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Scaling of root length density of maize in the field profile

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Abstract

Root length density is an important parameter in crop growth simulation and in evaluating consequences of root pattern on crop water and nutrient uptake. In this study, a scaling model was presented for estimating the profile distribution of root length density of maize (*Zea mays* L.). The model inputs are root length data of a reference profile and bulk densities of soil layers, as well as root length data in the first soil layer of a field profile to be investigated. Using the root length data of 10 soil profiles investigated over 2 years, the model was examined. The results show that the proposed scaling approach is effective in estimating the root length density of each layer of soil in the field profile. The relative root mean square error (RRMSE) of the developed scaling model was 25.28%, while that of the traditional exponential model was 39.53%. The scaling approach would facilitate determination of heterogeneous distributions of root length densities in the field.

Introduction

Operational models of crop growth and development require information on the root density distributions through space and time. A usual description of root systems is root profiles (Gerwitz and Page, 1974; Pagès et al., 1989). However, investigation of root distribution in the field is very difficult, laborious and costly. So far, available models describing root length distribution in the field profile belong to two types. One type describes the distribution of root systems in the soil profile at any time as a function of some mathematically generated pattern. For example, the empirical model of Gerwitz and Page (1974) describes root length density as decreasing exponentially with soil depth. This model was later modified by Addiscott and Whitmore (1987) by linking it to soil water and mineral nitrogen content of the soil. Another general type of root growth model, by assuming root growth rate is constant, generates root length density numerically or algebraically over time from the increase in length of individual axes and the density of branching (Lungley, 1973; Rose, 1983). Porter (1986) developed a model of this type, but it is based on cumulative thermal time instead of calendar time.

A problem with both of these models is that they ignore the heterogeneity of field soil properties. As is widely acknowledged, root length density varies with crop genotype, stage of development, depth of the layer, availability of soil water and nutrients (Robinson, 1994; Sattelmacher, et al., 1993), aluminum and manganese toxicity (Hoogenboom and Huck, 1986; Williams et al., 1984), and soil structure and strength (Barley and Greacen, 1967; Jakobsen and Dexter, 1987; Jones, 1983; Rosenberg, 1964). Furthermore, the potential root morphology is modified by responses of the crop to environmental factors. Grossman and Berdanier (1982) have discussed these effects and suggested that these factors should be considered in any comprehensive crop root growth model. However, as Passioura (1996) discussed, the errors associated with estimating additional parameters easily outweigh any possible improvements in precision due to refinement of the model structure. Incorpor-

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ation of soil heterogeneity into one-dimensional root distribution models will be a continuous challenge, in particular when they are the basis for water and nutrient uptake under supply-limited conditions (Pagès et al., 2000).

Root length in a specific site or total root length/mass in the whole field is a very important parameter in estimating water and nutrient uptake by the field crop (Zhuang et al., 2001). However, an effective approach for estimating root length or root mass in the whole field with a certain area, and in evaluating the root growth in the undergoing experimental site is still lacking, despite the many models that are useful in simulating root growth. The main problem involved is that spatial variability precludes precise characterization of the root distribution in the field profile, and as such causes difficulty in comparing root distribution between individual field sites. Some researchers have suggested that the root elongation rate should be simulated as a root-type-dependent rate modified by various soil conditions (Clausnitzer and Hompmans, 1994; Diggle, 1988; Pagès et al., 1989).

Therefore, it is very important to incorporate the field heterogeneity into the models of root growth or root length density. However, this is not an easy task. In our study on root water uptake of maize in the field, it was found that field profiles of the root length density distribution were significantly different from site to site. As a consequence, the water uptake rate of the roots also varied with the field sites (Zhuang et al., 2000). Therefore, we tried to address some responses of root growth to soil heterogeneity by assuming that root distribution in the field profiles have both similarity and non-similarity between sites. The non-similarity was caused by the modification of soil heterogeneity to the similarity which arises from the crop genotype. In this aspect scaling would be a useful technique, since it has some general advantages when compared to the regular measurements or modeling and simulation. Firstly, the scaling process needs a measured root distribution profile as a reference, and as such systematic error in measurements can be reduced. Moreover, it is not necessary to consider the factors that are not significantly different between field sites, although they can impact root growth. Evidently, the number of the parameters involved in the simulation or in the modeling can also be lowered. Thirdly, root distribution profile of any field site can be obtained by scaling the referenced profile of root distribution, based on some heterogeneous properties of soil layers. It is, thus, clear that the scaling technique is useful in reducing the cost and time of investigations, and simultaneously allows us to make root investigations for a large field area or for more field sites. The main objective of this work was to develop a scaling approach for estimating the field profile of the root length density distribution in different field sites, in addition to showing the heterogeneity of vertical or horizontal distribution of roots in the field.

Scaling approach

Root length density, $R(D_\mathrm{h})$, generally decreases exponentially with soil depth, D_h, in the field profile. A simple formulation for this (Gerwitz and Page, 1974) is

$$\frac{\mathrm{d}R(D)_\mathrm{h})}{\mathrm{d}D_\mathrm{h})} = -\gamma R(D_\mathrm{h}) \tag{1}$$

where γ represents the decreasing rate of $R(D_\mathrm{h})$ with depth D_h. This parameter can be fitted by Eq. (1) using the root data of the reference profile. Moreover, by considering that root growth rate (which results in different $R(D_\mathrm{h})$) in the field profile is highly responsive to physical, chemical and biological environmental conditions of the soil, two modification functions are combined to Eq. (1), leading to

$$\frac{\mathrm{d}R(D_\mathrm{h})}{\mathrm{d}D_\mathrm{h}} = -rR(D_\mathrm{h} f_{D_\mathrm{h}}(\rho_\mathrm{b}, N_\mathrm{c} S_\mathrm{e}) E(D_\mathrm{h}) \tag{2}$$

where f_{D_h} $(\rho_\mathrm{b}, N_\mathrm{c}\ S_\mathrm{e})$ is a responsive function of root growth rate or $R(D_\mathrm{h})$ to soil environmental conditions, such as, soil bulk density, ρ_b; available nutrient content, N_c; saturation degree of soil water, S_e. However, it is difficult to determine a specific expression for this modification function. In order to simplify the simulation, in this study only soil bulk density was considered as a factor responsible for the heterogeneous distribution of roots in the field. For this, based on the notion that root amount in a particular soil layer (D_h^i) is significantly impacted by the bulk densities of the immediate upper (D_h^{i-1}) and lower (D_h^{i+1}) soil layers, we assume a formula like

$$f_{D_\mathrm{h}^i}(\rho_{\mathrm{b},i}) = \left(1 + \ln\frac{\rho_{\mathrm{b},i}}{\rho_{\mathrm{b},i-1}} - \ln\frac{\rho_{\mathrm{b},i+1}}{\rho^0_{\mathrm{b},i+1}}\right)^{\frac{\rho_{\mathrm{b},i}}{\rho_{\mathrm{b},i-1}}} \tag{3}$$

where $\rho_{\mathrm{b},i}$ and $\rho_{\mathrm{b},i-1}$ are bulk densities of the ith $i-1$th layers of the investigated soil profile, respectively. $\rho_{\mathrm{b},i+1}$ and $\rho^0_{\mathrm{b},i+1}$ denote bulk densities of the $i+1$th soil layer of the investigated and referenced field profiles, respectively. For the first layer of the soil profile,

$$f_{D_{\mathrm{h}}^1}(\rho_{\mathrm{b},1}) = \left(1 - \ln \frac{\rho_{\mathrm{b},2}}{\rho^0_{\mathrm{b},2}}\right) \tag{4}$$

Eq. (3) relates the root length data not only to bulk densities in different soil layers but also to the bulk density in the corresponding layer of the reference profile.

Besides soil environment, growth of the above-ground part of the crop also impacts underground root growth significantly due to carbon allocation and ecological strategy. Thus, it is necessary to further modify the effectiveness of the function of $f_{D_{\mathrm{h}}}(\rho_{\mathrm{b}}, N_{\mathrm{c}}, S_{\mathrm{e}})$ where only soil factors are considered. In Eq. (2), $E(D_{\mathrm{h}})$ represents such an effective coefficient of response of $R(D_{\mathrm{h}})$ to soil environmental conditions. For a particular soil layer (D^i_{h}), this effective coefficient in the study was calculated with an empirical formula like

$$E\left(D^i_{\mathrm{h}} = \frac{1.2}{1 + \beta \mathrm{e}^{-\gamma(D^{\max}_{\mathrm{h}} - D^i_{\mathrm{h}})}}\right) \tag{5}$$

with

$$\beta = \max\left\{\frac{R(D^1_{\mathrm{h}})}{R^0(D^1_{\mathrm{h}})}, \frac{R^0(D^1_{\mathrm{h}})}{R(D^1_{\mathrm{h}})}\right\} \tag{6}$$

where $R(D^1_{\mathrm{h}})$, $R^0(D^1_{\mathrm{h}})$ are root length densities in the first soil layer of the investigated and referenced field profiles, respectively. The symbol of D^1_{h}denotes the depth of the first layer of soil from the ground surface, and $D^{\max}_{\mathrm{h}}$ in Eq. (5) is the maximum depth of the investigated field profile. The maximum value of $E(D^i_{\mathrm{h}})$ should be unity, and the minimum value 1.2/(1+β). Due to the value of $D^{\max}_{\mathrm{h}}$– D^i_{h} not being infinitely large, selection of the value of 1.2 in Eq. (5) allows us to get a maximum value $E(D^i_{\mathrm{h}})$ that approximates to unity.

The integral form of Eq. (2) for a particular layer (D^i_{h}) is

$$R(D^i_{\mathrm{h}}) = c\mathrm{e}^{-rf_{D^i_{\mathrm{h}}}(\rho_{\mathrm{b},i})E(D^i_{\mathrm{h}})D^i_{\mathrm{h}}} \tag{7}$$

The integral constant c is given as

$$c = R(D^1_{\mathrm{h}})e^{r\left(1 - \ln \frac{\rho_{\mathrm{b},2}}{\rho^0_{\mathrm{b},2}}\right)D^1_{\mathrm{h}}} \tag{8}$$

where $\rho_{\mathrm{b},2}$ and $\rho^0_{\mathrm{b},2}$ denote bulk densities of the second soil layer of the investigated and referenced field profiles, respectively. Thus, based on the data of root length distribution of the reference profile, and the data of soil bulk densities as well as the root length data of the surface layer of soil profile to be investigated, root length distribution of soil profile for investigation could be estimated by means of Eq. (7).

Materials and methods

Experimental site

Root data were collected from a field site near Tokyo, Japan (latitude 35° 46′N, longitude 139° 54′E, altitude 7.9 m). The soil is a Kanto sandy loam with averaged physical properties given in Table 1. Maize (*Zea mays* L.) was planted on May 25, 1998 and 30 April 1999 at a rate of 35 715 seeds ha^{-1} with 0.7-m row spacing and 0.4-m inter-row spacing.

Investigation method of root length

In 1998, immediately after completion of the field experiments, on 19 and 20 August, roots in 12 soil layers (each layer 70×40×5 cm) for each of the five sites (Site 1, Site 2, Site 3, Site 4, Site Ref) were collected down the soil profile to 0.60 m depth using a knife. At the same time, three soil samples were taken for determination of bulk density and particle-size distribution of each layer. In 1999, the same investigations were conducted twice. Once on 21 and 22 July for soil profiles labeled as E-1, M-1, W-1, and Ref-1, and again on 13 and 14 August for soil profiles labeled as E-2, M-2, W-2, and Ref-2. A line-intercept sampling method (Tennant, 1975) was used to obtain total root length in each soil layer.

Index for model evaluation

Two statistical properties, root mean square error, *RMSE*, and relative root mean square error,*RRMSE* were calculated to evaluate the differences between the measured and estimated root length density. The formulas are

$$RMSE = \left[\frac{1}{n-1}\sum(Y_{\mathrm{est}} - Y_{\mathrm{mea}})^2\right]^{1/2} \tag{9}$$

$$RRMSE = 100RMSE/\overline{Y}_{\mathrm{mea}} \tag{10}$$

where n is the number of pairs of data, Y_{est} represents the estimated values, Y_{mea} and $\overline{Y}_{\mathrm{mea}}$ are the measured values and their mean values, respectively.

Table 1. Symbols used in the equations

Symbol	Definition
Root and soil parameters	
$R(D_h)$	root length density (cm cm^3)
$R(D_h^1)$	root length density in the first soil layer of the investigated field profile (cm cm^{-3})
$R^0(D_h^1)$	root length density in the first soil layer of the referenced field profile (cm cm^{-3})
D_h	soil depth (m)
D_h^i	soil depth of the ith layer in the field profile (m)
D_h^{max}	maximum depth of the investigated field profile (m)
ρ_b	soil bulk density (Mg m^{-3})
$\rho_{b,i}$	soil bulk density of the ith soil layer of the investigated field profiles (Mg m^{-3})
$\rho^0{}_{b,i}$	soil bulk density of the ith soil layer of the referenced field profiles (Mg m^{-3})
N_c	available soil nutrient content (mg kg^{-1})
S_e	saturation degree of soil water
Symbols in the model	
γ	decreasing rate of $R(D_h)$ with depth D_h
$f_{D_h}(\rho_b, N_c, S_e)$	response function of root growth rate or $R(D_h)$ to soil environmental conditions
$E(D_h)$	effective coefficient of response of $R(D_h)$ to soil environmental conditions
c, c_0	integral constants
Statistical parameters	
RMSE	root mean square error (cm cm^{-3})
RRMSE	relative root mean square error (%)
Y_{est}	estimated values (cm cm^{-3})
Y_{mea}	measured data (cm cm^{-3})
$\bar{Y}_{mea}$	mean value of the measured data (cm cm^{-3})
R^2	determination coefficient
n	number of the pairs of data

Table 2. Some basic properties of soils in the experimental field*

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg m^{-3})	K_s (10^{-4} cm s^{-1})	Θ_s (m m^{-3})	Θ_r (m m^{-3})
0 - 5	26.79	33.53	39.68	0.806	1.56	0.661	0.264
5 -10	26.21	30.71	43.09	0.728	4.05	0.689	0.284
10-15	25.63	27.88	46.49	0.753	2.95	0.680	0.304
15-20	27.60	27.79	44.61	0.799	1.68	0.663	0.294
20-25	29.57	27.70	42.72	0.675	8.31	0.707	0.281
25-30	31.25	25.12	43.63	0.695	6.33	0.700	0.286
30-35	32.92	22.54	44.54	0.785	1.99	0.668	0.293
35-40	38.48	22.94	38.58	0.616	20.01	0.729	0.255
40-45	44.20	23.36	32.44	0.684	7.39	0.705	0.219
45-50	46.98	23.56	29.46	0.672	8.74	0.709	0.201
50-55	49.75	23.76	26.48	0.729	4.01	0.689	0.184
55-60	49.75	23.76	26.48	0.694	6.45	0.701	0.183

*The data listed are the averaged values of field soil. K_s, saturated hydraulic conductivity; Θ_s and Θ_r are saturated and residual soil water contents, respectively.

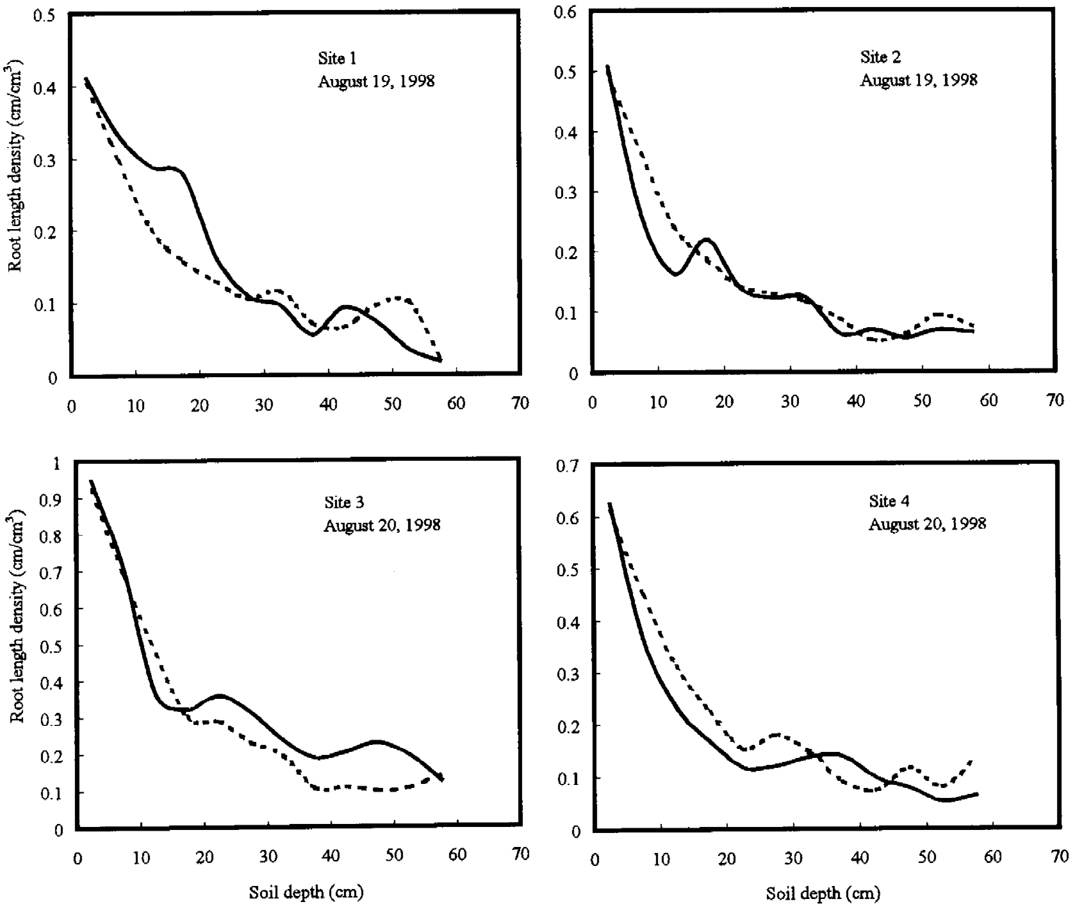

Figure 1. Root length density measured (solid line) and estimated (dashed line) by means of the scaling model in 1998.

Table 3. Statistical parameters of the scaling model for estimating root length density

Sampling time	Sampling sites	RMSE (cm/cm^3)	RRMSE (%)
August 19, 20	Site 1	0.051	31.13
1998	Site 2	0.041	26.32
	Site 3	0.075	21.71
	Site 4	0.040	16.15
July 21, 22	E-1	0.019	20.28
1999	M-1	0.019	17.11
	W-1	0.028	26.83
August 13,14	E-2	0.047	22.67
1999	M-2	0.024	12.15
	W-2	0.030	23.52

Results and discussions

Results presented in Figures 1 and 2 show that the distribution of root length density in the field profile which was estimated by means of the scaling approach agreed well with the investigated situation. The statistical results given in Table 3 indicate that the estimated deviations of the scaling model were acceptable. Also, from the figures, it can be seen that roots of maize plantations were not distributed evenly throughout the soil profile due to the inherent nature of maize rooting habits and the heterogeneity of the soil profile. Surface soil horizons have greater root length densities than subsurface horizons, and different soil profiles have different amounts of roots. These data suggest that, in addition to genetic influences, soil environment and physiological condition of plants also affects root growth. Roots are opportunistic, taking advantage of features within the soil profile where physical, chem-

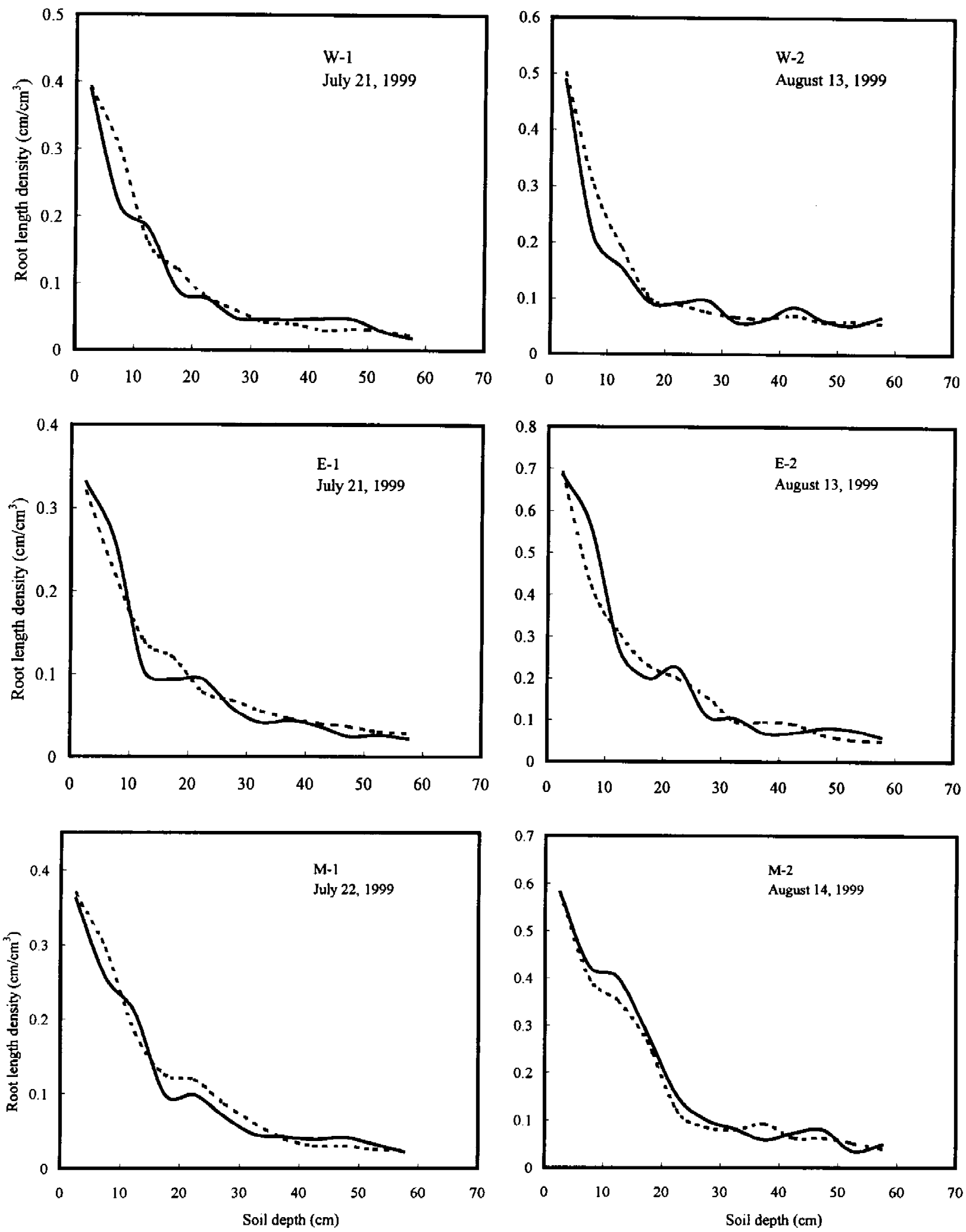

Figure 2. Root length density measured (solid line) and estimated (dashed line) by means of the scaling model in 1999.

ical, and biological factors are favorable for growth and survival.

An integral form of Eq. (1) for a particular soil layer (D_h^i) is

$$R(D_h^i) = c_0 e^{-\gamma D_h^i} \quad (11)$$

where

$$c_0 = R(D_h^1) e^{\gamma D_h^1} \quad (12)$$

We refer to this equation as the exponential model in this study. Based on the data of root length density of all of the 10 field profiles, the exponential model (Eq. (11)) and its modified scaling model (Eq. (7)) are com-

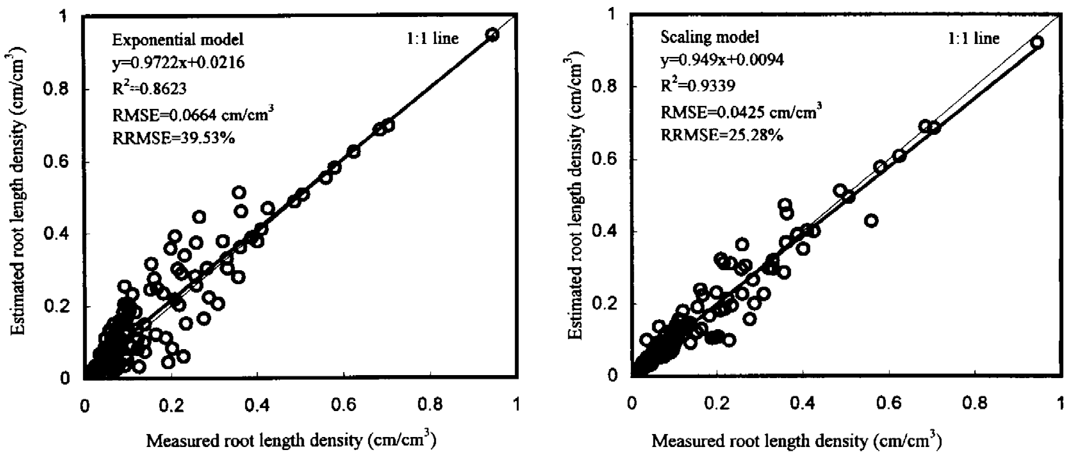

Figure 3. Comparison of the scaling model (Eq. (7)) and the exponential model Eq. (11)) in estimating root length density of all of the 10 soil profiles investigated in the two years.

pared in Fig. 3. From the statistical parameters listed in the figure, such as determination coefficient (R^2), RMSE and RRMSE, it is easily seen that the scaling model behaved better than the exponential model.

However, in the formulation of the scaling model as Eq. (7), we only considered the most common physical property, soil bulk density. This does not mean that other factors, for example, soil water and nutrient contents in individual soil layers, were not exerting significant influence on root growth. The reasons for doing this are that the experiments were conducted under no water stress and that the scaling approach could be simplified, since it is very difficult to distinguish between the roles of soil mechanics and soil nutrients. Nonetheless, to reduce the estimation deviation of the proposed model and increase its applicability, we still hold that the nutrient distribution in the field profile and soil water condition should be included in the scaling model for future improvement. At present, to determine the amount of roots in the field still remains a thorny problem for most agronomists. The scaling method, as shown in this study, is an efficient tool to identify heterogeneity of the field. Through this approach, many influential factors could be avoided from the simulation, resulting in the simplification of modeling or assessment of the root distribution. We believe that the combination of the growth model of roots based on the accumulative thermal time during crop growth and the developed scaling model as in Eq. (7) would increase our ability to precisely estimate the dynamics of root growth in field conditions.

Concluding remarks

The physical properties of soil have significant effects on root distributions in the field profile. By incorporating these physical factors of soil into the scaling model, the heterogeneity of root length density in the field profile could be effectively identified with an acceptable estimation deviation. The developed scaling model (Eq. (7) in the study) showed its feasibility for estimating root profile, based on a reference root profile and bulk densities of the soil layers in the investigation site. By conducting experiments of root growth in relation to nutrient distribution in the field profile and water stress, the developed scaling approach in this study would be expected to be improved and more complete.

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References

Addiscott T M and Whitmore A P 1987 Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring. J. Agric Sci. 109, 141–157.

Barley K P and Greacen E L 1967 Mechanical resistance as a soil factor influencing the growth of roots and underground shoots. Adv. Agron. 19, 1–43.

Clausnitzer V and Hopmans J W 1994 Simultaneous modeling of transient three-dimensional root growth and soil water flow. Plant Soil 164, 299–314.

Diggle A J 1988 ROOTMAP—a model in three-dimensional coordinates of the growth and structure of fibrous root systems. Plant Soil 105, 169–178.

Gerwitz A and Page E R 1974 An empirical mathematical model to describe plant root systems. J. Appl. Ecol. 11, 773–782.

Grossman R B and Berdanier C R 1982 Erosion tolerance for cropland: application of the soil survey data base. *In* Determinants of Soil Loss Tolerance. pp. 113–130. Ed. B L Schmidt. Am. Soc. of Agron., Madison, WI.

Hoogenboom G and Huck M G 1986 ROOTSIMU V 4.0. A dynamic simulation of root growth, water uptake, and biomass partitioning in a soil-plant-atmosphere continuum: update and documentation. Agronomy and Soils Departmental Series 109. pp 83. Auburn University, AL.

Jakobsen B F and Dexter A R 1987 Effect of soil structure on wheat root growth, water uptake and grain yield. A computer simulation model. Soil Tillage Res. 10, 331–345.

Jones C A 1983 Effect of soil texture on critical bulk densities for root growth. Soil Sci. Soc. Am. J. 47, 1208–1211.

Lungley D R 1973 The growth of root systems – a numerical computer simulation model. Plant Soil 38, 145–159.

Pagès L, Jordan M O and Picard D 1989 A simulation model of the three-dimensional architecture of the maize root system. Plant Soil 119, 147–154.

Pagès L, Asseng S, Pellerin S and Diggle A 2000 Modeling root system growth and architecture. *In* Root Methods: A Handbook. Eds. Smit A L et al. pp. 113–146. Springer, Berlin.

Passioura J B 1996 Simulation models: science, snake oil, education or engineering? Agron. J. 88, 690–694.

Porter J R 1986 A model (WHTROOT) which synchronizes root growth and development with shoot development for winter wheat. Plant Soil 92, 133–145.

Rosenberg N J 1964 Response of plants to the physical effects of soil compaction. Adv. Agron. 16, 181–196.

Robinson D 1994 The response of plants to non-uniform supplies of nutrients. New Phytol. 127, 635–674.

Rose D A 1983 The description of the growth of root systems. Plant Soil 75, 405–415.

Sattelmacher B, Gerendas K, Thoms K, Bruck H and Bagdady N H 1993 Interaction between root growth and mineral nutrition. Environ. Exp. Bot. 33, 63–73.

Tennant D 1975 Root growth of wheat. I. Early pattern of multiplication and extension of wheat roots including effects of levels of nitrogen, phosphorus and potassium. Austr. J. Agric. Res. 27, 183–196.

Williams J R, Jones C A and Dyke P T 1984 The EPIC model and its application. Proc. Int. Symp. on Minimum Data Sets for Agrotechnology Transfer, pp 111–121. Patancheru, India, 21–26 March 1983.

Zhuang J, Yu G R, Nakayama K and Urushisaki T 2000 Environmental dependence of sap flow of maize. Tech. Bull. Fac. Hortic. Chiba Univ. 54, 53–64.

Zhuang J, Nakayama K, Yu G R and Urushisaki T 2001 Estimation of root water uptake of maize: an ecophysiological perspective. Field Crops Res. 69, 201–213.

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