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Short communication

Root distribution by depth for temperate agricultural crops

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ABSTRACT

Root distribution pattern plays an important role in understanding and estimating of soil C allocation and the effect of crop roots C input on soil carbon balance in agroecosystems. A database of 96 profiles was compiled and root distribution pattern were fitted to a modified logistic dose response curve for 11 temperate crops. A slight linear decrease between the root mass: length distribution ratio and the soil depth was found for monocotyledons while an exponential decrease with depth was found for dicotyledons. These results indicated that roots were thicker at upper soil layers with the effect much larger for dicotyledons. The estimated depth at which 50% of total root was accumulated for different crops varied from 8 cm to 20 cm. Alfalfa (*Medicago sativa* L.) showed the deepest rooting profile with a fitted maximum rooting depth (d_{max}) of 177 cm but another perennial, fescue (*Festuca arundinacea* Shreb.), had the shallowest d_{max} of 78 cm. In general, cereal and pulse crop roots were distributed more evenly in soil profile while more roots were accumulated in the upper soil layers for oilseed crops. The estimated root distribution patterns from the present study could be incorporated into agroecosystem models for good representations of belowground processes and enhance the accuracy of carbon and water cycling estimation in agroecosystem.

1. Introduction

Roots play the vital role of connecting the plant to the soil and thereby the soil to the atmosphere. The growth and development of above-ground plants depends on the acquisition of soil nutrients and water and so are closely associated with root morphology and physiology (Ju et al., 2015).

The root distribution with depth is an important plant trait for global biogeochemical models and land surface models. Different root distribution models have been developed and used in many ecosystem models. A one-parameter exponential equation was fitted to 11 biomes by Jackson et al. (1996) by compiling a database of 115 root profiles, which had been used in the integrated terrestrial ecosystem carbon-budget model (InTEC V3.0) to estimate root distribution for different forest types (Ju and Chen, 2005). It was modified to a two-parameter exponential equation (Zeng, 2001) by getting a deeper maximum rooting depth and then used by the Community Land Model, version 4 (CLM4) (Koven et al., 2013). Schenk and Jackson (2002) expanded the database of 115 root profiles to 475 root profiles and fitted them to a logistic dose–response curve. Jackson et al. (1996) and Zeng (2001) treated cropland as a single biome in their study while cropland was excluded from the study of Schenk and Jackson (2002). However, crop species differ in root biomass, root turnover, vertical root distribution, and maximum rooting depth (Canadell et al., 1996; Liu et al., 2011). To capture the effects of these root differences on the uptake of water and nutrients by crops as well as the deposition and accumulation of carbon and nutrients with depth, it is necessary to use specific root distribution patterns for different crops in agroecosystem models.

One important use of root distribution information is to estimate the effect of crop roots C input on soil C balance in agroecosystems. To assess the overall plant derived C inputs into the soil, an accurate accounting of total root C is required (Johnson et al., 2006), which is typically estimated from multiplying shoot mass by the root/shoot (R/S) ratio. Because of labor requirements in root sampling, estimated R/S ratio was often based on incomplete root samplings including sometimes only sampling of the topsoil. For instance, Bolinder et al. (1997) estimated R/S ratios for different cereal species by using root biomass measured in 0–30 cm soil, while Izaurralde et al. (2001) estimated carbon input by using R/S ratios measured in 15 cm. There is a lack of robust root mass with depth relationships based on observations to make adjustments of root measurements for part of rooting depth to root mass for the

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full rooting depth. Furthermore, root distribution had significant effects on water and nutrient cycling and soil carbon sequestration (Cornelissen et al., 2003). The objective of this study was to develop representative root distribution patterns for a range of crops grown in temperate regions.

2. Material and methods

2.1. The database

A database was compiled to estimate root distribution for temperate crops from journals and book chapters by searching databases of Scopus and Google Scholar. A reference was included in the analysis if root samples were taken in at least four soil depth increments. About 64 references met this criterion and some included multiple sites or multiple crops per study (Table A1). For reference with different treatments, the treatment with moderate fertilization level and/or without water, salt or other stress was used. All data were converted to an area basis (e.g., g/m^2 for root mass or cm/cm^2 for root length) and cumulative root mass or length was calculated and used for analysis. In total, 96 root profiles were incorporated in the database. For each study, we also noted the location, latitude and longitude, sampling method, units of measurements and sampling depth (Table A1). The data from references were separated into 11 crops: wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), pea (*Pisum sativum* L.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* L.), soybean (*Glycine max* L.), canola (*Brassica napus* L.), alfalfa, and fescue.

2.2. Estimating of root distribution pattern

A logistic dose–response curve was used by Schenk and Jackson (2002) to fit the cumulative root distribution based on the following equation:

$$\frac{R_i}{R_{\max-i}} = \frac{1}{1+\left(\frac{d}{d_{50}}\right)^c} \tag{1}$$

where R_i is the cumulative amount (*i.e.*, biomass mass or root length) of roots for the *i*th profile to soil depth *d* (cm), $R_{\text{max-}i}$ is the total amount of roots of *i*th profile, d_{50} is depth at which 50% of total root amount was accumulated, *c* is a dimensionless shape-parameter.

Of all profiles in our database, 46% reported as root mass and 54% as root length. To standardize the distributions to root mass, we developed a relationship, *r(d)* that is the ratio of root mass distribution to root length distribution with soil depth. We derived the relationships by fitting data for 9 profiles where both root mass and length were measured together. Separate relationships were fit for dicotyledonous and monocotyledonous crop types to account for their different root architecture (fibrous root *vs* tap root, respectively). For studies only having root length, root mass was estimated from root length for profile *i* using the root mass to length function, *r(d)*.

Eq. (1) indicates an infinite rooting depth but most process models of soil-crop systems require a fixed maximum crop rooting depth. Therefore, we suggest a slight modification to Eq. (1) to have all roots confined to a maximum rooting depth, $d_{\max}$:

$$Y_i(d) = \frac{1}{1+\left(\frac{d}{d_a}\right)^c} + \left[1 - \frac{1}{1+\left(\frac{d_{\max}}{d_a}\right)^c}\right] * \frac{d}{d_{\max}} \tag{2}$$

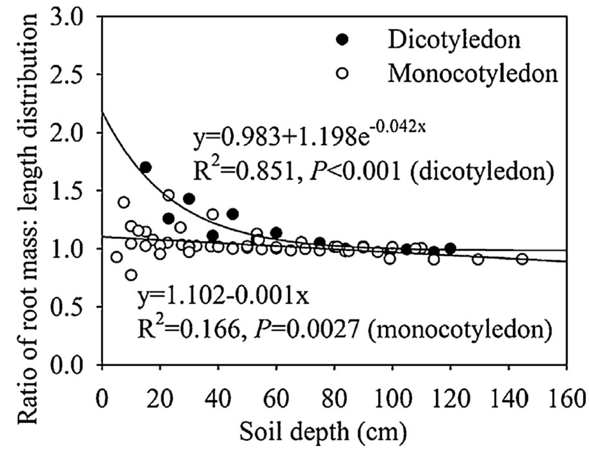

Fig 1. Relationship between the ratio of root mass distribution to root length distribution and soil depth for dicotyledonous and monocotyledonous crops. Monocotyledon data derived from Allmaras et al. (1975) (maize), Ball-Coelho et al. (1998) (maize), Cannell et al. (1985) (oat), Feng et al. (2009) (wheat), Germida and Walley (1996) (wheat), Guan et al. (2015) (wheat), Tadesse et al. (1995) (oat). Dicotyledon data derived from Allmaras et al. (1975) (soybean), Ali et al. (2005) (chickpea).

$$Y_i(d) = \begin{cases} \dfrac{RM_i(d)}{RM_{\max-i}} : \text{mass} \\[2ex] \dfrac{RL_i(d)}{RL_{\max-i}} \times r(d) : \text{length} \end{cases} \tag{3}$$

where *$Y_i(d)$* is root distribution for profile *i* at depth *d*, *$RM_i(d)$* is root mass for profile *i* at depth *d*, $RM_{\text{max-}i}$ is the total root mass for profile *i*, *$RL_i(d)$* is root length for profile *i* at depth *d*, $RL_{\text{max-}i}$ is the total root length for profile *i*, and d_a is another fitting parameter having dimension of cm.

If the authors stated the profiles had been sampled to maximum root depth, $RM_{\text{max-}i}$ or $RL_{\text{max-}i}$ was set to cumulative root mass or root length where mass or length measured. Otherwise, $RM_{\text{max-}i}$ or $RL_{\text{max-}i}$ was fit simultaneously with the other parameters of *c*, d_a, and $d_{\max}$ in Eq. (2) to all observations for each crop. We used this methodology to derive a root distribution for crop groups of cereals (barley, maize, oat, wheat), pulses (chickpea, lentil, pea), oilseed crops (canola, soybean) or general crop (all crops in this study). The fitting of the equation were done by nonlinear least-squares regression following the Gauss–Newton algorithm by R software (R Core Team, 2015).

The Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) was used to evaluate the goodness of regression:

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{N}(S_i - O_i)^2}{\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2}$$

3. Results

3.1. Relationship between root distribution ratio of mass/length and soil depth

The ratio of root mass distribution to root length distribution for monocotyledonous crops decreased linearly ($P<0.01$) at 0.1% per centimeter (Fig. 1). In contrast, this ratio decreased exponentially ($P<0.001$) with soil depth for dicotyledonous crops (Fig. 1). This relationship represents the rapid thickening of the tap roots of decotyledons as they get closer to the plant crown.

Table 1
Estimated parameters, calculated d_{50} and d_{95}, associated NSE, and reported maximum rooting depth ($d_{max\text{-}r}$, cm) for different crops.

Crops	d_a	c	d_{max} (cm)	d_{50} (cm)	d_{95} (cm)	NSE[a]	$d_{max\text{-}r}$[b]
Wheat	17.2	−1.286	150.4	16.8	103.8	0.899	300[1]
Maize	14.9	−1.151	118.3	14.4	88.9	0.853	240[1]
Oat	12.0	−0.924	97.2	11.2	77.7	0.894	180[1]
Barley	11.8	−1.060	146.1	11.5	99.6	0.717	170[2]
Cereals	14.5	−1.165	128.1	14.1	92.9	0.857	
Pea	18.9	−1.394	111.3	18.2	85.0	0.870	160[3]
Chickpea	19.3	−1.014	101.0	17.4	84.8	0.897	180[4]
Lentil	11.9	−0.980	92.9	11.2	73.7	0.805	100[5]
Pulse crops	16.2	−1.115	104.8	15.3	83.6	0.859	
Soybean	11.6	−0.626	172.1	10.9	138.0	0.583	180[6]
Canola	9.9	−0.473	105.6	8.4	90.2	0.626	160[7]
Oilseed crops	10.0	−0.671	133.0	9.4	106.3	0.577	
Alfalfa	20.7	−1.032	176.8	19.8	135.6	0.907	370[1]
Fescue	13.7	−1.144	78.4	12.8	63.7	0.796	120[8]
All crops	15.0	−1.117	141.9	14.6	102.7	0.838	

[a] NSE: Nash–Sutcliffe efficiency.
[b] Reported maximum rooting depth obtained from: [1]: Canadell et al. (1996); [2]: Hoad et al. (2001); [3]: Armstrong et al. (1994); [4]: Gregory (1988); [5]: Liu et al. (2011); [6]: Huck et al. (1986); [7]: Zhang et al. (2004a); [8]: Bennett and Doss (1960).

3.2. Root distribution of different crops

At least half of the root biomass could be found in the upper 20 cm of soil for all crops (Table 1, Fig. A1). Oat, barley, lentil, soybean, canola, and fescue had the shallowest d_{50} (<13 cm) with 67–76% of their roots in the upper 30 cm soil profile. However, wheat, pea, chickpea, and alfalfa, with 61–68% of their roots in the uppermost 30 cm soil profile, showed deeper d_{50} (>15 cm) than other crops (Table 1).

Alfalfa showed the deepest rooting profile with 95% of roots in the 136 cm of soil and a maximum rooting depth (d_{max}) of 177 cm but another perennial, fescue, had the shallowest profile with d_{max} of 78 cm (Table 1). For annual crops, wheat, barley and soybean showed deeper rooting depth than other crops, with 95% of roots occurring in the top 100–138 cm and d_{max} of 146–172 cm. Oat, pea, chickpea, and lentil, had the shallowest rooting profile of annual crops, with 95% of roots obtaining in the top 64–85 cm and d_{max} of 78–110 cm (Table 1).

In general, oilseed crops had shallower d_{50} (9.4 cm) than cereal and annual pulses (14.1 and 15.3 cm) but deeper d_{max} (133 cm) than cereal and pulses (128 and 105). Consequently, the roots of cereal and annual pulse distributed more evenly in their rooting depth than those of oilseeds (Fig. A1).

4. Discussion and conclusion

Despite the variability in methods and sites, Eq. (2) provided a generally good fit for all crops, with an NSE of 0.8 or greater for 7 of the 11 crops. The oilseed crops had the greatest variation between studies (Fig. A1) and so had the lowest NSE (0.583–0.626) among the crops.

Effective root zone is the depth within which most crop roots are concentrated, which was estimated as ∼50–100 cm for wheat, maize, barley and canola, as ∼60–70 cm for peas, as ∼120 cm for alfalfa (ARD, 2013). These values were comparable with our estimated d_{95} values (Table 1), which were used as a measure of soil depth that holds the bulk of roots (Schenk and Jackson, 2002). Therefore, we argue that d_{95} values estimated from our root distribution pattern for different crops could be used as an indicator for soil root sampling or soil core experiment design to get a soil depth that contained most of crop roots. Despite this predominance of crop roots in the upper soil layers, deep roots are important for C deposition and H_2O dynamics within the whole rooting depth (Jackson et al., 1996).

The estimated maximum rooting depth (d_{max}) by Eq. (2) was normally shallower than the deepest observed rooting depths obtained from literature (Table 1). The depth of root growth can be limited by various factors, such as soil bulk density, soil structure, oxygen status, bedrock, water table, so that the deepest observations of roots are mainly found in sandy loose soils where mechanical impedance to root penetration is less than many other soils (Canadell et al., 1996). Therefore, we expected the maximum observed rooting depth to be deeper than the fitted maximum rooting depth that is representative of a range of soil and growth situations. To better represent their site conditions, a user of Eq. (2) may want to use a d_{max} different than the value we estimated from multiple distributions. To illustrate the effect of using an arbitrary d_{max}, we inserted the deepest observed d_{max} from Table 1 but used the fitted c and d_a. The regression results increased estimated d_{50}, ranging from 1% for lentil and soybean to 27% for canola, while decreased NSE by almost zero for soybean to 0.042 for canola (data not shown).

To illustrate an application of our root distribution to improve analysis of agroecosystems, Izaurralde et al. (2001) and Bolinder et al. (1997) estimated R/S ratio of 0.115 and 0.144 for wheat using root biomass measured in 0–15 and 0–30 cm soil, respectively. Using present results, 46.2% and 68.3% of wheat roots are distributed in upper 15 and 30 cm, respectively, and this yields different adjusted R/S ratios of 0.21–0.25, which agree better with an estimation of 0.20 by lysimeter study (Gan et al., 2009).

In summary, we developed an improved equation to estimate root distribution pattern over soil depth for several important temperate crops. The information derived from this equation could be used to adjust experimental measurements of rooting depth and root mass for the full rooting depth. Further the estimated root patterns can be applied when modeling crop growth in agroecosystems.

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Appendix A

Table A1
References included in the database for the analysis of root distribution.

Crop	Reference	Location	Coordinates	Sampling method	Measurement
Wheat	Asseng et al. (1997)	Muencheberg, Germany	52°30′N, 14°08′E	Not specify	RLD cm/cm^3 to 85 cm
	Chen et al. (2014)	Buntine, Australia	29°59′S, 116°34′E	24 × 100 cm	RLD cm/cm^2 to 80 cm
	Drew and Saker (1980)	Oxfordshire, UK	51°45′N 1°15′W	7 cm diameter soil core	RWD µg/cm^3 to 100 cm
	Entz et al. (1992)	Floral, Outlook, and Clair, SK, Canada	52°34′N, 106°31′W; 51°30′N, 107°3′W; 52°1′N, 104°4′W	Profile wall method	RLD m/m^2 to 110 cm
	Feng et al. (2009)	Wuwei, Gansu Province, China	37°30′N, 103°5′E	8 cm diameter soil core	RWD µg/cm^3 to 70 cm
	Guan et al. (2015)	Cangzhou, Hebei Province, China	37°41′N, 116°37′E	8 cm diameter soil core	RWD mg/cm^3 to 110 cm
	Kang et al. (2014)	Changwu, Shannxi Province, China	35°12′N, 107°48′E	10 cm diameter soil core	RWD g/m^3 to 100 cm
	Lv et al. (2010)	Tongzhou district, Beijing, China	39°36′N, 116°48′E	5 cm diameter soil core	RLD cm/cm^2 to 95 cm
	Officer et al. (2009)	Wimmera, Australia	36°40′S, 142°17′E	15 cm diameter soil core	RLD cm/cm^2 to 50 cm
	Osaki et al. (1995)	Hokkaido, Japan	43°14′N 141°57′E	60 × 40 cm box shape	% dry weight to 60 cm
	Qin et al. (2004)	Berne, Swiss	47°00′N, 7°28′E	5 cm diameter soil core	RLD cm/cm^2 to 50 cm
	Wadey et al. (1994)	Silwood Park, London, UK	51°24′N, 0°38′W	Lysimeter	RLD cm/cm^2 to 70 cm
	Yu et al. (2010)	Chaoyang district, Beijing, China	39°42′N, 116°38′E	5 cm diameter soil core	RLD cm/cm^2 to 75 cm
	Zhang et al. (2004b)	Luancheng, Hebei Province, China	37°53′N, 114°41′E	7 cm diameter soil core	RLD cm/cm^2 to 160 cm
	Zhou et al. (2008)	Wuqiao, Hebei Province, China	39°38′N, 116°31′E	8 cm diameter soil core	% root weight to 200 cm
	Entz et al. (1992).	Floral, Outlook, and Clair, SK, Canada	52°34′N, 106°31′W; 51°30′N, 107°3′W; 52°1′N, 104°4′W	Profile wall method	RLD m/m^2 to 110 cm
	Gan et al. (2011)	Swift current, SK, Canada	50°15′N, 107°44′W	Lysimeter	% root volume to 100 cm
	Germida and Walley (1996)	Hagen, SK, Canada	52°56′N, 105°33′W	10.2 cm diameter soil core	RWD mg/cm^3 to 60 cm
	Herrera et al. (2011)	Monte Vista, CO, USA	37°34′N, 106°8′W	15 cm diameter soil core	RWD g/cm^3 to 60 cm
	Riedell et al. (2003)	Brookings, SD, USA	44°19′N, 96°46′W	Minithizotron	Root length cm to 50 cm
	Zhang et al. (2004a)	Kojonup, Western Australia	33°55′S, 116°54′E	10 cm diameter soil core	RLD cm/cm^3 to 140 cm
Maize	Allmaras et al. (1975)	Lamberton, MN, USA	44°13′N, 95°16′W	Soil monolith	RLD cm/cm3 to 144.7 cm
	Ball-Coelho et al. (1998)	Ontario, ON, Canada	42°52′N, 80°31′W	10 cm diameter soil core	RWD kg/m^3 to 30 cm
	Buyanovsky and Wagner (1986)	Columbia, MO, USA	38°57′N, 92°19′W	10 cm diameter soil core	RWD g/m^2 to 50 cm
	Dwyer et al. (1996)	Ottawa, ON, Canada	45°23′N, 75°43′W	5 cm diameter soil core	RWD g/m^3 to 95 cm
	Laboski et al. (1998)	Princeton, MN, USA	45°34′N, 93°35′W	4.5 cm diameter soil core	% root length to 105 cm
	Osaki et al. (1995)	Hokkaido, Japan	43°14′N, 141°57′E	60 × 40 cm box shape	% dry weight to 60 cm
	Qin et al. (2006)	Schafisheim and Zollikofen, Switherland	47°23′N, 8°09′E; 47°00′N, 7°28′E;	5 cm diameter soil core	RLD cm/cm^3 to 100 cm
Oat	Bloodworth et al. (1958)	Texas, USA	31°58′N, 99°54′W	6-inch soil core	RWD lb/acre to 60 cm
	Bragg et al. (1983)	Oxfordshire, UK	51°45′N, 1°15′W	7 cm diameter soil core	RLD cm/cm^3 to 90 cm
	Cannell et al. (1985)	Vale of York,UK	53°57′N, 1°6′W	Lysimeter	RWD g/m^2 to 95 cm
	Ehlers et al. (1983)	Göttingen, Germany	51°32′N, 9°56′E	Profile wall	RLD cm/cm^3 to 45 cm
	Pietola and Alakukku (2005)	Jokioinen, Finland	60°49′N, 23°28′E	Minithizotron	RWD mg/cm^2 to 55 cm
	Pietola (2005)	Jokioinen, Finland	60°49′N, 23°28′E	Minithizotron	RLD cm/cm^3 to 40 cm
	Tadesse et al. (1995)	Brookings, SD, USA	44°19′N, 96°46′W	7 cm diameter PVC cylinder	RWD mg/m^2 to 108 cm

Table A1 (*Continued*)

Crop	Reference	Location	Coordinates	Sampling method	Measurement
Barley	Arslan (1996)	Jillin, South-west Syria	32°25′N, 35°35′E	Not specify	RWD kg/ha to 120 cm
	Dwyer et al. (1988)	Central Experimental Farm, Ottawa, ON, Canada	45°23′N, 75°43′W	Excavate by 0.3 m × 0.3 m	RLD cm/cm^3 to 80 cm
	Gregory (1988)	Jindiress, Aleppo, Syria	36°23′N, 36°41′E	Not specify	RLD cm/cm^3 to 110 cm
	Hansson and Andrén (1987)	Uppsala, Sweden	59°51′N, 17°38′E	8 cm diameter soil core	% root weight to 100 cm
	Heeraman and Juma (1993)	Ellerslie Research Station, AB, Canada	53°25′N, 113°33′W	Soil monolith	RWD $\mu g/cm^2$ to 70 cm
	Kautz et al. (2013)	Bonn, Germany	6°59′N, 50°37′E	Profile wall dig	RLD cm/cm^3 to 200 cm
	Pietola (2005)	Jokioinen, Finland	60°49′N, 23°28′E	Minithizotron	RLD cm/cm^3 to 40 cm
Pea	Armstrong et al. (1994)	Wongan Hills, Australia	30°54′S, 116°43′E	10 cm diameter auger	RWD g/m^2 to 160 cm
	Cutforth et al. (2013)	Swift current, SK, Canada	50°16′N, 107°28′W	Trench dig	RLD cm/cm^3 to 120 cm
	Gan et al. (2009)	Swift current, SK, Canada	50°16′N, 107°28′W	Lysimeter	% root weight to 100 cm
	Gan et al. (2011)	Swift current, SK, Canada	50°16′N, 107°28′W	Lysimeter	% root volume to 100 cm
	Williams et al. (2013)	Pendleton, OR, USA	45°40′N, 118°47′W	Excavate by 18 cm × 18 cm	% root weight to 40 cm
Chickpea	Benjamin and Nielsen (2006)	Akron, CO, USA	40°10′N, 103°13′W	7.5 cm diameter soil core	RWD g/cm^2 to 120 cm
	Gan et al. (2009)	Swift current, SK, Canada	50°16′N, 107°28′W	Lysimeter	% root weight to 100 cm
	Gan et al. (2011)	Swift current, SK, Canada	50°16′N, 107°28′W	Lysimeter	% root volume to 100 cm
	Gregory (1988)	Jindiress, Aleppo, Syria	36°23′N, 36°41′E	Not specify	RLD cm/cm^3 to 110 cm
	Weber et al. (1993)	Tel Hadya, Syria	36°40′N, 37°20′E	5.5 cm diameter auger	RLD cm/cm^3 to 60 cm
Lentil	Gan et al. (2009)	Swift current, SK, Canada	50°16′N, 107°28′W	Lysimeter	% root weight to 100 cm
	Gan et al. (2011)	Swift current, SK, Canada	50°16′N, 107°28′W	Lysimeter	% root volume to 100 cm
	Liu et al. (2011)	Swift current, SK, Canada	50°16′N, 107°28′W	Lysimeter	RLD cm/cm^3 to 100 cm
	Shrestha et al. (2005)	Khumaltar, Nepal	27°24′N, 85°12′E	5 cm diameter auger	RLD cm/cm^3 to 70 cm
Soybean	Benjamin and Nielsen (2006)	Akron, CO, USA	40°10′N, 103°13′W	7.5 cm diameter soil core	RWD g/cm^2 to 100 cm
	Devries et al. (1989)	Gainesville, FL, USA	29°39′N, 82°19′W	4.8 cm diameter soil core	RLD cm/cm^3 to 120 cm
	Dwyer et al. (1988)	Central Experimental Farm, Ottawa, ON, Canada	45°23′N, 75°43′W	Excavate by 0.3 m × 0.3 m	RLD cm/cm^3 to 80 cm
	Huck et al. (1986)	Auburn, AL, USA	32°î36N, 85°29′W	Compartments at Auburn rhizotron	RLD m/m^3 to 180 cm
	Osaki et al. (1995)	Hokkaido, Japan	43°14′N, 141°57′E	60 × 40 cm box shape	% root weight to 60 cm
	Allmaras et al. (1975)	Lamberton, MN, USA	44°13′N, 95°16′W	Soil monolith	RWD mg/cm3 to 144.3 cm
	Xu et al. (2014)	Jixian, Shanxi Province, China	35°53′N, 110°27′E	Not specify	RLD cm/cm^3 to 60 cm
	Zhang and Huang (2003)	Baiying, Gansu Province, China	36°32′N, 104°8′E	5 cm diameter soil core	RWD g/m^2 to 75 cm
Canola	Cutforth et al. (2013)	Swift current, SK, Canada	50°16′N, 107°28′W	Trench dig	RLD cm/cm^3 to 120 cm
	Gan et al. (2009)	Swift current, SK, Canada	50°16′N, 107°28′W	Lysimeter	% root weight to 100 cm
	Gan et al. (2011)	Swift current, SK, Canada	50°16′N, 107°28′W	Lysimeter	% root volume to 100 cm
	Gregory (1998)	Beverley, Western Australia	32°08′S, 117°10′E	Not specify	RLD cm/cm^3 to 80 cm
	Williams et al. (2013)	Pendleton, OR, USA	45°40′N, 118°47′W	Excavate by 18 cm × 18 cm	% root weight to 40 cm
	Zhang et al. (2004a)	Kojonup, Western Australia	33°55′S, 116°54′E	10 cm diameter soil core	RLD cm/cm^3 to 130 cm
Alfalfa	Abdul-Jabbar et al. (1982)	Las Cruces, NM, USA	32°18′N, 106°46′W	7.8 cm diameter soil core	RWD mg/cm^2 to 180 cm
	Bell (2005)	Perth, Western Australia	31°59′S, 115°53′E	Glasshouse	% root length to 80 cm
	Denton et al. (2006)	Perth, Western Australia	31°59′S, 115°53′E	Glasshouse	RLD cm/cm^3 to 75 cm
	Gentile et al. (2003)	INIA La Estanzuela, Uruguay	34°20′S, 57°41′W	4.25 cm diameter soil core	RWD kg/m^2 to 100 cm
	Luo et al. (1995)	Davis, CA, USA	38°30′N, 121°45′W	2.2 cm diameter soil core	RWD g/m^2 to 150 cm
	Raza et al. (2013)	BOKU, Vienna, Austria	48°14′N, 16°20′E	7 cm diameter auger	RLD cm/cm^3 to 130 cm
	Xu et al. (2007)	Ansai, Shannxi Province, China	36°51′N, 109°19′E	9 cm diameter auger	RWD g/m^2 to 150 cm
Fescue	Beyrouty et al. (1990)	Fayetteville, AR, USA	36°4′N, 94°9′W	7.5 cm × 7.5 cm tube	RLD cm/cm^3 to 40 cm
	Durand et al. (2010)	Lusignan, France	46°24′N, 0°15′W	8 cm diameter soil core	RWD g/m^2 to 80 cm
	Kim et al. (1999)	Lincoln, NE, USA	40°49′N, 96°42′W	75 cm deep PVC pipe	RWD g/m^2 to 75 cm
	Malcolm et al. (2014)	Christchurch, New Zealand	43°38′S, 172°28′E	Excavated soil profile	RLD cm/cm^3 to 80 cm

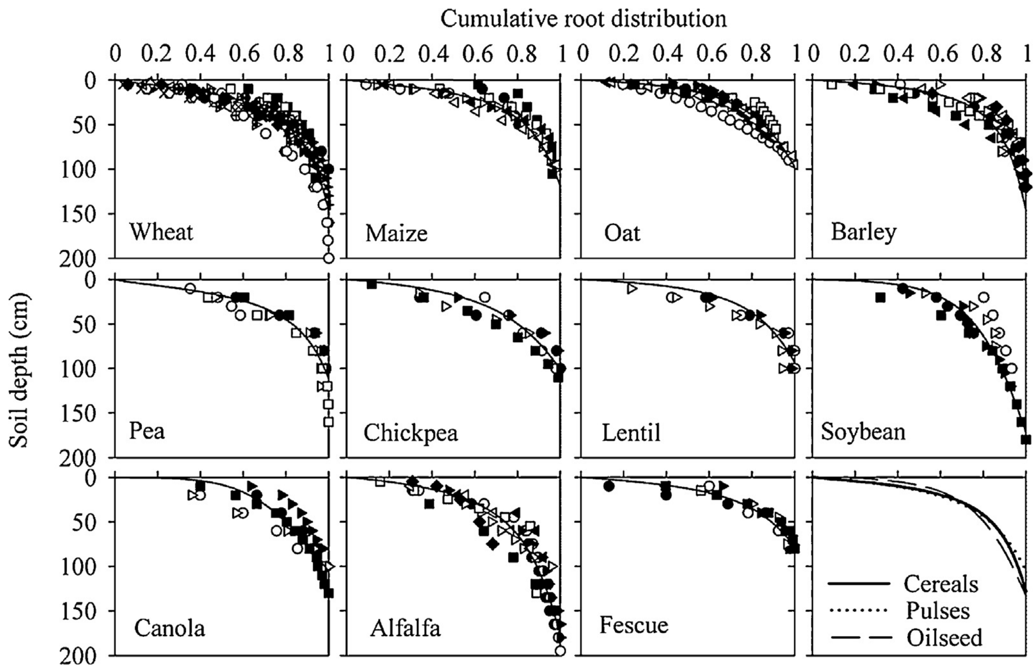

Fig. A1. Cumulative root distribution as a function of soil depth for 11 crops.

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