Abbadie L 2007 Soil-plant potassium transfer: impact of plant activity on
779 clay minerals as seen from X-ray diffraction. Plant Soil 292, 137-146.
780 Benderitter Y and Schott J J 1999 Short time variation of the resistivity in an unsaturated soil: The
781 relationship with rainfall. European J. Env. Eng. Geophys. 4, 37-49.
782 Benzerara K, Yoon T, Tyliszak T, Constantz A, Sportmann A and Brown G 2004 Scanning
783 transmission X-ray microscopy study of microbial calcification. Geobiology 2, 249-259.
784 Bergström L and Stenström J 1998 Environmental fate of chemicals in soil. Ambio 27, 16-23.
785 Bertin C, Yang X and Weston L A 2003 The role of root exudates and allelochemicals in the
786 rhizosphere. Plant Soil 256, 67-83.
787 Blossfeld S, Gansert D 2007 A novel non-invasive optical method for quantitative visualization of pH
788 dynamics in the rhizosphere of plants. Plant Cell Environ. 30, 176-186.
789 Blute N K, Brabander D J, Hemond H F, Sutton S R, Newville M G, and Rivers M L 2004 Arsenic
790 sequestration by ferric iron plaque on cattail roots. Environ. Sci. Technol. 38, 6074-6077.
791 Bravin MN, Travassac F, Le Floch M, Hinsinger P, Garnier JM 2008 Oxygen input controls the
792 spatial and temporal dynamics of arsenic at the surface of a flooded paddy soil and in the
793 rhizosphere of lowland rice (Oryza sativa L.): a microcosm study. Plant Soil (in press DOI
794 10.1007/s11104-007-9532-x)
795 Bruneau P M C, Ostle N, Davidson D A, Grieve I C and Fallick A E 2002 Determination of
796 rhizosphere C-13 pulse signals in soil thin sections by laser ablation isotope ratio mass
797 spectrometry. Rapid Commun. Mass Spectrom. 16, 2190–2194.
798 Calba H, Firdaus, Cazevieille P, Thée C, Poss R and Jaillard B 2004 The dynamics of protons,
799 aluminum, and calcium in the rhizosphere of maize cultivated in tropical acid soils:
800 experimental study and modelling. Plant Soil 260, 33-46.
801 Cardon Z G, Gage D J 2006 Resource exchange in the rhizosphere: molecular tools and the microbial
802 perspective. Annu. Rev. Ecol. Evol. Syst. 37, 459–488.
803 Chaignon V and Hinsinger P 2003 A biotest for evaluating copper bioavailability to plants in a
804 contaminated soil. J. Environ. Qual. 32, 824-833.

805 Chudek J A and Hunter G 1997 Magnetic resonance imaging of plants. Progr. Nucl. Magn. Res.
806 Spectr. 31, 43-62.
807 Corgié S, Joner E and Leyval C 2003 Rhizospheric degradation of phenanthrene is a function of
808 proximity to roots. Plant Soil 257, 143-150.
809 Cornu JY, Staunton S, Hinsinger P 2007 Copper concentration in plants and in the rhizosphere as
810 influenced by the iron status of tomato (Lycopersicum esculentum L.). Plant Soil 292, 63-77.
811 Cosby B J, Hornberger G M, Galloway J N and Wright R F 1985 Modeling the effects of acid
812 deposition: Assessment of a lumped parameter model of soil water and streamwater chemistry.
813 Water Resour. Res. 21, 51-63.
814 Dane J H and Topp G C 2002 Methods of soil analysis. Part 4. Physical methods. SSSA Book Series
815 5, Soil Science Society of America, Madison Wisconsin, 1692 pp.
816 Darrah P R 1993 The rhizosphere and plant nutrition: a quantitative approach. Plant Soil 155/156, 1-
817 20.
818 Darrah P R, Jones D L, Kirk G J D and Roose T 2006 Modeling the rhizosphere: a review of methods
819 for 'upscaling' to the whole-plant scale. Eur. J. Soil Sci. 57, 13-25.
820 DeRito C M, Pumphrey G M and Madsen E L 2005 Use of field-based stable isotope probing to
821 identify adapted populations and track carbon flow through a phenol-degrading soil microbial
822 community. Appl. Environ. Microbiol. 71, 7858-7865.
823 Derrien D, Marol C and Balesdent J 2005 The dynamics of neutral sugars in the rhizosphere of wheat.
824 An approach by 13C pulse-labelling and GC/C/IRMS. Plant Soil 267, 243-253.
825 Dessureault-Rompré J, Nowack B, Schulin R and Luster J 2006 Modified micro suction cup/ rhizobox
826 approach for the in-situ detection of organic acids in rhizosphere soil solution. Plant Soil 286,
827 99-107
828 Dieffenbach A and Matzner E 2000 In situ soil solution chemistry in the rhizosphere of mature
829 Norway spruce (*Picea abies* [L.] Karst) trees. Plant Soil 222, 149-161.
830 Dieffenbach A, Göttlein A and Matzner E 1997 In-situ investigation of soil solution chemistry in an
831 acid soil as influenced by growing roots of Norway spruce (*Picea abies* [L.] Karst.). Plant Soil
832 192, 57-61.

833 Diggle A J 1988 Rootmap - a Model in 3-dimensional coordinates of the growth and structure of
834 fibrous root systems. Plant Soil 105, 169-178.
835 Dinkelaker B and Marschner H 1992 In vivo demonstration of acid phosphatase activity in the
836 rhizosphere of soil-grown plants. Plant Soil 144, 199-205.
837 Dinkelaker B, Hahn G, Römheld V, Wolf G A and Marschner H 1993 Non-destructive methods for
838 demonstrating chemical changes in the rhizosphere I. Description of methods. Plant Soil 155,
839 67-70.
840 Doussan C, Pierret A, Garrigues E and Pagès L 2006 Water uptake by plant roots: II - Modeling of
841 water transfer in the soil root-system with explicit account of flow within the root system -
842 Comparsion with experiments. Plant Soil 283, 99-117.
843 Dunbabin V M, Diggle A J, Rengel Z and VanHugten R 2002 Modelling the interactions between
844 water and nutrient uptake and root growth. Plant Soil 239, 19-38.
845 Dunbabin V M, McDermott S and Bengough A G 2006 Upscaling from rhizosphere to whole root
846 system: Modelling the effects of phospholipid surfactants on water and nutrient uptake. Plant
847 Soil 283, 57-72.
848 Ekberg A, Buchmann N and Gleixner G 2007 Rhizospheric influence on soil respiration and
849 decomposition in a temperate Norway spruce stand. Soil Biol. Biochem. 39, 2103-2110.
850 Engels C, Neumann G, Gahoonia T, George E and Schenk M 2000 Assessment of the ability of roots
851 for nutrient acquisition. In Root methods. A handbook. Eds A L Smit, A G Bengough, C
852 Engels, M Van Noordwijk, S Pellerin and S C Van de Geijn. pp. 403-459. Springer,
853 Heidelberg.
854 Fan T W M, Lane A N, Pedler J, Crowley D and Higashi R M 1997 Comprehensice analysis of
855 organic ligands in whole root exudates using nuclear magnetic resonance and gas
856 chromatography-mass spectrometry. Anal. Biochem. 251, 57-68.
857 Fischer W R, Flessa H and Schaller G 1989 pH values and redox potentials in microsites of the
858 rhizosphere. Z. Pflanzenernähr. Bodenk. 152, 191-195.
859 Fitz W J, Wenzel W W, Wieshammer G and Istenic B 2003a Microtome sectioning causes artefacts in
860 rhizobox experiments. Plant Soil 256, 455-462.

861 Fitz W J, Wenzel W W, Zhang H, Nurmi J, Stipek K, Fischerova Z, Schweiger P, Kollensperger G,
862 Ma L Q and Stingeder G 2003b Rhizosphere characteristics of the arsenic hyperaccumulator
863 *Pteris vittata* L. and monitoring of phytoremoval efficiency. Environ. Sci. Technol. 37, 5008-
864 5014.
865 Fitz W J, Puschenreiter M and Wenzel W W 2006 Growth systems. In Handbook of methods used in
866 rhizosphere research. Eds. Luster J and Finlay R. pp. 9-15. Swiss Federal Research Institute
867 WSL, Birmensdorf.
868 Fomina M, Hillier S, Charnock J M, Melville K, Alexander I J and Gadd G M 2005 Role of oxalic
869 acid overexcretion in transformations of toxic metal minerals by *Beauveria caledonica*. Appl.
870 Environ. Microbiol.71, 371-381.
871 Frommberger M, Schmitt-Kopplin P, Ping G, Frisch H, Schmid M, Zhang Y, Hartmann A and Kettrup
872 A 2004 A simple and robust set-up for on-column sample preconcentration – nano-liquid
873 chromatography – electrospray ionization mass spectrometry for the analysis of *N*-
874 acylhomoserine lactones. Anal. Bioanal. Chem. 378, 1014-1020.
875 Frossard E and Sinaj S 1997 The isotope exchange kinetic technique: A method to describe the
876 availability of inorganic nutrients. Applications to K, P, S and Zn. Isotopes Environ. Health
877 Studies 33, 61-77.
878 Gadd G M 2007 Geomycology: biogeochemical transformations of rocks, minerals, metals and
879 radionuclides by fungi, bioweathering and bioremediation. Mycol. Res. 111, 3-49.
880 Gahoonia T S and Nielsen N E 1991 A method to study rhizosphere processes in thin soil layers of
881 different proximity to roots. Plant Soil 135, 143-146.
882 Garrigues E, Doussan C and Pierret A 2006 Water uptake by plant roots: I- Formation and propagation
883 of a water extraction front in mature root systems as evidenced by 2D light transmission
884 imaging. Plant Soil 283, 83–98.
885 Geelhoed J S, Van Riemsdijk W H and Findenegg G R 1999 Simulation of the effect of citrate
886 exudation from roots on the plant availability of phosphate adsorbed on goethite. Eur. J. Soil
887 Sci. 50, 379-390.

888 Gerke J, Beissner L and Römer W 2000a The quantitative effect of chemical phosphate mobilization
889 by carboxylate anions in P uptake by a single root. I. The basic concept and determination of
890 soil parameters. J. Plant Nutr. Soil Sci. 163, 207-212.
891 Gerke J, Römer W and Beissner L 2000b The quantitative effect of chemical phosphate mobilization
892 by carboxylate anions in P uptake by a single root. II. The importance of soil and plant
893 parameters for uptake of mobilized P. J. Plant Nutr. Soil Sci. 163, 213-219.
894 Glaser B 2005 Compound-specific stable isotope (∂13C) analysis in soil science. J. Plant Nutr. Soil
895 Sci. 168, 633-648.
896 Göttlein A 1998 Measurement of free Al^{3+} in soil solutions by capillary electrophoresis. Eur. J. Soil
897 Sci. 49, 107-112.
898 Göttlein A 2006 Metal speciation in micro samples of soil solution by Capillary electrophoresis (CE)
899 and ICP-OES with microinjection. In Handbook of methods used in rhizosphere research. Eds.
900 Luster J and Finlay R. p. 251. Swiss Federal Research Institute WSL, Birmensdorf.
901 Göttlein A and Blasek R 1996 Analysis of small volumes of soil solution by capillary electrophoresis.
902 Soil Sci. 161, 705-715.
903 Göttlein A, Hell U and Blasek R 1996 A system for microscale tensiometry and lysimetry. Geoderma
904 69, 147-156.
905 Göttlein A, Heim A and Matzner E 1999 Mobilization of aluminium in the rhizosphere soil solution of
906 growing tree roots in an acidic soil. Plant Soil 211, 41-49.
907 Göttlein A, Heim A, Kuhn A J and Schröder W H 2005 In-situ application of stable isotope tracers in
908 the rhizosphere of an oak seedling. Eur. J. For. Res. 124, 83-86.
909 Gregory P J 2006 Roots, rhizosphere, and soil: The route to a better understanding of soil science?
910 Eur. J. Soil Sci. 57, 2-12.
911 Gregory P J, Hinsinger P 1999 New approaches to studying chemical and physical changes in the
912 rhizosphere: an overview. Plant Soil 211, 1-9.
913 Guivarch A, Hinsinger P and Staunton S 1999 Root uptake and distribution of radiocaesium from
914 contaminated soils and the enhancement of Cs adsorption in the rhizosphere. Plant Soil 211,
915 131-138.

916 Häussling M, Leisen E, Marschner H and Römheld V 1985 An improved method for non-destructive
917 measurement of pH at the root-soil interface (Rhizosphere). J. Plant Physiol. 117, 371-375.
918 Hamza M and Aylmore L A G 1991 Liquid ion-exchanger microelectrodes used to study soil solute
919 concentrations near plant-roots. Soil Sci. Soc. Am. J. 55, 954-958.
920 Hamza M and Aylmore L A G 1992 Soil solute concentration and water uptake by single lupin and
921 radish plant roots. I. Water extraction and solute accumulation. Plant Soil 145, 187-196.
922 Hansel C M, Fendorf S, Sutton S and Newville M 2001 Characterization of Fe plaque and associated
923 metals on the roots of mine-waste impacted aquatic plants. Environ. Sci. Technol. 35, 3863-
924 3868.
925 Hansen L H and Sørensen S J 2001 The use of whole-cell biosensors to detect and quantify
926 compounds or conditions affecting biological systems. Microb. Ecol. 42, 483-494.
927 Heim A, Brunner I, Frossard E and Luster J 2003 Aluminum Effects on *Picea abies* at Low Solution
928 Concentrations. Soil Sci. Soc. Am. J. 67, 895-898.
929 Hendriks L, Claassen N, Jungk A 1981 Phosphatverarmung des wurzelnahen Bodens und
930 Phosphataufnahme von Mais und Raps. J. Plant Nutr. Soil Sci. 144, 486-499.
931 Herrmann K-H, Pohlmeier A, Gembris D and Vereecken H 2002 Three-dimensional imaging of pore
932 water diffusion and motion in porous media by nuclear magnetic resonance imaging. J.
933 Hydrol. 267, 244-257.
934 Hinsinger P and Gilkes R J 1997 Dissolution of phosphate rock in the rhizosphere of five plant species
935 grown in an acid, P-fixing mineral substrate. Geoderma 75, 231-249.
936 Hinsinger P, Elsass F, Jaillard B, Robert M 1993 Root-induced irreversible transformation of a
937 trioctahedral mica in the rhizosphere of rape. Eur. J. Soil Sci. 44, 535-545.
938 Hinsinger P, Gobran GR, Gregory PJ, Wenzel WW 2005 Rhizosphere geometry and heterogeneity
939 arising from root-mediated physical and chemical processes. New Phytol.168, 293-303.
940
941 Hinsinger P, Bengough AG, Vetterlein D, Young IM 2008 Rhizosphere : biophysics, biogeochemistry
942 and ecological relevance. Plant Soil, *this volume, in prep.*

943 Hodge A, Grayston S J and Ord B G 1996 A novel method for characterization and quantification of
944 plant root exudates. Plant Soil 184, 97-104.
945 Hodge A, Robinson D, Griffiths B S and Fitter A H 1999 Why plants bother: root proliferation results
946 in increased nitrogen capture from an organic patch when two grasses compete. Plant Cell
947 Environ. 22, 811-820.
948 Hodge A et al. 2008 Plant roots : growth and architecture, Plant Soil, *this volume, submitted.*
949 Houghton H A, Donald A M 2008 An environmental scanning electron microscopy study of aqueous
950 gibbsite suspensions. Scanning 30, 223-227.
951 Hopmans J W and Bristow K L 2002 Current capabilities and future needs of root water and nutrient
952 uptake modeling. Adv. Agron. 77, 103-183.
953 Hübel F, Beck E 1993 In-situ determination of the P-relations around the primary root of maize with
954 respect to inorganic and phytate-P. Plant Soil 157, 1-9.
955 Hui P and Tian C Z 1998 Fabrication of redox potential microelectrodes for studies in vegetated soils
956 or biofilm systems. Environ. Sci. Technol. 32, 3646-3652.
957 Jones D L 1998 Organic acids in the rhizosphere – a critical review. Plant Soil 205, 25-44.
958 Jones D L and Brassington D S 1998 Sorption of organic acids in acid soils and its implications in the
959 rhizosphere. Eur. J Soil Sci. 49, 447-455.
960 Jones D L, Dennis P G, Owen G and Hees P W 2003 Organic acid behavior in soil-misconceptions
961 and knowledge gaps. Plant Soil 248, 31-41.
962 Jungk A and Claassen N 1997 Ion diffusion in the soil-root system. Adv. Agron. 61, 53-110.
963 Keizer M G and van Riemsdijk W H 1995 ECOSAT, a computer program for the calculation of
964 chemical speciation and transport in soil-water systems. Wageningen Agricultural University.
965 Kelleher B P, Simpson M J and Simpson A J 2006 Assessing the fate and transformation of plant
966 residues in the terrestrial environment using HR-MAS NMR spectroscopy. Geochim.
967 Cosmochim. Acta 70, 4080-4094.
968 Killham K and Yeomans C 2001 Rhizosphere carbon flow measurement and implications: from
969 isotopes to reporter genes. Plant Soil 232, 91-96.

970 Kirk G J D 1999 A model of phosphate solubilization by organic anion excretion from plant roots.
971 Eur. J. Soil Sci. 50, 369-378.
972 Kirk G J D 2002 Use of modeling to understand nutrient acquisition by plants. Plant Soil 247, 123-
973 130.
974 Kodama H, Nelson S, Yang F, Kohyama N 1994 Mineralogy of rhizospheric and non-rhizospheric
975 soils in corn fields. Clays Clay Min. 42, 755-763.
976 Kraemer S M, Crowley D E and Kretzschmar R 2006 Geochemical aspects of phytosiderophore-
977 promoted iron acquisition by plants. Adv. Agron. 91, 1-46
978 Kuo S 1996 Phosphorus. In Methods of soil analysis. Part 3. Chemical Methods. Ed. D L Sparks. pp.
979 869-919. Soil Science Society of America, Madison.
980 Kuzyakov Y, Raskatov A V and Kaupenjohann M 2003 Turnover and distribution of root exudates of
981 Zea mays. Plant Soil 254, 317-327.
982 Lemon E R and Erickson A E 1952 The measurement of oxygen diffusion in the soil with a platinum
983 microelectrode. Soil Sci. Soc. Am. J. 16, 160-163.
984 Leyval C and Berthelin H 1991 Weathering of mica by roots and rhizospheric microorganisms of pine.
985 Soil Sci. Soc. Am. J. 55, 1009-1016.
986 Li C S, Frolking S and Harriss R 1994 Modeling carbon biogeochemistry in agricultural soils. Global
987 Biogeochem. Cycles 8, 237-254.
988 Lindahl B, Finlay R D and Olsson S 2001 Simultaneous bidirectional translocation of ^{32}P and ^{33}P
989 between wood blocks connected by mycelial cords of Hypholoma fasciculare. New Phytol.
990 150, 189-194.
991 Liu Q, Loganathan P, Hedley M J and Skinner M F 2004 The mobilisation and fate of soil and rock
992 phosphate in the rhizosphere of ectomycorrhizal *Pinus radiata* seedlings in an Allophanic soil.
993 Plant Soil 264, 219-229
994 Lofthouse S D, Greenway G M and Stephen S C 1997 Microconcentric nebuliser for the analysis of
995 small sample volumes by inductively coupled plasma mass spectrometry. J. Anal. Atom.
996 Spectr. 12, 1373-1376.

997 Luster J and Finlay R (eds) 2006 Handbook of methods used in rhizosphere research. Swiss Federal
998 Research Institute WSL, Birmensdorf. 536 pp.; online at www.rhizo.at/handbook
999 Luster J, Menon M, Hermle S, Schulin R, Goerg-Günthardt M S and Nowack B 2008 Initial changes
1000 in refilled lysimeters built with metal polluted topsoil and acidic or calcareous subsoils as
1001 indicated by changes in drainage water composition. Water Air Soil Poll. Focus 8, 163-176.
1002 Lynch J P, Nielsen K L, Davis R D and Jablokow A G 1997 SimRoot: Modelling and visualization of
1003 root systems. Plant Soil 188, 139-151.
1004 Majdi H 1996 Root sampling methods – applications and limitations of minirhizotron technique. Plant
1005 Soil 185, 225-258.
1006 Manceau A, Marcus M A and Tamura N 2002 Quantitative speciation of heavy metals in soils and
1007 sediments by synchrotron X-ray techniques. In Applications of Synchrotron Radiation in Low-
1008 Temperature Geochemistry and Environmental Science. Eds P Fenter, M Rivers, N Sturchio
1009 and S Sutton. pp. 341-428. Reviews in Mineralogy and Geochemistry, Mineralogical Society
1010 of America, Washington D.C.
1011 Manceau A, Nagy K L, Marcus M A, Lanson M, Geoffroy N, Jacquet T and Kirpichtchikova T 2008
1012 Formation of Metallic Copper Nanoparticles at the Soil−Root Interface. Environ. Sci. Technol.
1013 42, 1766-1772.
1014 Martell A E and Smith R M 1974–1989 Critical Stability Constants, Vol. 1 to 6. Plenum Press, New
1015 York.
1016 Mayer K U, Frind E O and Blowes D W 2002 Multicomponent reactive transport modeling in variably
1017 saturated porous media using a generalized formulation for kinetically controlled reactions.
1018 Water Resour. Res. 38, 1174-1194.
1019 Meeussen J C L 2003 ORCHESTRA: an object-oriented framework for implementing chemical
1020 equilibrium models. Environ. Sci. Technol. 37, 1175-1182.
1021 Menon M, Robinson B, Oswald S E, Kaestner A, Abbaspour K C, Lehmann E and Schulin R 2007
1022 Visualisation of root growth in heterogeneously contaminated soil using neutron radiography.
1023 Eur. J. Soil Sci. 58, 802-810

1024 Mermet J M and Todolí J L 2004 Towards total-consumption pneumatic liquid micro-sample-
1025 introduction systems in ICP spectrochemistry. Anal. Bioanal. Chem. 378, 57–59.
1026 Michot D, Benderitter Y, Dorigny A, Nicoullaud B, King D and Tabbagh A 2003 Spatial and temporal
1027 monitoring of soil water content with an irrigated corn crop cover using surface electrical
1028 resistivity tomography. Water Res Res.39, 1138, doi:10.1029/2002WR001581
1029 Minchin P E H and McNaughton G S 1984 Exudation of recently fixed carbon by non-sterile roots. J.
1030 Exp. Bot. 35, 74-82
1031 Mooney S J, Morris C, and Berry P M 2006a Visualization and quantification of the effects of cereal
1032 root lodging on three-dimensional soil macrostructure using X-ray computed tomography. Soil
1033 Science 171, 706-718.
1034 Mooney S J, Foot K, Hutchings T R, and Moffat A J 2006b Micromorphological investigations into
1035 root penetration in a landfill mineral cap, Hertfordshire, UK. Waste Manag. 27, 1225-1232.
1036 Moran C J, Pierret A and Stevenson A W 2000 X-ray absorption and phase contrast imaging to study
1037 the interplay between plant roots and soil structure. Plant Soil 223, 99-115.
1038 Myneni S C B 2002 Soft X-ray spectroscopy and spectromicroscopy studies of organic molecules in
1039 the environment. In Reviews in Mineralogy and Geochemistry. Applications of Synchrotron
1040 Radiation in Low-Temperature Geochemistry and Environmental Science. Eds P Fenter, M
1041 Rivers, N Sturchio and S Sutton. pp. 485-579. Mineralogical Society of America.
1042 Nachtegaal M, Marcus M A, Sonke J E, Vangronsveld J, Livi K J T, Van der Lelie D and Sparks D L
1043 2005 Effects of in situ remediation on the speciation and bioavailability of zinc in a smelter
1044 contaminated soil. Geochim. Cosmochim. Acta 69, 4649.
1045 Naim M S 1965 Development of rhizosphere and rhizoplane microflora of *Artistida coerulescens* in
1046 the Lybian desert. Archiv Mikrobiol. 50, 321-325.
1047 Neumann G 2006. Root exudates and organic composition of plant roots. In Handbook of methods
1048 used in rhizosphere research. Eds. Luster J and Finlay R. pp. 52-61. Swiss Federal Research
1049 Institute WSL, Birmensdorf.

1050 Neumann G and Römheld V 2001 The release of root exudates as affected by the plant's physiological
1051 status. In The rhizosphere: biochemistry and organic substances at the soil-plant interface.
1052 Eds. R Pinton, Z Varanini and P Nannipieri. pp. 41-93. Marcel Dekker, New York.
1053 Neumann G et al. 2008 Strategies and methods – the plant science toolbox. Plant Soil, *this volume,*
1054 *submitted*
1055 Nollet L M L (Ed.) 2007 Handbook of water analysis, 2nd Ed. CRC Press, Boca Raton. 769 pp.
1056 Nowack B, Köhler S and Schulin R 2004 Use of diffusive gradients in thin films (DGT) in
1057 undisturbed field soils. Environ. Sci. Technol. 38, 1133-1138.
1058 Nowack B, Mayer K U, Oswald S E, VanBeinum W, Appelo C A J, Jacques D, Seuntjens P, Gérard F,
1059 Jaillard B, Schnepf A and Roose T 2006 Verification and intercomparison of reactive
1060 transport codes to describe root-uptake. Plant Soil 285, 305-321.
1061 Nye P H and Tinker P B 1977 Solute movement in the soil-root system. Blackwell, Oxford. 342 pp.
1062 Ochs M, Brunner I, Stumm W and Cosovic B 1993 Effects of root exudates and humic substances on
1063 weathering kinetics. Water Air Soil Poll. 68, 213-229.
1064 Oswald S E, Menon M, Carminati A, Vontobel P, Lehmann E and Schulin R 2008 Quantitative
1065 imaging of infiltration, root growth, and root water uptake via neutron radiography. Vadose
1066 Zone J 7, 1035-1047.
1067 Pagès L, Vercambre G, Drouet J L, Lecompte F, Collet C and LeBot J 2004 Root Typ: a generic
1068 model to depict and analyse the root system architecture. Plant Soil, 258, 103-119.
1069 Panfili F, Manceau A, Sarret G, Spadini L, Kirpichtchikova T, Bert V, Laboudigue A, Marcus M,
1070 Ahamdach N and Libert M 2005 The effect of phytostabilization on Zn speciation in a
1071 dredged contaminated sediment using scanning electron microscopy, X-ray fluorescence,
1072 EXAFS spectroscopy and principal components analysis. Geochim. Cosmochim. Acta 69,
1073 2265-2284.
1074 Panikov N S, Mastepanov M A and Christensen T R 2007 Membrane probe array: technique
1075 development and observation of CO_2 and CH_4 diurnal oscillations in peat profile. Soil Biol.
1076 Biochem. 39, 1712-1723.

1077 Pansu M and Gautheyrou J 2006 Handbook of soil analysis: mineralogical, organic and inorganic
1078 methods. Springer, Berlin. 993 pp.
1079 Parker D R and Pedler J F 1997 Reevaluating the free-ion activity model of trace metal availability to
1080 higher plants. Plant Soil 196, 223-228.
1081 Parkhurst D L and Appelo C A J 1999 User's guide to PHREEQC (version 2). A computer program
1082 for speciation, batch-reaction, one-dimensional transport, and inverse geochemical
1083 calculations. Water resources investigations Report 99-4259. US Geological Survey. 312 pp.
1084 Paterson E, Sim A, Standing D, Dorward M and McDonald A J S 2006 Root exudation from *Hordeum*
1085 *vulgare* in response to localized nitrate supply. J. Exp. Bot. 57, 2413-2420.
1086 Pierret A, Doussan C, Garrigues E and McKirby J 2003 Observing plant roots in their environment:
1087 current imaging options and specific contribution of two-dimensional approaches. Agronomie
1088 23, 471-479.
1089 Pierret A, Doussan C, Capowiez Y, Bastardie F, Pagès L 2007 Root functional architecture: a
1090 framework for modeling the interplay between roots and soil. Vadose Zone J 6, 269-281.
1091 Pinjuv G, Mason E G and Watt M 2006 Quantitative validation and comparison of a range of forest
1092 growth model types. Forest Ecol. Manag. 236, 37-46.
1093 Plassard C, Meslem M, Souche G and Jaillard B 1999 Localization and quantification of net fluxes of
1094 H^+ along maize roots by combined use of pH-indicator dye videodensitometry and H^+-
1095 selective microelectrodes. Plant Soil 211, 29-39.
1096 Plassard C, Guérin-Laguette A, Véry A A, Casarin V and Thibaud J B 2002 Local measurements of
1097 nitrate and potassium fluxes along roots of maritime pine. Plant Cell Environ. 25, 75-84.
1098 Polomski J and Kuhn N 2002. Root research methods. In Plant roots – the hidden half, 3rd ed. Eds. Y
1099 Waisel, A Eshel and U Kafkafi. pp. 295-321 Marcel Dekker, New York.
1100 Prabhu R K, Vijayalahshimi S, Mahalingam T R, Viswanathan K S and Methews C K 1993 Laser
1101 vaporization inductively-coupled plasma-mass spectrometry - A technique for the analysis of
1102 small volumes of solutions. J. Anal. Atom. Spectr. 8, 565-569.
1103 Psenner R, Boström B, Dinka M, Pettersson K, Pucsko R and Sager M 1988 Fractionation of
1104 phosphorus in suspended matter and sediment. Arch. Hydrobiol. Beih. 30, 99-103.

1105 Puschenreiter M, Wenzel WW, Wieshammer G, Fitz WJ, Wieczorek S, Kanitsar K and Kollensperger
1106 G 2005a Novel micro-suction-cup design for sampling soil solution at defined distances from
1107 roots. J. Plant Nutr. Soil Sci. 168, 386-391.
1108 Puschenreiter M, Schnepf A, Millan I M, Fitz W J, Horak O, Klepp J, Schrefl T, Lombi E and Wenzel
1109 W W 2005b Changes of Ni biogeochemistry in the rhizosphere of the hyperaccumulator
1110 *Thlaspi goesingense*. Plant Soil 271, 205-218.
1111 Raab T K and Vogel J P 2004 Ecological and agricultural applications of synchrotron IR microscopy.
1112 Infrared Phys.Technol. 45, 393-402.
1113 Raich J W and Mora G 2005 Estimating root plus rhizosphere contributions to soil respiration in
1114 annual croplands. Soil Sci. Soc. Am. J. 69, 634-639.
1115 Rais D, Nowack B, Schulin R and Luster J 2006 Sorption of trace metals by different standard and
1116 micro suction cups used as soil water samplers as influenced by dissolved organic carbon. J.
1117 Environ. Qual. 35, 50-60.
1118 Rangel Castro J I, Killham K, Ostle N, Nicol G W, Anderson I C, Scrimgeour C M, Ineson P, Meharg
1119 A and Prosser J I 2005 Stable isotope probing analysis of the influence of liming on root
1120 exudate utilization by soil microorganisms. Environ. Microbiol. 7, 828-838.
1121 Rappoldt C 1995 Measuring the millimeter scale oxygen diffusivity in soil using microelectrodes. Eur.
1122 J. Soil Sci. 46, 169-177.
1123 Reichard P U, Kraemer S M, Frazier S W and Kretzschmar R 2005 Goethite dissolution in the
1124 presence of phytosiderophores: rates, mechanisms, and the synergistic effect of oxalate. Plant
1125 Soil 276, 115-132.
1126 Rodriguez-Mozaz S, Lopez de Alda M and Barceló D 2006 Biosensors as useful tools for
1127 environmental analysis and monitoring. Anal. Bioanal. Chem. 386, 1025–1041.
1128 Römheld V 1986 pH changes in the rhizosphere of various crop plants in relation to the supply of
1129 plant nutrients. In: Potash Review 12, Internat. Potash Institute, Bern Switzerland, Subject 6,
1130 55th Suite
1131 Roose T and Fowler A C 2004a A mathematical model for water and nutrient uptake by plant root
1132 systems. J. Theor. Biol. 228, 173-184.

1133 Roose T and Fowler A C 2004b A model for water uptake by plant roots. J. Theor. Biol. 228, 155-171.

1134 Roose T, Fowler A C and Darrah P R 2001 A mathematical model of plant nutrient uptake. J. Math.
1135 Biol. 42, 347-360.

1136 Rosling A, Lindahl B and Finlay R D 2004 Carbon allocation to ectomycorrhizal roots and mycelium
1137 colonising different mineral substrates. New Phytol. 162, 795-802.

1138 Rothfuss F and Conrad R 1994 Development of a gas diffusion probe for the determination of
1139 methane concentrations and diffusion characteristics in flooded paddy soil. FEMS Microb.
1140 Ecol. 14, 307-318.

1141 Sandnes A and Eldhuset T D 2003 Soda glass beads as growth medium in plant cultivation
1142 experiments. J. Plant Nutr. Soil Sci. 166, 660-661.

1143 Sawhney B L 1996 Extraction of organic chemicals. In Methods of soil analysis. Part 3. Chemical
1144 Methods. Ed. D L Sparks. pp. 1071-1084. Soil Science Society of America, Madison.

1145 Schnepf A, Schrefl T and Wenzel W W 2002 The suitability of pde-solvers in rhizosphere modeling,
1146 exemplified by three mechanistic rhizosphere models. J. Plant Nutr. Soil Sci. 165, 713-718.

1147 Schumacher M, Christl I, Scheinost A C, Jacobsen C and Kretzschmar R 2005 Chemical heterogeneity
1148 of organic soil colloids investigated by scanning transmission X-ray microscopy and C-1s
1149 NEXAFS microspectroscopy. Environ. Sci. Technol. 39, 9094-9100.

1150 Senesi N 1996 Electron spin (or paramagnetic) resonance spectroscopy. In Methods of soil analysis.,
1151 Part 3. Chemical Methods. Ed. D L Sparks. pp. 323-356. Soil Science Society of America,
1152 Madison.

1153 Seuntjens P, Nowack B and Schulin R 2004 Root-zone modeling of heavy metal uptake and leaching
1154 in the presence of organic ligands. Plant Soil 265, 61-73.

1155 Shen J and Hoffland E 2007 In situ sampling of small volumes of soil solution using modified micro-
1156 cups. Plant Soil 292, 161-169.

1157 Siegel L S, Alshawabkeh A N, Palmer C D and Hamilton M A 2003 Modeling cesium partitioning in
1158 the rhizosphere: a focus on the role of root exudates. Soil Sediment Contam. 12, 47-68.

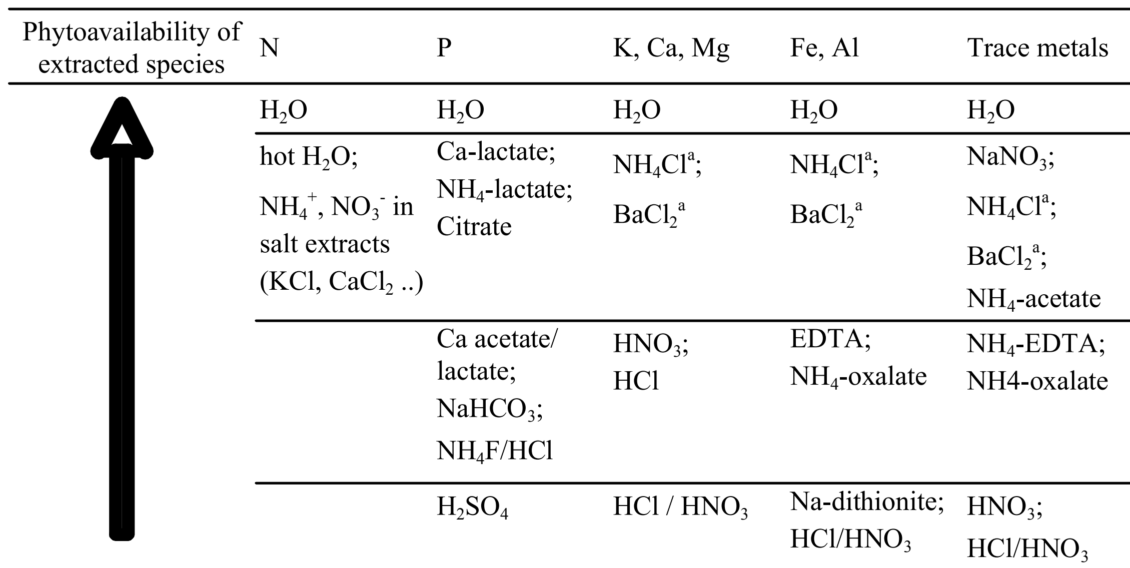
1159 Somma F, Hopmans J W and Clausnitzer V 1998 Transient three-dimendional modeling of soil water
1160 and solute transport with simultaneous root growth, root water and nutrient uptake. Plant Soil
1161 202, 281-293.
1162 Sørensen J et al. 2008 Strategies and methods – the microbial ecology toolbox. Plant Soil*, this volume,*
1163 *submitted*
1164 Sparks D L (Ed.) 1996 Methods of soil analysis. Part 3. Chemical Methods. SSSA Book Series 5, Soil
1165 Science Society of America, Madison. 1358 pp.
1166 Stevenson F J 1996 Nitrogen-organic forms. In Methods of soil analysis., Part 3. Chemical Methods.
1167 Ed. D L Sparks. pp. 1185-1200. Soil Science Society of America, Madison.
1168 Ström L, Owen A G, Godbold D L and Jones D L 2002 Organic acid mediated P mobilization in the
1169 rhizosphere and uptake by maize roots. Soil Biol. Biochem. 34, 703-710.
1170 Sulzmann E W, Brant J B, Bowden R D and Lajtha K 2005 Contribution of aboveground litter,
1171 belowground litter, and rhizosphere respiration to total soil CO_2 efflux in an old growth
1172 coniferous forest. Biogeochemistry 73, 231-256
1173 Tang C S and Young C C 1982 Collection and identification of allelopathic compounds from the
1174 undisturbed root-system of bigalta limpograss (*hemarthria-altissima*). Plant Physiol. 69, 155-
1175 160.
1176 Tercier-Waeber M-L , Buffle J, Koudelka-Hep M and Graziottin F 2002 Submersible voltammetric
1177 probes for in-situ real-time trace element monitoring in natural aquatic systems. In
1178 Environmental electrochemistry: Analysis of trace element biogeochemistry. Eds. M Taillefert
1179 and T F Rozan. pp. 16-39. ACS Series No. 811, Washington D.C.
1180 Tessier, A, Campbell P G C and Bisson M 1979 Sequential extraction procedure for the speciation of
1181 particulate trace metals. Anal. Chem. 51, 844-851.
1182 Turpault M P 2006 Sampling of rhizosphere soil for physico-chemical and mineralogical analyses by
1183 physical separation based on dyeing and shaking. In Handbook of methods used in
1184 rhizosphere research. Eds. Luster J and Finlay R. pp. 196-197. Swiss Federal Research
1185 Institute WSL, Birmensdorf.

1186 VanBochove E, Beauchemin S and Theriault G 2002 Continuous multiple measurement of soil redox
1187 potential using platinum microelectrodes. Soil Sci. Soc. Am J. 66, 1813-1820.
1188 Vereecken H, Kasteel R, Vanderborght J and Harter T 2007 Upscaling hydraulic properties and soil
1189 water flow processes in heterogeneous soils: a review. Vadose Zone J. 6, 1-28.
1190 Vetterlein D and Jahn R 2004. Combination of micro suction cups and time-domain reflectometry to
1191 measure osmotic potential gradients between bulk soil and rhizosphere at high resolution in
1192 time and space. Eur. J. Soil Sci. 55, 497-504.
1193 Vink J P M and Meeussen J C L 2007 BIOCHEM-ORCHESTRA: A tool for evaluating chemical
1194 speciation and ecotoxicological impacts of heavy metals on river flood plain systems. Environ.
1195 Poll. 148, 833-841.
1196 Voegelin A, Weber F-A and Kretzschmar R 2007 Distribution and speciation of arsenic around roots
1197 in a contaminated riparian floodplain soil: Micro-XRF element mapping and EXAFS
1198 spectroscopy. Geochim. Cosmochim. Acta 71, 5804-5820.
1199 VonLützow M, Kögel-Knabner I, Ekschmitt K, Flessa H, Guggenberger G, Matzner E and Marschner
1200 B 2007 SOM fractionation methods: Relevance to functional pools and to stabilization
1201 mechanisms. Soil Biol Biochem 39, 2183-2207.
1202 Wang E and Smith C J 2004 Modeling the growth and water uptake function of plant root systems: a
1203 review. Aust. J. Agric. Res. 55, 501-523.
1204 Wang Z, Göttlein A and Bartonek G 2001 Effects of growing roots of Norway spruce (*Picea abies*
1205 [L.] Karst.) and European beech (*Fagus sylvatica* L.) on rhizosphere soil solution chemistry. J.
1206 Plant Nutr. Soil Sci. 164, 35-41.
1207 Warnken K, Zhang, H and Davison W 2004 Analysis of polyacrylamide gels for trace metals using
1208 diffusive gradients in thin films and laser ablation inductively coupled plasma mass
1209 spectrometry. Anal. Chem. 76, 6077-6084.
1210 Watteau F and Villemin G 2001 Ultrastructural study of the biogeochemical cycle of silicon in the soil
1211 and litter of a temperate forest. Eur. J. Soil Sci. 52, 385-396.

1212 Weaver R W, Angle S and Bottomley P (Eds.) 1994 Methods of soil analysis. Part 2. Microbiological
1213 and biochemical properties. SSSA Book Series 5, Soil Science Society of America, Madison.
1214 1121 pp.
1215 Wenzel W W, Wieshammer G, Fitz W J and Puschenreiter M 2001. Novel rhizobox design to assess
1216 rhizosphere characteristics at high spatial resolution. Plant Soil 237, 37-45.
1217 Whiting S N, Leake J R, McGrath S P and Baker A J M 2000 Positive responses to Zn and Cd by
1218 roots of the Zn and Cd hyperaccumulator *Thlaspi caerulescens*. New Phytol. 145, 199-210.
1219 Wolf D C and Skipper H D 1994 Soil sterilization. In: Methods of soil analysis, Part 2;
1220 microbiological and biochemical properties. Eds. R W Weaver, S Angle and P Bottomley. pp.
1221 41-51. Soil Science Society of America, Madison.
1222 Wu L, McGechan M B, McRoberts N, Baddeley J A and Watson C A 2007 SPACSYS: Integration of
1223 a 3D root architecture component to carbon, nitrogen and water cycling-model description.
1224 Ecol. Model. 200, 343-359.
1225 Yanai R D, Majdi H and Park B B 2003 Measured and modelled differences in nutrient concentrations
1226 between rhizosphere and bulk soil in a Norway spruce stand. Plant Soil 257, 133-142.
1227 Yevdokimov I V, Ruser R, Buegger F, Marx M and Munch J C 2007 Carbon turnover in the
1228 rhizosphere under continuous plant labeling with (CO_2)-C-13: Partitioning of root, microbial,
1229 and rhizomicrobial respiration Eurasian Soil Sci. 40, 969-977.
1230 Yu K W and DeLaune R D 2006 A modified soil diffusion chamber for gas profile analysis. Soil Sci.
1231 Soc. Am. J. 70, 1237-1241.
1232 Zeien H and Brümmer G W 1989 Chemische Extraktion zur Bestimmung von
1233 Schwermetallbindungsformen in Böden. Mitteilgn. Dtsch. Bodenkundl. Ges. 59, 505-510.
1234 Zhang T C and Pang H 1999. Applications of microelectrode techniques to measure pH and oxidation-
1235 reduction potential in rhizosphere soil. Environ. Sci. Technol. 33, 1293-1299.
1236 Zhang H, Davison W, Knight B and McGrath S 1998 In situ measurement of solution concentrations
1237 and fluxes of trace metals in soils using DGT. Environ. Sci. Technol. 32, 704-710.

1238 Zhang H, Zhao F J, Sun B, Davison W and McGrath S P 2001 A new method to measure effective soil
1239 solution concentration predicts copper availability to plants. Environ. Sci. Technol. 35, 2602-
1240 2607.
1241 Zhao L Y L, Schulin R and Nowack B 2007 The effects of plants on the mobilization of Cu and Zn in
1242 soil columns. Environ. Sci. Technol. 41, 2770-2775.
1243

Table 1: Common extractants for elements and ions grouped approximately in decreasing order of plant availability as compiled from standard method collections. For most extractants there are several slightly different protocols in terms of extractant concentration, extraction time, etc.. Also, there can be large differences in the extractive power of a given extractant depending on soil properties such as pH or soil organic matter content (e.g. some extractants can only be used either for calcareous or acidic soils).



Phytoavailability of extracted species	N	P	K, Ca, Mg	Fe, Al	Trace metals
↑	H_2O	H_2O	H_2O	H_2O	H_2O
	hot H_2O; NH_4^+, NO_3^- in salt extracts (KCl, $CaCl_2$ ..)	Ca-lactate; NH_4-lactate; Citrate	NH_4Cl[a]; $BaCl_2$[a]	NH_4Cl[a]; $BaCl_2$[a]	$NaNO_3$; NH_4Cl[a]; $BaCl_2$[a]; NH_4-acetate
		Ca acetate/ lactate; $NaHCO_3$; NH_4F/HCl	HNO_3; HCl	EDTA; NH_4-oxalate	NH_4-EDTA; NH4-oxalate
		H_2SO_4	HCl / HNO_3	Na-dithionite; HCl/HNO_3	HNO_3; HCl/HNO_3

[a]methods to determine exchangeable cation contents; from the sum of all major cations the cation exchange capacity of the soil can be calculated

1252 Tab.2: Techniques for analyzing main parameters of aqueous solutions and their applicability to

1253 rhizosphere research

Technique (analytes)	Availability, costs	suitability for / adaptation to rhizosphere research (limited sample amount)
potentiometry (pH)	common, low	ISFET instead of glass electrodes
flow injection analysis (NH_4)	common, low	autosampler and sample loop limiting
Voltammetry (labile metal cations)	special, low	micro-sensors necessary, however sample demand still in ml-range
TC/TN analyser (DOC, CO_3, N_{tot})	common, intermediate	autosampler and sample injection limiting; direct injection option reduces sample demand to 50 µl
ion chromatography (inorganic anions, organic acids, NH_4)	common, intermediate	autosampler and sample loop limiting; microbore systems allow reduction of sample demand to the sub-µl-range
HPLC (organic acids, sugars, etc.)	common, intermediate	as for ion chromatography
Flame AAS (total metal conc.)	common, intermediate	hardly possible because of high sample demand
Graphite furnace AAS (total metal conc.)	special, intermediate	suitable, sample demand of 20 to 50 µl for single element analysis
capillary electrophoresis (inorganic anions, organic acids, free metal cations, NH_4)	special, intermediate	with a demand of 20 nL suitable for the analysis of minimal sample amounts
ICP-OES	common, expensive	special nebulizers for lowering sample demand to about 100µl for multielement analysis
ICP-MS	special, expensive	as for ICP-OES

1254

1255

1256 Table 3: Approaches and scales in rhizosphere modeling

Model type		**Model scale**	**Main model targets**	**Examples**
Macroscopic (empirical)		Agricultural field / forest	Plant yield, forest growth	Pinjuv et al. (2006); Siegel et al. (2003); Cosby et al. (1985)
		Ecosystem	Element and nutrient cycles	Li et al. (1994)
		Soil profile	Water transport	Somma et al. (1998)
		Whole root system	Root growth	Diggle (1988); Doussan et al. (2006); Dunbabin et al. (2002); Lynch et al. (1997)
Microscopic (explanatory)	semi-empirical	Single root	Root processes	Nye and Tinker (1977); Barber (1995); Kirk (1999); Roose et al. (2001)
		Root system	Root system development	Roose and Fowler (2004ab)
	molecular	Soil solution	Speciation in solution	Calba et al. (2004); Puschenreiter et al. (2005b)
		Single root	Integration of chemical reactions	Geelhoed et al. (1999); Nowack et al. (2006)
		Soil profile	Integration of all mechanisms	Seuntjens et al. (2004)

1257

1258

1259 **Figure captions**

1260 Fig. 1. Rhizosphere as 3-phase system with soil solid phase (SP), soil solution (SS), and soil gas phase
1261 (SG); spatial heterogeneity along and perpendicular to root growth added by a developing root system
1262 is emphasised and is overlaid by temporal variability: root growth (A), turnover of roots and fungal
1263 hyphae (B), diurnal or seasonal changes in the activity of roots (exudation, uptake; C), or associated
1264 organisms (D).

1265

1266 Fig. 2. Example of a root mat type microcosm. It is composed of a lower part containing a thin soil
1267 layer (1-3 mm thick; or, alternatively, a soil cylinder of greater height if aiming at studying
1268 rhizosphere gradients), and of an upper part containing the root mat, separated by a polyamide
1269 membrane. For pregrowth, the upper part is immersed in aerated nutrient solution (adapted from
1270 Guivarch et al. 1999, Figure 1; with kind permission from Springer Science+Business Media); for
1271 further explanations see Chaignon and Hinsinger (2003).

1272

1273 Fig. 3. Studying the influence of a growing oak root on soil solution chemistry using a micro suction
1274 cup array installed in a "Hohenheim" type microcosm (adapted from Göttlein et al. 1999; with kind
1275 permission from Springer Science+Business Media)

1276

1277 Fig. 4 Effect of soil-buffering capacity ($CaCO_3$ content) on the extension of root-induced rhizosphere
1278 acidification of chickpea *(Cicer arietinum* L.) seedlings 12 DAS, detected in "Hohenheim" type
1279 microcosms by soil impregnation with pH-indicator (bromocresol purple) agar (from Römheld 1986;
1280 courtesy of the International Potash Institute, Switzerland)

1281

1282 Fig. 5: Zn K-edge bulk EXAFS spectra of a Zn-contaminated sediment (control), treated with mineral
1283 amendments and planted with *Agrostis tenuis*, and distribution of Zn species determined from the
1284 analysis of these data and µEXAFS spectra. The amendments induce a significant oxidation of ZnS
1285 and the formation of secondary species. These effects are strongly enhanced in the presence of *A.*

1286 *tenuis*, with an almost complete removal of ZnS (adapted from Panfili et al. 2005; Copyright Elsevier
1287 (2005)).
1288
1289 Fig. 6: Peat microcosm containing *Pinus sylvestris* seedlings colonised by *Hebeloma crustuliniforme*
1290 and pure mineral patches of either K feldspar (K) or quartz (Q). Fifteen weeks after introducing
1291 mineral patches at the growing mycelial front (a), the shoots were pulse labelled with $^{14}CO_2$. Greater
1292 amounts of labelled carbon are allocated to root tips and mycelia associated with patches of F feldspar
1293 compared to patches of quartz (b). CPM: counts per min. (adapted from Rosling et al. 2004; with kind
1294 permission from the New Phytologist Trust).
1295
1296 Fig. 7: Changes in soil moisture in a profile during drying shown as difference between the inverted
1297 electrical resistivity at about 8 days after irrigation and immediately after irrigation. Root zones of
1298 corn rows (R1 to R8) show as dark zones that dry out quickly (adapted from Michot et al. 2003;
1299 Reproduced/modified by permission of American Geophysical Union)
1300
1301 Figure 8: Examples of different rhizosphere models. a) Macroscopic model, whole root system scale:
1302 modeled root system of *Lupinus albus* (from Doussan et al. 2006; with kind permission from Springer
1303 Science+Business Media). b) Microscopic, mechanistic single root model of citrate exudation and its
1304 influence on phosphate solubilization (dots: experimental; black line: modeled P in soil; dotted line: P
1305 in solution; dashed line: citrate in soil) (from Kirk 1999; with kind permission from Blackwell
1306 Publishing). c) Microscopic single root model, molecular scale: influence of citrate on phosphate
1307 mobilization (P in solution in the absence and presence of citrate exudation) (from Geelhoed et al.
1308 1999; with kind permission from Blackwell Publishing).

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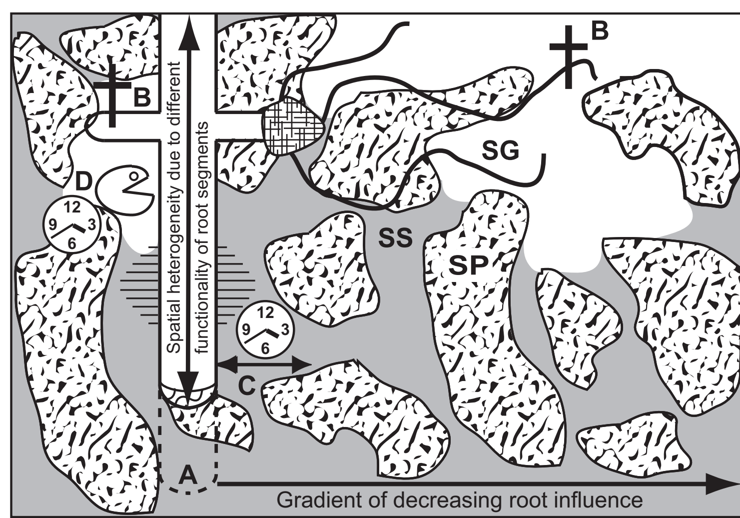

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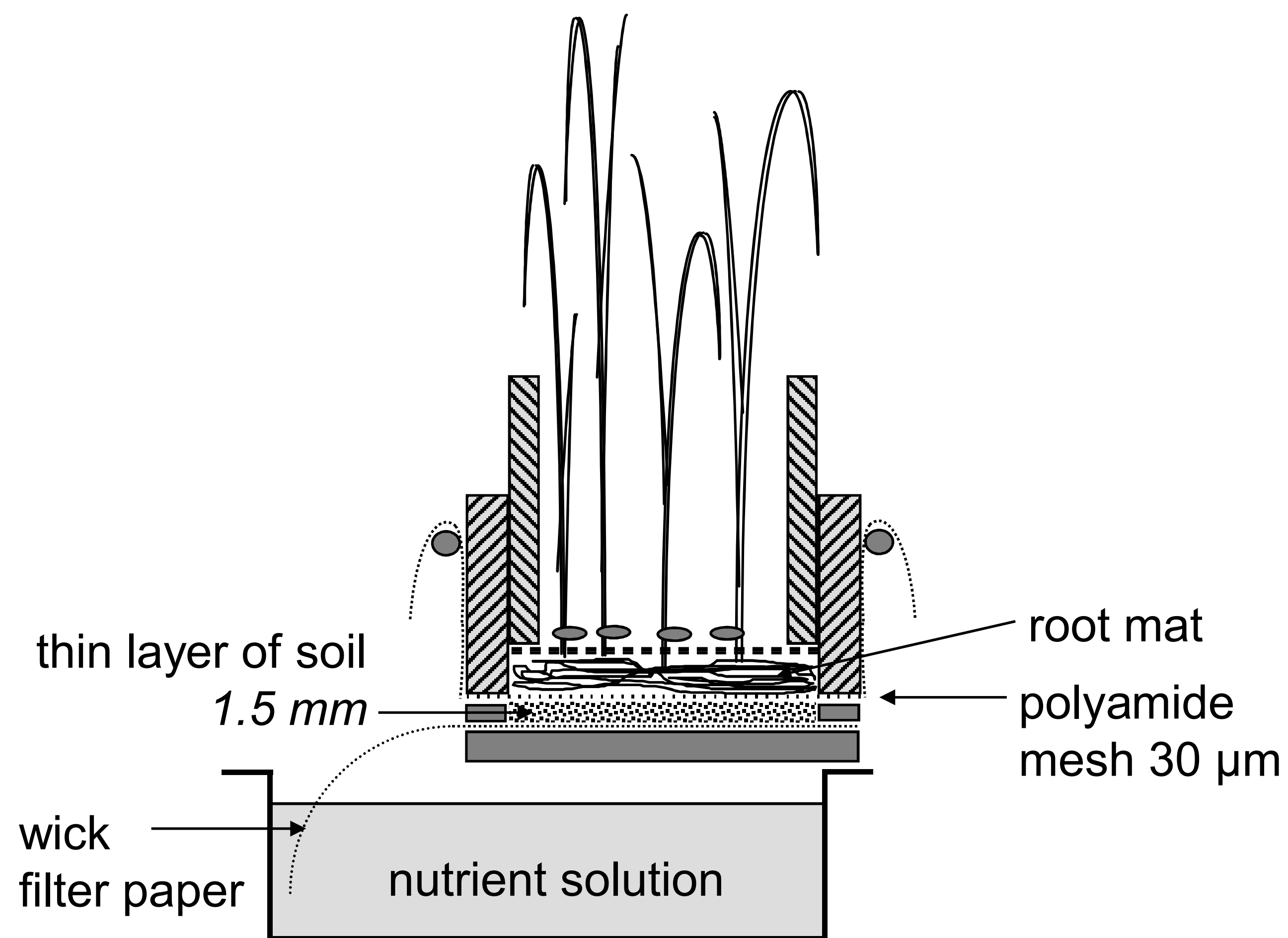

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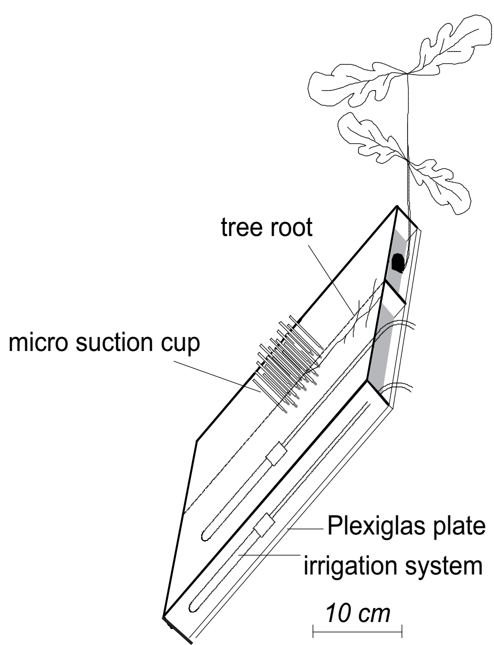

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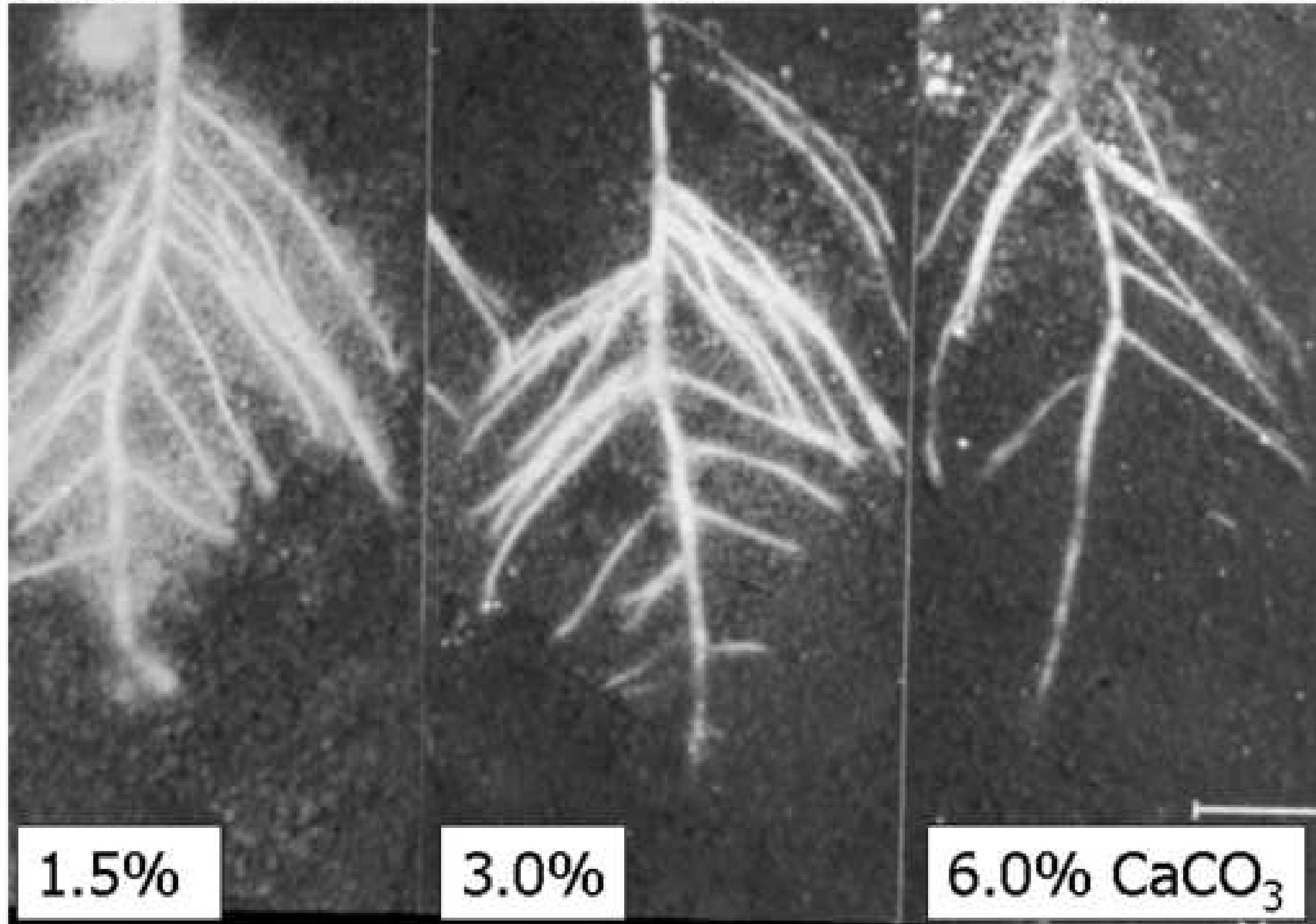

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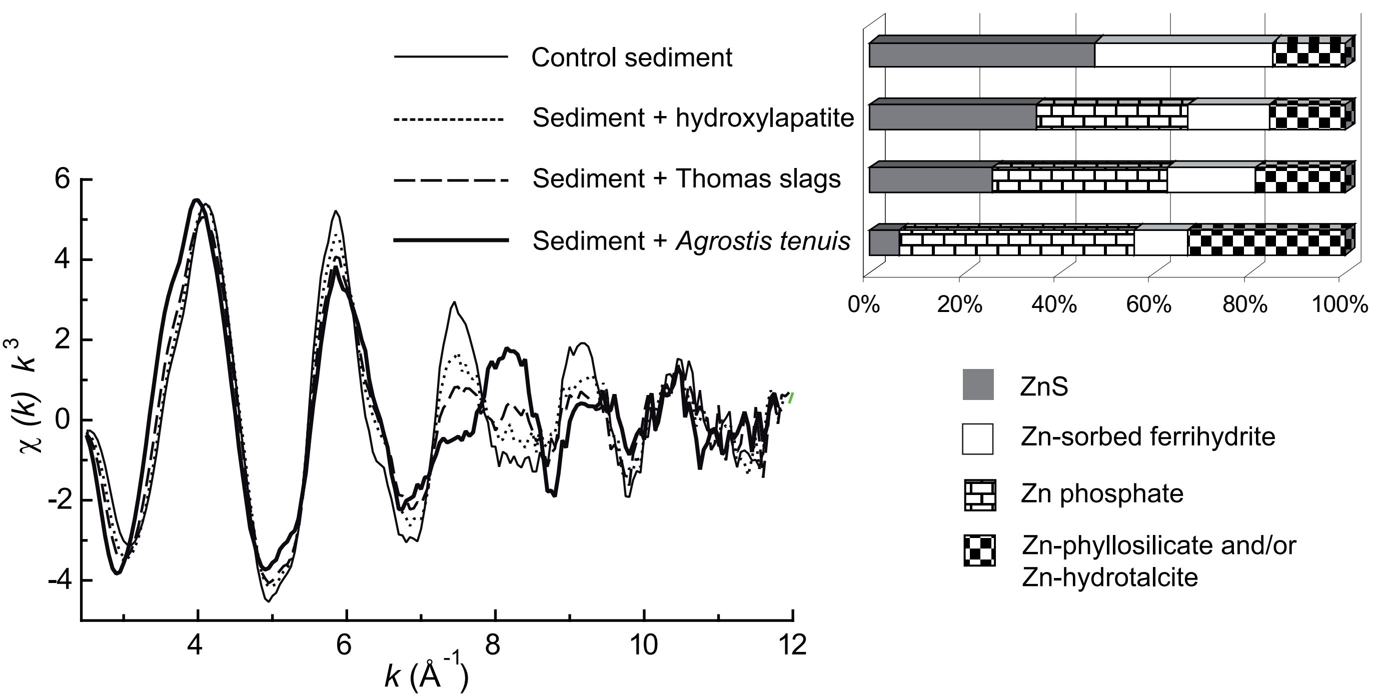

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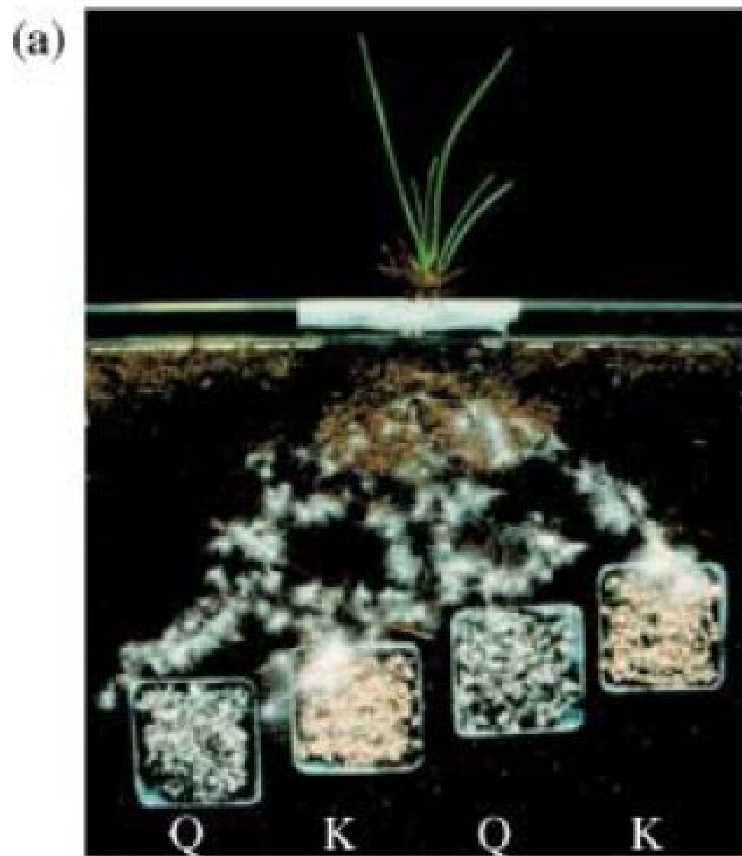

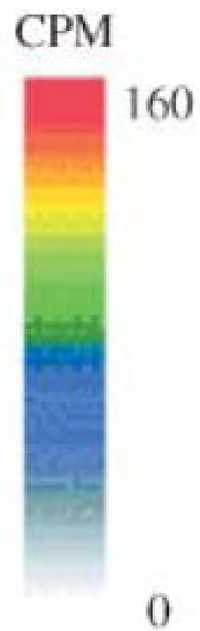

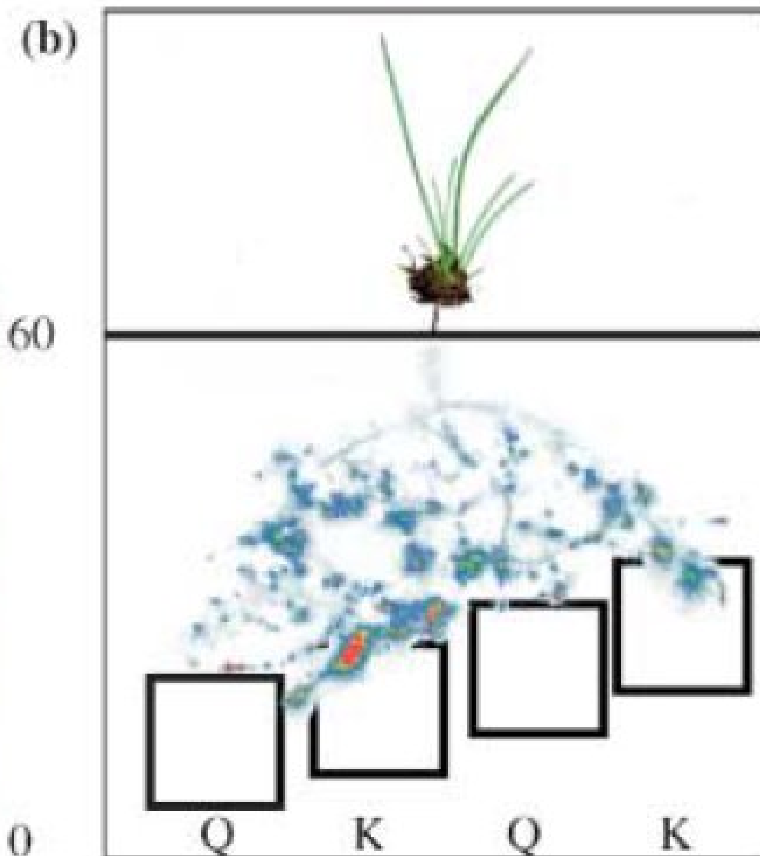

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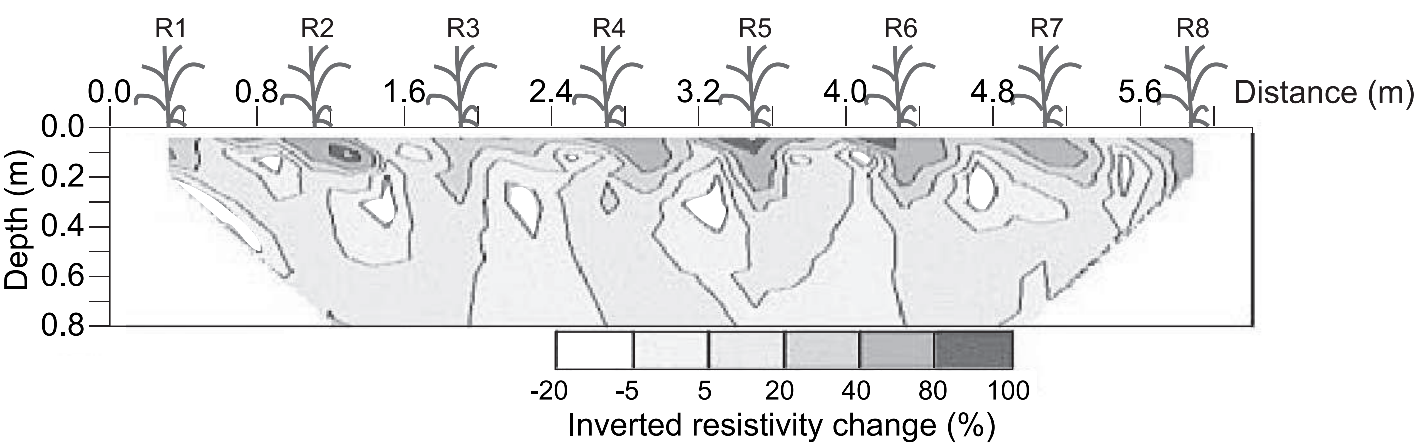

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