Root-depth profiles of important agricultural crops

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ABSTRACT

Based on a literature review we describe root density profiles in terms of a logistic dose-response function for important global agricultural crops (wheat, maize, rice, barley, soybean, pulses, cotton, potato, sunflower, rye, rapeseed, and sugarbeet). These root density profiles can be used in 1-D macroscopic root water uptake models. For use in 1-D microscopic root water uptake models, we analyze root density data in terms of the half mean distance between roots. Based on the database there is little support for a predictive relationship between parameters of the root density distribution of agricultural crops and climate or management factors. Constancy of the shape of the root density distribution with time is shown not to hold in some experiments, but evidence is anecdotical. At present the basis to describe rooting profiles with depth only seems to allow profiles which are constant in time and with depth. The correlation between half mean distance and drought sensitivity is investigated and conclusions will be presented.

KEYWORDS: modelling, root length density.

INTRODUCTION

Describing root systems is an important topic for modellers. The topics range from use in global circulation models (Zeng et al., 1998) to that in field scale models (e.g. Bouman et al., 1996) to models at the scale of a single root (e.g Darrah et al. 2006). At a global scale, and for natural vegetation, results presented by Schenk and Jackson (2005) support a relation between deep roots, soil type and climate. The review presented here focuses on the most important agricultural crops (in terms of area), and on the experimentally established crop root density profiles with depth, following the setup of the database compiled by Schenk and Jackson (2002). We assess the constancy of the shape of the root distribution as a function of depth over time, and analyze whether parameters describing the root density profiles are related to geographical or meteorological parameters. Finally, parameters describing the cumulative root density profile with depth are presented for use in land surface schemes of global circulation models and models for water-limited agricultural production. In addition, we provide the mean root half-distance for use in single root models for nutrient and water uptake, and discuss its effect on the limiting matric head.

THEORY

The cumulative root length density R ($cm.cm^{-2}$) describes the integral of root length density ρ ($cm.cm\text{-}^{3}$) over depth (cm) as a function of depth, up to the maximum sampling depth D_x, at a given time. We define R to be zero at the soil surface. The units of R depend on the measurement procedure, generally x. cm^{-2}, where x can be a length (cm), counts (-), or a weight (g). A logistic dose response is used by Schenk and Jackson (2002) to describe cumulative root density profiles

$$\frac{R}{R_x} = \frac{1}{1+\left(\frac{D}{D_{50}}\right)^c} \text{ with } c < 0, \tag{1}$$

where D is depth; D_{50} is the depth at which $R/R_x = ½$; c, a shape parameter. The derivative of this function is the root density profile ρ(D). It is a function which has a maximum at an intermediate depth, but which asymptotically decreases to 0 with depth.

The equivalent root half distance according to Gardner (1960) $\bar{r}$ is calculated from the average root density $\bar{\rho}$ as:

$$\bar{r} = \sqrt{\frac{1}{\pi\bar{\rho}}} \tag{2}$$

Using a numerical result from de Jong van Lier et al. (2006) the value at which matric flux potential becomes limiting (i.e. defining the onset of water stress from a soil physical point of view) is calculated from

$$M_l = 23.5 T_p \bar{r}^{2.367} \tag{3}$$

Based on this result -given the same potential transpiration rate and in the same soil - the average root half distance $\bar{r}$ allows to rank species directly in terms of their sensitivity to water stress. An assumption implicitly used in water balance models (Buyuktas and Wallender, 2002; Hao et al., 2005) is that the cumulative root density distribution R retains its shape during the growing season, i.e. for Equation 1 the shape parameter c is constant, and only R_x and D_{50} change.

METHODS

A literature search was executed for those food crops which cover large areas globally. The database setup followed the description of a root database given by Schenk and Jackson (2002). The cumulative root density distribution was fitted using the GENSTAT directive “fitcurve” (Genstat Comittee, 2003). In the integration the data pair (ε,0), where ε was calculated as $1/D_x$ was used as a starting point. After numerical integration average root length density was calculated using maximum calculated R over observation depth D_x. Parameters fitted using R were used as initial estimates to fit the root length density ρ as a function of depth D. Data sets with more than four measurements with depth were used in the analysis.

The possibility of predicting cumulative root density functions R from simpler variables was analyzed testing relations using non-parametric correlation analysis between the parameters D_{50} and D_{95}, and climatic variables, Log_{10} Mean Annual Precipitation (P_a) and Log_{10} annual ET_p. The available data also allowed checking of the constancy of the shape of the cumulative root density profile R as a function of time (days after seeding or days after transplanting). This was done using ordinary least squares linear regression. The analysis was restricted to experiments that sampled root profiles more than four times during the course of a single treatment where experimental conditions remained constant. A total of seven experiments qualified and comprised one with Helianthus, four with Oryza, one with Sorghum, and one with Triticum.

RESULTS AND DISCUSSION

Parameter values in Table 1 are pooled over different measurement types (counts, weights and lengths) based on the comparison between the different measurement procedures as discussed by Schenk and Jackson (2002). Parameters for the mean root half-distance (Eq 2) are based on measurements of root length densities ($cm.cm^{-3}$) alone. At present no significant effects of climate characteristics could be established. Crops are sorted in terms of the magnitude of the half mean distance.

None of the Oryza or the Sorghum examples that were assessed for a change in the shape of R-function in terms of the parameter “*c*” over time delivered a significant result (Table 5). In contrast, Helianthus and Triticum both exhibited significantly negative slopes, indicating *c* diminished (became more negative) over the course of the experiment. Whereas the degrees of freedom are clearly restricting the analysis, these results are interesting as many models, whilst assuming root depth increases over time, also assume the shape to remain constant.
Given the predominance of experiments with two levels of a factor, statistical analyses, such as ANOVA, would allow to analyze relative importance of factors at least for the individual experiments. The effects of management factors were established in single source experiments. At present the database also does not support quantitative management effects, which may be a structural problem in the analysis of root density data.

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Table 1. Crop name, area, number of sources, representing a total of 77% of the cropped area. Other: Arachis hypogea (Peanut) Avena sativa (Oats) Lolium multiflorum (Italian ryegrass) Pennisetum glaucum (Pearl millet) Raphanus sativus oleiformis (Fodder radish) Sorghum bicolor (Sorghum) Trifolium incarnataum (Crimson clover) Vicia villosa (Hairy vetch)

Crop group	Contains species	Species local name	Relative proportion of the area	Number of sources in database
Wheat	Triticum aestivum Triticum turgidum xTriticosecale	Bread wheat Durum wheat Triticale	22	12
Maize	Zea mays		13	9
Rice	Oryza sativa Oryza glaberrima		11	7
Barley	Hordeum vulgare		9	2
Soybean	Glycine max		5	6
Pulses	Cajanus cajan Phaseolus aureus Pisum sativum Vicia faba Vigna unguiculata (V. sinensis)	Pigeon pea Mung bean Pea Faba bean Cowpea	4	6
Cotton	Gossypium hirsutum		3	6
Potato	Solanum tuberosum		3	3
Sunflower	Helinathus annuus		2	4
Rye	Secale cereale		2	3
Rapeseed	Brassica napus Brassica rapa		2	4
Sugarbeet	Beta vulgaris saccharifera		1	3
Other	Other		-	11

Table 2. Mean and weighted mean D_{50}, D_{95}, c, and r_n. D_{50}, and D_{95} calculated using n observations. Minimum half-distance r_n calculated using n_r observations. Parameter c is added for convenience, and calculated from the weighted mean D_{50} and D_{95}. In brackets the standard error for individual observations.

Crop group name	D_{50} (cm)	Weighted D_{50} (cm)	D_{95} (cm)	Weighted D_{95} (cm)	c	n	r_n (cm)	(n_r)
All crops	28. (±21)	19	172. (±190)	90.	-1.89	603	0.74 (±0.69)	490
Barley	19. (±8)	16	97. (±48)	63.	-2.15	10	0.30 (±0.01)	2
Rye	27. (±7)	24	216. (±173)	154.	-1.58	6	0.33 (±0.03)	2
Rapeseed	16. (±6)	14	99. (±38)	73.	-1.78	30	0.50 (±0.21)	20
Potato	33. (±9)	30	125. (±78)	83.	-2.89	50	0.51 (±0.07)	47
Sugarbeet	47. (±19)	45	154. (±57)	129.	-2.80	11	0.52 (±0.25)	5
Rice	11. (±7)	10	53. (±36)	25.	-3.21	91	0.53 (±0.42)	85
Cotton	41. (±19)	33	291. (±212)	162.	-1.85	98	0.72 (±0.19)	95
Maize	42. (±29)	30	252. (±246)	64.	-3.89	52	0.73 (±0.29)	44
Pulses	25. (±15)	23	155. (±158)	41.	-5.09	49	0.74 (±0.23)	41
Sunflower	24. (±31)	14	181. (±288)	32.	-3.56	28	0.78 (±0.18)	25
Soybean	23. (±17)	16	166. (±169)	89.	-1.72	41	0.88 (±1.02)	41
Wheat	19. (±13)	13	128. (±129)	42.	-2.51	80	0.90 (±0.71)	50
Other	38. (±28)	24	259. (±265)	45.	-4.68	57	1.42 (±1.86)	33