Root distribution functions of spring barley, winter rye and maize

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Wurzelverteilungsfunktionen von Sommergerste, Winterroggen und Mais

1 Introduction

Root impact on water movement has been widely considered in models of water and solute transport. Water uptake by roots has been classically described at both microscopic and macroscopic level (FEDDES et al., 2001; FEDDES and RAATS, 2004). Different complexity of information is introduced according to the scale of operation and processes taken into consideration (LOISKANDL et al., 2005). Bottom-up or microscopic approaches contain detailed description of individual roots and functions and surrounded growth medium, and parameters describing their interactions. This is relevant for rhizosphere or single root models (TINKER and NYE, 2000; DARRAH et al., 2006). Macroscopic or top-down models such as hydrologically oriented models of water transport within Soil-Plant-Atmosphere continuum (SPAC) (FEDDES et al., 2001), rely on a Darcyan approach to energy and mass transfer. In these models, the rate of water uptake is assumed proportional to the root density and stands for the uptake averaged over many different roots. Similar approach has been also applied in crop models (WANG and SMITH, 2004).

Two controversial techniques have been proposed to optimise the representation of roots: either via increasing complexity of the physically and physiologically based models or by keeping them as simple as possible (FEDDES et al., 2001; HOPMANS and BRISTOW, 2002). The first approach allows a comprehensive description of root functioning and

Zusammenfassung

Wurzelparameterverteilungen sind benötigt, um die Wasseraufnahme der Pflanzen in den makroskalen Modellen abschätzen zu können. Das Hauptziel dieser Studie war die vertikalen Verteilung der Wurzeltrockenmassen-, der Wurzellängen- und der Wurzeloberflächendichte von unter denselben Umweltbedingungen gewachsenen Sommergerste, Winterroggen und Mais, zu untersuchen und zu vergleichen. Die Wurzelproben wurden mittels Bodenmonolithen in einem frühen Entwicklungsstadium der Pflanzen erhoben. Es wurde beobachtet, dass die relative Verteilungen aller gemessenen Wurzelparameters, angegeben als Wurzelverteilungsfunktionen, annähernd exponentiell verlaufen. Es wurden keine wesentlichen Unterschiede zwischen deren Formen diagnostiziert. Statistisch hochsignifikante Beziehungen zwischen der Wurzelntrockenmasse, und der Wurzellänge und der Wurzeloberfläche wurden abgeleitet, was für die alternative Erfassung der Wurzelparameter im Senkenterm wesentlich ist.

Schlagworte: Modellierung der Wasseraufnahme, Wurzelparameter, Senkenterm, Getreide.

Summary

Root parameter distributions are needed for estimation of water uptake by plants in macroscale models. The main objective of the study was to assess and compare vertical distributions of dry mass, length and surface area of roots of spring barley, winter rye and maize grown under equivalent environmental conditions. Root samples were collected using soil monolith method at early crop growth stages. The relative vertical distributions of all studied parameters expressed as root distribution functions were approximately exponential, with no considerable differences between their shapes. Statistically highly significant relationships were established between the dry mass density, and the length and surface area densities of roots, which is essential for alternative expressions by the root sink term estimation.

Key words: Water uptake modelling, root parameters, root sink term, crops.

fluxes also inside the roots (*e.g.* ROOSE and FOWLER, 2004; DOUSSAN et al., 2006), growth and branching patterns (*e.g.* SOMMA et al., 1998, DUNBABIN et al., 2002), etc., and theoretically characterises the soil-root system close to reality. It has been mostly applied at micro- and mesoscopic (plant) scales of modelling. A detailed review of this approach is given by RAATS (2007) and HOPMANS and BRISTOW (2002). At the same time, such models need plenty of input data, which are difficult to be measured and thus makes their practical application and verification complicated (WANG and SMITH, 2004). The second approach tends to parameterise roots more simply and requires a few key parameters. Generally, the roots are represented using two main characteristics: a maximum rooting depth, which defines the upper boundary of the plant available water in the root zone, and a vertical distribution of roots, which gives the distribution of the water uptake according to the fraction of roots at a certain depth (RAATS, 2007). This modelling approach is used in large scale models of water transport (FEDDES and RAATS, 2004), climate and land surface models (JACKSON et al., 2000).

Most mathematical models of water transfer in SPAC are based on the one-dimensional Richards equation, describing water flow in vertical direction and incorporate a root uptake sub-model by means of a volumetric extraction (sink) term (Eq. 1). To characterise this term in its complexity is a challenging task. Especially qualitative properties of roots in relation to their conductivity to water are not completely parameterised until now. For that reason, integral characteristics for the entire root system are assumed and easily measurable parameters such as density distributions of roots are used (FEDDES and RAATS, 2004). The roots are considered uniformly distributed within each soil layer (*i.e.* horizontally) and having the same capability for uptake in spite of their topology, size, age, etc. Detailed descriptions of the root distribution parameters down the soil profile, the way they have been estimated and then treated in the models, however, is not always offered in the literature (JACKSON et al., 2000).

It has been recognised that the root water uptake is closely related to the root geometrical characteristics length and radius (RAATS, 2007). On the other hand, comprehensive root datasets are still scarce (*e.g.* Van NOORDWIJK and BROUWER, 1991 for agricultural crops; JACKSON et al., 1996 for different kinds of land cover) and rarely offer a comparable information about the distribution of the different root morphological parameters. A detailed database for grasses, shrubs and trees presented by SCHENK and JACKSON (2002) consisted of 475 root profiles, where 74 % were in units of mass, 16 % in units of numbers, 9 % in units of length, and only 1 % in units of surface area. The majority of the existing root datasets includes only root biomass distributions. Therefore, it is appropriate to relate more easily accessible root mass density to the length and surface area densities of roots.

The objectives of this study were: to estimate root morphological parameters dry mass, length and surface area for spring barley, winter rye and maize during early stages of their ontogenesis under equivalent climate and soil conditions, and compare the corresponding root density distributions from a point of view of their applicability in the sink term estimation.

2 Methods and Material

2.1 Theory

Movement of water in soils covered with a plant canopy is described by the Richards equation, where the water extraction by roots is expressed with an extra term (FEDDES et al., 1978).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k(h,z)\left(\frac{\partial h}{\partial z}+1\right)\right] - S(z,t) \qquad (1)$$

where h is the soil water potential, expressed here as water pressure head (m), q is the volumetric water content ($m^3\ m^{-3}$), t is time (d), z is the vertical co-ordinate (m), (positive upward), $k\ (h,\ z)$ is the hydraulic conductivity of soil ($m\ d^{-1}$), $S\ (z,\ t)$ is the root sink term ($m^3\ m^{-3}\ d^{-1}$), which quantifies the actual volume of water taken up by roots from a volume of soil per unit of time and it is involved with a negative sign.

The commonly used approach to describe the root sink term is based on the originally Feddes' proposal applied in the simulation model SWATR (FEDDES et al., 1978). For that, the transpiration rate is estimated independently and distributed along the root depth according to the vertical distribution of relevant root parameters.

$$S(z,t) = S_p(z,t)P(h) = E_{tp}P(h)n_r(z,t) \qquad (2)$$

where $S\ (z,t)$ and $S_p\ (z,t)$ express the actual and the potential root uptake of water not limited by the soil water potential, respectively ($m^3\ m^{-3}\ d^{-1}$); $P(h)$ is the dimensionless function of the soil water potential h, E_{tp} is the potential transpiration rate (m^3 m^{-2} d^{-1}), and $n_r(z,t)$ is the root distribution function for water uptake down the rooting zone (m^{-1}).

The term $n_r(z,t)$ is the parameter related to the root system properties, under the assumption of equal capacity for uptake along the root axes. In case of unstressed root uptake non-limited by the soil water pressure head, it is appropriate to consider that

$$S_p(z,t) = n_r(z,t)E_{tp} \quad (3)$$

The root distribution function can be expressed as

$$n_r(z,t) = \frac{R(z,t)}{R_t} \quad (4)$$

where

$$R_t = \int_0^{z_r} R(z,t)dz \quad (5)$$

$R(z,t)$ is the root parameter value at depth z and at time t (expressed as mass, length or surface area of roots per unit volume of soil, *i.e.* in kg m^{-3}, m m^{-3} and m^2 m^{-3}, respectively) and R_t is the total root parameter value for the whole rooting depth z_r (i.e. mass, length and surface area of roots per unit area of soil in kg m^{-2}, m m^{-2} and m^2 m^{-2}, respectively).

2.2 Site and soil

The study was conducted at the experimental field of the Hydromelioration State Agency, Bratislava, near the site Most pri Bratislave. The soil is a Haplic Chernozem (FAO classification) and is classified as silt loam (USDA) with 23 % clay, 63 % silt and 14 % sand. For the rooted soil layers, the soil bulk density varies from 1.25 to 1.45 kg m^{-3} and the hydraulic conductivity at saturation ranges from 0,07 to 0,35 m d^{-1}. Spring barley (*Hordeum vulgare L.*), winter rye (*Secale cereale L.*) and maize (*Zea mais, L.*) were cultivated according to the usual agricultural practice in this region.

2.3 Sampling procedure and analyses

Root samples were taken intentionally at relatively early stages of plant development: at tillering (10.05.2006, hereafter denoted as 1st sampling) and at the stage of stem elongation (30.05.2006, denoted as 2nd sampling) for spring barley, at heading (10.05.2006) for winter rye and at the 5th leaf stage (30.05.2006) for maize. Soil monoliths (covering a complete row width including seven plants) were sampled to 0,25 m soil depth in 0,05 m thick slices (depths). The depth of 0.25 m matching the rooting depth of the crops during the early ontogenesis, was established in the course of the sampling. Roots (mix of at least seven root systems) were carefully washed out from the soil over a set of sieves up to 0.5 mm and cleaned from debris. An image analyzer was used to assess their length, surface area, average diameter and diameter class distributions. Representative fractions of the root material were taken for this analysis in case of very large root samples. First, the roots were stained, then spread in a thin water layer on a tray and scanned to get digital images of the samples. The images were further analysed with WinRHIZO V4.1 software (regent.qc.ca) to get the geometrical characteristics of the roots following HIMMELBAUER et al. (2004). After the image analysis, the roots were oven dried (60° C) for dry mass estimation and to find out its proportions to the length and the surface area values, *i.e.* specific root length and specific surface area for each sample. Obtained ratios were used to calculate the total length and surface area of the root samples. The rest of the root material was oven dried at 60° C to a constant weight for estimation of the total values of the considered root parameters.

3 Results and Discussion

Using the results of the image analyses, bulk densities of root length, root surface area and root dry mass per unit (volume and area) of soil were estimated. The bulk densities along with the diameter measurements, specific length and specific surface area of roots averaged over the sampled soil depth are presented in Table 1. The proportions shared by fine roots having diameter smaller than 0.5 mm are also shown. The vertical distribution of the fine root only is not further discussed, since many modelling studies showed that water balances estimated using total and fine root distributions were very close to each other (*e.g.* ZENG, 2001; HIMMELBAUER et al., 2008). However, for nutrient uptake studies of low mobile ions such as phosphorus, it would not be the case.

For the time of sampling, the root bulk densities considered as dry mass, length and surface area of roots per unit volume of soil were the highest for winter rye and the low-

Table 1: Root morphological parameters of spring barley (1st and 2nd sampling), winter rye and maize. Presented are the mean values for the 0–0.25 m soil depth.

Tabelle 1: Wurzelmorphologische Parameter von Sommergerste (1. und 2. Probenahme), Winterroggen und Mais. Angabe in Mittelwerten für 0–0,25 m Bodentiefe.

Plants	**Root mass** density kg m^{-3}	**Root length** density 10^4 x m m^{-3}	**Root length** fine roots < 0.5 mm %	**Root surface area** density m^2 m^{-3}	**Root surface area** fine roots < 0.5 mm %	**Average root diameter** mm	**Specific root length** 10^3 x m kg^{-1}	**Specific root surface area** m^2 kg^{-1}
Spring barley I	0,25	2,38	78,8	25,6	56,7	0,342	94,4	101,6
Spring barley II	0,34	3,14	81,4	31,9	57,3	0,327	93,0	94,5
Winter rye	0,41	4,97	92,9	40,7	73,9	0,253	120,7	98,9
Maize	0,02	0,04	38,6	0,93	14,4	0,732	26,9	60,0

est for maize. Relative vertical distributions of roots were calculated using Eq. 4 and plotted against the relative root depth. The results expressed as root distribution functions are shown in Figure 1.

The relative distributions of all measured root parameters were approximately exponential except for maize, where the maximum root densities were measured in the 0.05 to 0.10 m soil layer. The specific structure of the maize root system at the time of sampling was the foremost reason for that. Maize had the highest average root diameter values compared to the other crops (Table 1). According to the diameter classes analysis of the root images, the main class of maize roots was 1 to 1.25 mm (data not shown), which corresponds to the diameter category of the firstly developed seminal roots but not to those of their branches (VARNEY and CANNY, 1993). Specific root length is another morphological indicator for the roots thickness (ATKINSON, 2000). High values suggest more fine roots as in the case of rye and barley, while lowest ones refer to coarse roots as found for maize (Table 1). The sampling took place at the early beginning of maize ontogenesis, where the root systems were still developing with a small number of root branches formed.

Vertical root distributions varied among different plant species, plant ages and growth conditions (JACKSON et al., 2000). In general, woody plants are much more deeply rooted than grasses and agricultural plants. At the same time, the shape of the relative root distributions down the root depth has been observed to be rather unvarying and following an exponential type of curve for a wide range of plant species (JACKSON et al., 1996; ZENG, 2001; SHENK and JACKSON, 2002). One-parameter expression of a cumulative root biomass as a function of root depth, originally developed by GALE and GRIGAL (1987) for trees, was fitted to the profiles of numerous different root distributions. Recently, a modification of this equation that allows rooting depth increases with time to be taken into account, was proposed by ARORA and BOER (2003).

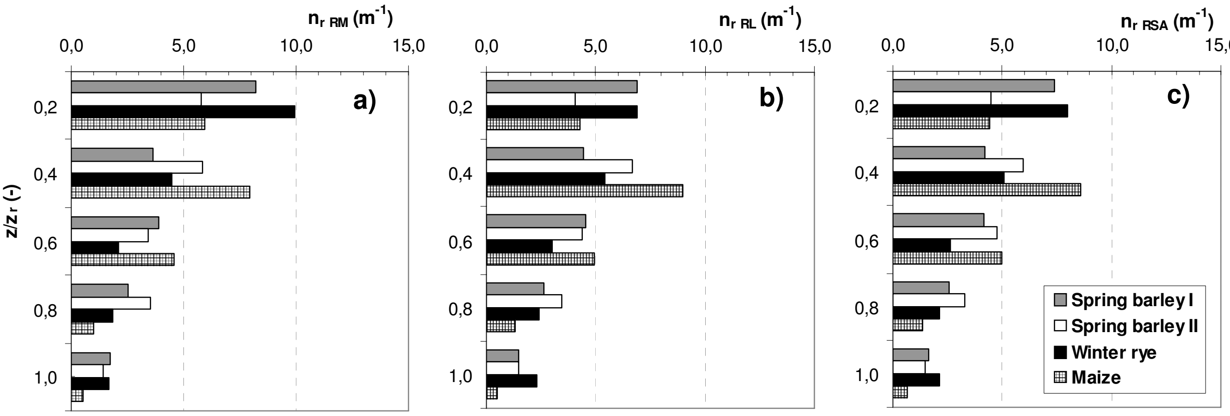

Figure 1: Root distribution function down the relative root depth z/z_r for a) root dry mass density, $n_{r\ RM}$; b) root length density, $n_{r\ RL}$ and c) root surface area, $n_{r\ RSA}$ density of spring barley (1st and 2nd sampling), winter rye and maize.

Abbildung 1: Die Wurzelverteilungsfunktion in Abhängigkeit von der relativen Wurzeltiefe z/z_r betrachtet als a) Wurzeltrockenmassendichte, $n_{r\ RM}$; b) Wurzellängendichte $n_{r\ RL}$ und c) Wurzeloberflächedichte, $n_{r\ RSA}$ von Sommergerste, Winterroggen und Mais.

Vertical root distributions of wheat, maize, cotton, and bean were analysed by WU et al. (1999) using the root length data cited in the literature. The results showed that the relative root distributions measured at different growth stages were quite similar within each plant species. The authors concluded that is reasonable to use one single function for each crop. For wheat, ZUO et al. (2004), also showed a general trend of the relative root distribution, independent of soil and climate conditions and growing seasons. Instead of the polynomial function, proposed by WU et al. (1999), an exponential kind of function was defined using laboratory and field experiments on different soils, growing stages, climate and soil water conditions.

For maize, NOVÁK (1987; 1994) found that the relative root mass density distribution was exponential for the whole growing period and can be expressed as:

$$n_r(z) = B\exp[-b(z/z_r)] \quad (6)$$

where B is the coefficient characterizing the position of the distribution function, b is the shape coefficient and z/z_r is the relative root depth.

The results of presented study confirmed this statement for spring barley, winter rye and maize at early stages of their development. Consequently, we used the exponential function Eq. 6 to describe the root distributions functions of root dry mass, root length and root surface area densities for each of the crops (Table 2).

Coefficients of determination of the estimated distribution functions were mainly higher than 0,8. The slightly lower coefficients in the case of maize and the 2nd sampling of barley resulted from the higher root length and surface area densities measured in the subsurface soil depth, where more fine root branches developed compared to the top one. Coefficient b is the shape factor representing the root allocation down the soil profile. Higher values suggest shallower root profiles. Values between 1.6 and 4 were reported for steppe and grasslands against 0.8 for forests (cited in FEDDES et al., 2001). The values found for maize were close to 3.5 established in prior studies of maize root mass distributions (NOVÁK, 1987). Under examined conditions, there were no considerable differences between the shapes of the distribution curves of the three root morphological parameters estimated for each crop. Thus, they can be expressed by similar (exponential) root distribution functions.

As stated by HOPMANS and BRISTOW (2002), one could use root length density to represent the root distribution function in the sink term estimation procedure. Root length is the most often considered root characteristic with regard to plant uptake (NOORDWIJK and DE WILLIGEN, 1991; ATKINSON, 2000). Many studies have shown, however, that root surface area rather than root length controls the uptake of water and nutrient by roots (*e.g.* VARNEY and CANNY, 1993). On the other hand, it is easier to measure root mass, and therefore root mass density distribution has been frequently used to estimate the root sink term in the Richards equation. For that reason, one of the objectives was to find out the relationships between the root dry mass density, root length density and root surface area density of the crops at the sampling occasions and soil under study. The results are presented in Figure 2.

The estimated relationships between the root mass and the other geometrical root parameters were highly significant, and can be approximated by linear equations. This statement is rather restrained by the limited dates of observation. One could expect that the relationship will shift to the right, when the root systems get older and the small root brunches started to decease, since coarse roots have much higher mass than fine roots. Relationships between mass and length were found to vary for different classes of roots (ATKINSON, 2000; FITTER, 2002). However, such differences are more pronounced for tap root systems and less distinct for fibrous type of root systems as the examined ones

Table 2: Coefficients B and b of the root distribution functions calculated for root dry mass, root length and root surface area of spring barley (1st and 2nd sampling), winter rye and maize. Coefficients of determination are denoted as R^2.

Tabelle 2: Koeffizienten B und b der Wurzelverteilungsfunktion berechnet für die Wurzeltrockenmasse, die Wurzellänge und die Wurzeloberfläche von Sommergerste (1. und 2. Probenahme), Winterroggen und Mais. Das Bestimmtheitsmaß ist angegeben als R^2.

Plant	Root distribution functions of dry mass			length			surface area		
	B	b	R^2	B	b	R^2	B	b	R^2
Spring barley I	8,335	1,752	0,903	8,641	1,792	0,924	8,455	1,743	0,954
Spring barley II	8,170	1,655	0,827	7,045	1,350	0,584	7,313	1,404	0,675
Winter rye	9,485	2,244	0,864	7,662	1,503	0,917	8,310	1,756	0,890
Maize	14,413	3,432	0,838	12,55	3,138	0,720	11,43	2,818	0,725

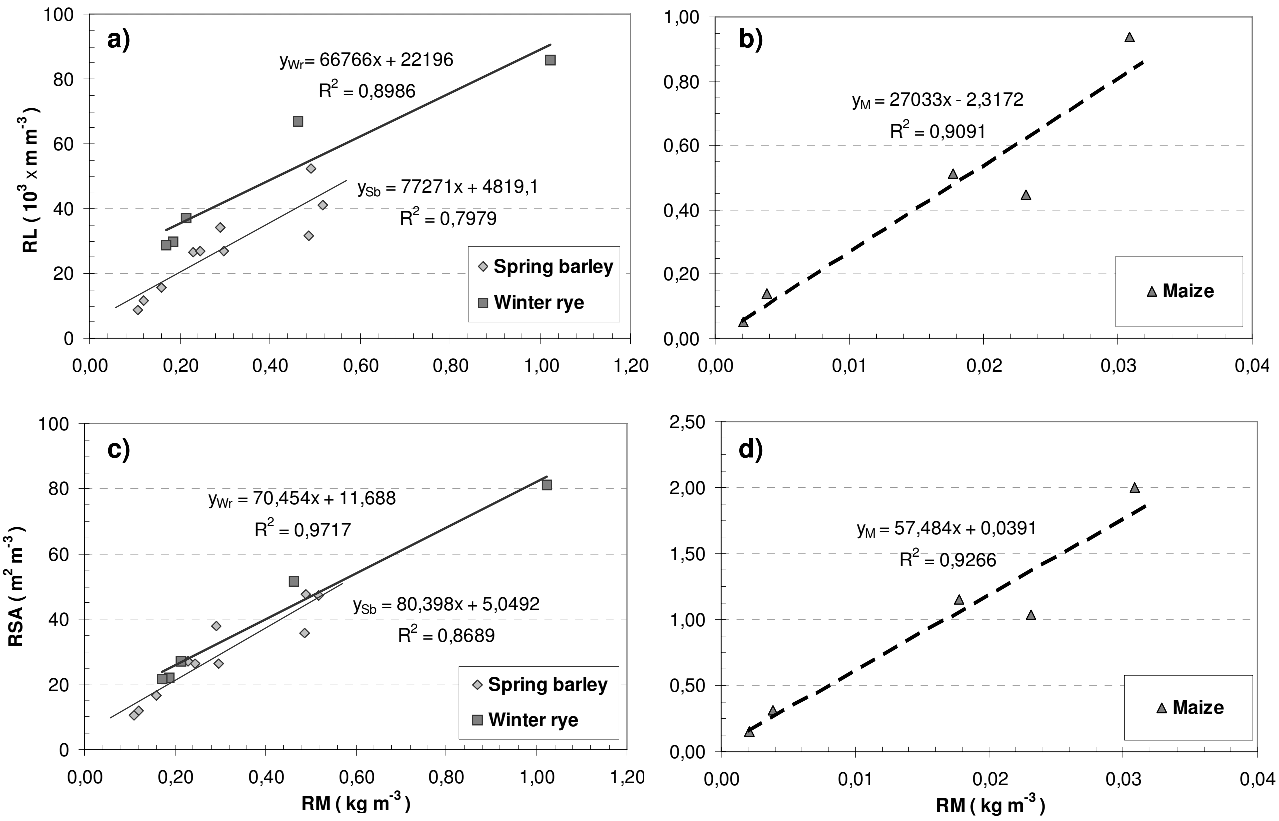

Figure 2: Relationships between root dry mass density (RM) and root length density (RL) for a) spring barley and winter rye and b) for maize; and between root dry mass density (RM) and root surface area density (RSA) for c) spring barley and winter rye, and d) for maize.

Abbildung 2: Die Beziehung zwischen Wurzeltrockenmassedichte (RM) und Wurzellängendichte (RL) für a) Sommergerste und Winterroggen and b) Mais; und zwischen Wurzeltrockenmassedichte (RM) und Wurzeloberflächendichte (RSA) für c) Sommergerste und Winterroggen and d) Mais.

in our case. More over, the modelling approach applied here is based on the uptake characteristics averaged over numbers of roots of different size and age simultaneously developed in the same soil layer. Therefore, any of the examined root morphological parameter can be used to estimate the root distribution functions in the sink term for the environmental conditions and crops under study.

4 Conclusions

The results of this study showed that at early stages of plant ontogenesis of spring barley, winter rye and maize, the relative vertical distributions of root dry mass, root length and root surface area densities approximated the exponential type of curve with no considerable differences between the shapes of their profiles. Hence, these root morphological parameters can be expressed by similar root distribution functions in model simulations of water uptake by roots. Statistically highly significant linear relationships were established between the dry mass density, and the length and surface area densities of roots for each of the three crops, which is essential for alternative expressions of the root distribution profiles. Thus, the root dry mass density, which is easier to obtain, can be applied for the estimation of the root distribution function in the sink term in case of lack of root length or surface area measurements.

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