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REGULAR ARTICLE

Evaluation of a core sampling scheme to characterize root length density of maize

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Abstract Information about root distribution is important for characterization and modeling of water and nutrient uptake, biomass, and yield. Due to the heterogeneous distribution of roots in row crops, the reliability and representativeness of estimates of RL and root morphology using core sampling depend on the number of samples and their location. The objectives of this study were to evaluate errors when assessing RLD and root morphology from auger core sampling schemes, to estimate 2D distributions of RLD by auger core sampling, and to assess the number of samples necessary for representative estimates of RLD and RD classes. The reference dataset utilized in this study is based on completely sampled 3D soil monoliths under maize, taken at three different dates (55, 78, and 104 days after planting) and two different row spacings (75 and 37.5 cm). A hypothetical auger core sampling scheme with one core within the row and another midway between rows mostly overpredicted total RLD. Bias was lower when using an 1:3 weighting scheme. Estimation of 2D vertical RLD distribution by calculating the ratio of RLD in the plant row to RLD midway between rows yielded reasonable estimates only when the average of eight cores was used. An assessment of the proportions of RD classes yielded high bias values, even when using the average of eight cores. An analysis of sampling errors using successively more cores revealed that for total RLD, to attain a bias <20%, more than ten samples would be necessary. This suggests that the number of core samples taken in many root studies could be too low. This bias was even higher when taking core samples for estimation of proportions of RD classes, where a reasonably low bias between estimated and "true" values could not be attained in this study even with ten core samples. Consequently, when taking samples for measurement of root morphological parameters, more detailed and site-adapted sampling schemes have to be devised. For estimating total averaged RLD, two core

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samples (within-row and midway between rows) could be sufficient when using a 1:3 weighting scheme for calculating the average RLD. When samples are taken in a more random manner and no weighting is applied, the necessary number of samples would be at least ten.

Keywords Maize (*Zea mays* L.) · Root length density · Row spacing · Spatial variability · Sampling scheme · Root diameter

Abbreviations

DAP	days after planting (d)
RD	root diameter (mm)
RFM	root fresh mass (g)
RL	root length (cm)
RLD	root length density (cm cm^{-3})
$RLD_{av,c}$	mean value of RLD estimated by core sampling
RLD_{mo}	mean value of RLD estimated by monolith sampling
RLD-RR	RLD row ratio: ratio between RLD in the plant row to RLD midway between rows
RMD	root mass density (g cm^{-3})
wf	weighting factor (−)

Introduction

Temporal and spatial distributions of root length density (RLD) and root mass distribution (RMD) in arable soils are important for characterization and modeling of water and nutrient uptake, and plant biomass and crop yield development (e.g., van Noordwijk and van den Geijn 1996; Wang and Smith 2004). In addition to overall RLD and RMD, the relative proportion of root diameter classes is important since roots may functionally be different depending on certain diameter classes (e.g., Chassot et al. 2001; Pierret et al. 2005; Huang et al. 2008). For instance, finer roots of mean diameters smaller than about 0.5 mm are assumed to carry the 'active sites' for nutrient uptake (Zobel 2003).

The spatial distribution of total RLD in row crops has been described in several experimental studies (e.g., Mengel and Barber 1974; Amato and Ritchie 2002). However, the spatial patterns and heterogeneity of RLD for different root diameter (RD) classes in row crops like maize have been characterized only rarely until now (e.g., Qin et al. 2005). For maize, mean root diameters were found to be larger (1) within than between the plant rows (Anderson 1987) and (2) in the topsoil than in greater soil depths (Schenk and Barber 1980; Qin et al. 2005). Soil sampling to obtain representative estimates of RLD and RD (i.e., according to root morphology) is regarded to be fraught with difficulties (Van Noordwijk et al. 1985; Bengough et al. 2000). Often it is, however, unclear whether a 1D vertical root distribution assuming horizontally averaged RLD may be sufficient or whether a complete spatial characterization of RLD is required. In most studies, auger core sampling methods are applied, since a complete soil volume sampling is relatively time and labour intensive (Böhm 1979; Van Noordwijk et al. 1985). Any representative estimate of root distribution by auger sampling requires large numbers of core samples (Schuurman and Goedewaagen 1971). However, the issue concerning the amount of samples and the proper sampling schemes seems to be unresolved: Most typically for maize crops, about one to five soil cores were extracted per plot (e.g., Wiesler and Horst 1994; Sharratt and McWilliams 2005) and taken either (1) within the plant row and midway between rows (Van Noordwijk et al. 1985; Kuchenbuch and Barber 1987; Dwyer et al. 1996; Sharratt and McWilliams 2005) or (2) within the row and at one single other location between rows (Ball-Coelho et al. 1998). Even one single core location with respect to the plant row has been deemed to represent horizontally averaged RLD (e.g., Gajri et al. 1994; Oikeh et al. 1999), or one core at a random location relative to the plant row was extracted (Ewel et al. 1982).

Most of the cited studies implicitly assumed that the number of soil cores they used yielded sufficiently reliable assessments of RLD distribution. However, a few systematic studies evaluating the deviation between RLD obtained with auger core sampling procedures and spatially distributed monolith sampling indicated that a substantial degree of error could be incurred by using simplified sampling schemes (Van Noordwijk et al. 1985; Kumar et al. 1993; Gajri et al. 1994).

For row crops such as maize or wheat, the mean RLD may be approximated by single-site augering at about one-third of distance from the plant base to midway between rows (Gajri et al. 1994). For wheat with a row spacing of 22 cm, the mean RLD could be best approximated by using soil cores of 10 or 7.5 cm in diameter, extracted at two sites in the row and midway between rows (Kumar et al. 1993). Neither of the above two studies investigated the distribution of different RD classes.

Van Noordwijk et al. (1985) suggested that the RMD distribution in a unit soil strip can be approximated by a negative exponential function of the distance to the plant row, and that the bias for a sampling scheme with two cores (i.e., in the row and midway between rows) increases with non-linearity of the distribution function.

We are not aware of any study addressing the possible errors for auger core sampling schemes with respect to both total RLD and spatial distribution of RD classes based on data from a complete 3D soil volume sampling.

The objectives of this study were (1) to evaluate errors when assessing mean 1D vertical total RLD and the proportions of different root diameter classes from relatively simple auger core sampling schemes, (2) to test the possibility of estimating the 2D distributions of RLD by auger core sampling using ratios of within-row and between-row RLD, and (3) to estimate how many auger core samples would be necessary to obtain representative estimates of RLD and RD classes.

As a novelty, this study is based on data obtained from a completely sampled 3D soil monolith (i.e., encompassing also the direction parallel to the row) as the reference for any simplified sampling scheme (or "ground truth" data). Furthermore, four different root diameter classes are considered.

Material and methods

This analysis utilizes three-dimensional (3D) spatially distributed RLD data of maize (*Zea mays* L.), which were obtained by means of a complete soil sampling procedure similar as that described by Böhm (1979). Soil monolith excavations were carried out at an experimental field site near the village of Paulinenaue (52° 41′ N; 12° 42′ E), which is located about 50 km west–northwest of Berlin in the flat landscape called "Havelländisches Luch". The soil type is Mollic Gleysol (FAO 2006) with predominantly sandy texture, originating from a degraded shallow fen overlying glacio-fluviatile sands. Maize row spacing was 75 cm (i.e., conventional, index "W" for "wide") and 37.5 cm (i.e., index "N" for "narrow"); soils including roots were sampled for one date in the year 2003 (index "03-d1") and two dates in 2004 ("04-d1" and "04-d2"). All plots were tilled in a conventional way with mould board ploughing in autumn. In both years, silage maize (cv. Tassilo) was planted end of April at a density of 74,000 plants per hectare irrespective of row spacing, and 32 kg P per hectare and 99 kg K per hectare were applied in March and 140 kg N per hectare distributed as urea in the beginning of April. The first sampling in 2004, "04-d1", was carried out 55 days after planting (DAP) when the maize was at a growth stage close to canopy closure; the sampling in 2003, "03-d1", (78 DAP) and the second sampling in 2004, "04-d2", (104 DAP) were at the time of tasseling. The excavated soil monoliths were all 70 cm long perpendicular to plant rows (*x*-direction), 40 cm wide parallel to plant rows (*y*-direction), and 30 cm deep (*z*-direction; Fig. 1). The soil volume of 0.084 m^3 in total was sampled completely in form of 84 cube-shaped 1 l samples for each date and row spacing. The purpose of this sampling scheme was to obtain the complete 3D soil volumes including the root system. After mass determination, samples were air-dried for storage purposes. Before starting root separation, the air-dried samples were submerged in water for 24 h to rehydrate the roots and to avoid root disruption. Roots were manually washed free of soil by using a nozzle and low water pressure on a stack of two sieves with mesh sizes of 1.0 and 0.4 mm. Only fresh roots of the actual year were used in this study. Dead roots remaining from crops grown in the previous year could be easily separated from the fresh roots of the actual year. Special care was taken not to disrupt the original continuum of the root system, so very few roots were visible on the bottom sieve, and no roots were detected in the outwash below the bottom sieve. On the other hand, the smallest recorded diameters of recovered roots were well below 0.3 mm. The elutriated roots were stored in 60 vol.% aqueous ethanol solution. Total RL and RFM were determined using the modified Newman-line-intersect method (Tennant 1975). During the washing procedure, RL and RFM of all the roots and of each sample were separated into size fractions representing root diameter classes that were distinctly different as assessed using a microscope equipped with a microscale: >3,

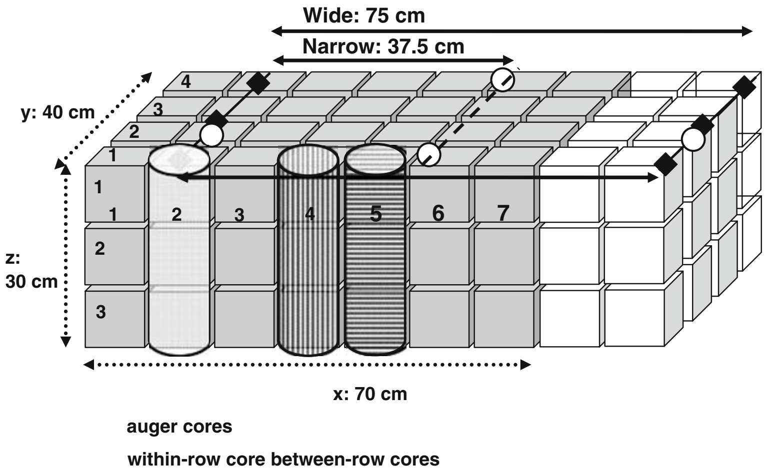

Fig. 1 Hypothetical within- and between-row auger core samples for the wide (*horizontal lines*, *blocks 2* and *5*) and the narrow (*vertical lines*, *blocks 2* and *4*) row spacing with respect to the locations of cubic samples of the soil monolith. The location of maize plants is denoted by *black-filled rhombic symbols* for the wide and by *white-filled circular symbols* for the narrow row spacing

1.3–3, 0.35–1.3, and <0.35 mm. For the class 0.35–1.3 mm, two visual fractions "coarse" and " fine" were found to be mutually exclusive (i.e., roots of diameter class 0.35–1.3 mm were either pertaining to "fine" or "coarse"). Errors may have been introduced into the root diameter data because samples were air-dried and then re-hydrated prior to the measurements. Since this affected all roots in the same manner (roots were treated according to the same laboratory protocol), it can be assumed that the relative proportions of root diameter classes remained little affected. On the other hand, the absolute values of root diameters may be subject to some degree of error, which should be accounted for when comparing them with data obtained with other methods. Note that at positions where root mass was high (i.e., large root diameters and close to maize plants within rows) a significant fraction of soil water was stored in the roots (Gerke and Kuchenbuch 2007).

Based on the RLD data of the completely sampled soil monoliths, a hypothetical auger core (with core diameter 10 cm) sampling scheme with a single core taken within the row and another one taken midway between the rows was assumed (Fig. 1); consequently, for "W", soil slices 2 (X=10–20 cm) and 5 (X=40–50), and for "N", soil slices 2 (X=10–20 cm) and 4 (X=30–40 cm) were evaluated using the four replicates parallel to plant rows. The RLD-values hypothetically sampled were assumed to be comparable with the mean values obtained from the corresponding cubic samples. The horizontally-averaged RLD value ($RLD_{av,c}$) was calculated from the two hypothetical auger core values RLD within (RLD_{win}) and RLD between (RLD_{bet}) the rows as:

$$RLD_{av,c}=(RLD_{win}+RLD_{bet} \times wf)/(1+wf) \qquad (1)$$

where the weighting factor wf is equal to 1 in case of arithmetic mean. The bias (%) of $RLD_{av,c}$ in relation to the monolith reference data (RLD_{mo}) was computed as (van Noordwijk et al. 1985; Kumar et al. 1993):

$$\mathrm{Bias}(\%) = 100 \times \left(RLD_{av,c} - RLD_{mo}\right)/RLD_{mo} \qquad (2)$$

Results

RLD depth distribution

The comparisons between $RLD_{av,c}$ and RLD_{mo} (Fig. 2) show that hypothetical auger core samplings differ substantially from the mean RLD of the whole soil monolith. The deviations from the reference data set reflect the variability of RLD among the separate four 2D vertical (i.e., x-, z-) soil slices along the y-axis. On one hand, the relatively large variability of RLD among the four slices is in line with that parallel to plant rows at this site, especially for the narrow row spacing. On the other hand, the mean $RLD_{av,c}$ values averaged over the four slices ("S1–S4" in Fig. 2) are

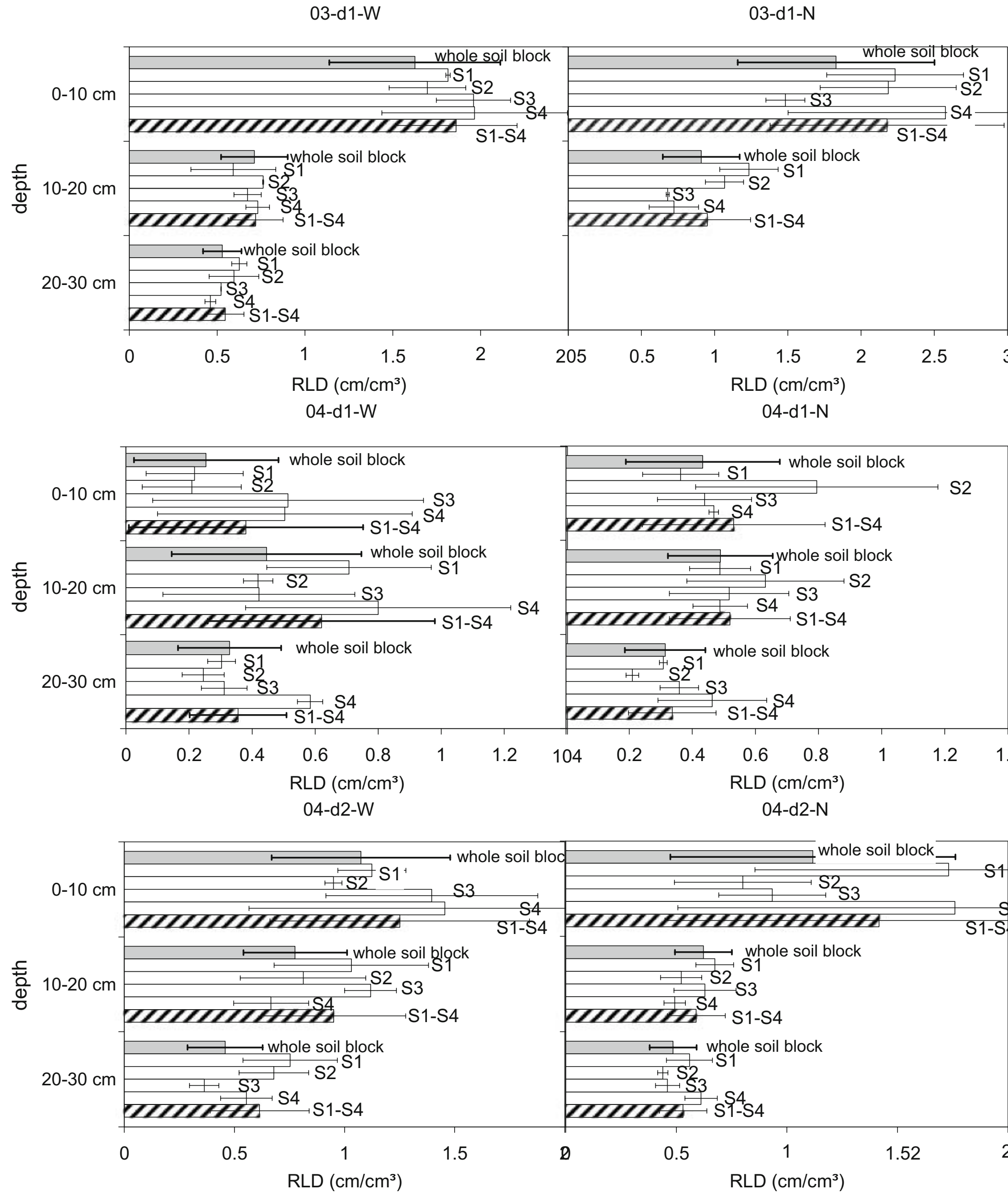

Fig. 2 Horizontally averaged RLD for the whole sampled soil block (RLD_{mo}; n=28; *upper filled horizontal bar*) and estimated mean RLD based on two auger core samples ($RLD_{av,c}$) in the row and midway between the rows taken at the four vertical slices (denoted *S1*…*S4*); the *lower hatched bar* (*S1–S4*) in each figure denotes RLD averaged for all eight auger cores; the *error bars* denote standard deviations for the case of the whole soil block and averaged *S1–S4* auger core samplings, whereas they denote min/max values in case of the auger core samples of the four separate soil slices

always within the range of the standard deviation of RLD_{mo}. Note that the standard deviations of RLD_{mo} are relatively high, especially in the uppermost soil layer. The bias values for the separate hypothetical auger core samplings are similarly high and apparently erratic (Table 1). For RLD data from 04-d1 and 03-d1, the bias for the values averaged over slices S1–S4 is highest for the upper soil layer and decreases with depth, whereas no such trend is observed for sampling 04-d2. For RLD data of both samplings in

Table 1 Bias (%; Eq. 2) of estimated RLD (all diameter classes) of hypothetical auger samplings ($RLD_{av,c}$; for soil slices S1–S4) from RLD of the whole sampled monolith (RLD_{mo}); "S1"…"S4" denote the four sampled soil slices perpendicular to the plant rows separately, "S1–S4" denotes the mean of the four soil slices; in the acronyms for the plots, "03" and "04" denote the year of monolith sampling (2003 and 2004), "d1" and "d2" denote the successive sampling date of the year, and "W" denotes wide and "N" narrow row spacing

Plot	Depth (cm)	S1	S2	S3	S4	S1–S4
03-d1-W	0–10	12	4	21	21	14
	10–20	−17	7	−5	3	1
	20–30	18	13	−1	−13	3
03-d1-N	0–10	22	19	−19	41	19
	10–20	36	18	−25	−21	5
04-d1-W	0–10	−14	−18	102	98	50
	10–20	59	−6	−5	79	39
	20–30	−8	−25	−5	78	11
04-d1-N	0–10	−16	83	1	8	23
	10–20	0	29	6	0	11
	20–30	−2	−33	14	48	7
04-d2-W	0–10	5	−12	30	36	15
	10–20	33	−29	44	−14	17
	20–30	64	48	−21	21	28
04-d2-N	0–10	55	−28	−16	58	7
	10–20	8	−16	1	−21	−9
	20–30	15	−10	−5	26	4

2004, average bias for S1–S4 is lower for the narrow than for the wide row spacing, whereas the opposite is true for the data from 2003.

The mean bias (in terms of absolute numbers) is mostly lower than for simple averaging when using a 1:3 weighting scheme (Table 2). The "ideal" weighting factors, wf, for which the bias was minimized were highly different such that no improvement over the simple averaging could be found.

Two-dimensional distribution of RLD

To assess how the 2D vertical RLD distribution could be approximated by an auger core sampling scheme, the ratio of RLD in the plant row to RLD midway between rows ($RLD\text{-}RR=RLD_{win}/RLD_{bet}$) is given in Table 3 for the reference dataset of the sampled monolith block, the slices S1–S4 and averaged for S1–S4. For the reference dataset, this ratio in general is highest in the top soil layer and decreases with depth.

Bias values are relatively high when extracting only two samples (Table 3). Even for the average of S1–S4, the bias is relatively large between estimated and reference values (e.g., 04-d1-W at 0–10 cm depth, 04-d2-N at 0–10 cm depth), in some cases even larger than the bias for estimated mean RLD (cf. Table 1).

Proportion of root diameter classes

Bias values between proportions of diameter classes estimated by the auger core samplings and the "true" proportions of diameter classes (Table 4; for the second sampling of 2004, 04-d2) are in general larger than bias values for estimation of total RLD (Table 1) and the deviations are high both for wide as well as for narrow row spacing. Especially for the fine (RD< 0.35 mm) and coarse (RD>3 mm) roots, bias values are for some cases extremely high (100% or more). This holds true in some cases (e.g., 04-d2-N, 10–20 cm depth, RD classes >3 and <0.35 mm) also for the auger core samples averaged over all four sampled slices (S1–S4).

Relation between bias and number of core samples

Bias values for estimated total RLD compiled in Table 1 and for fractions of RLD pertaining to different RD classes (Table 4) revealed largely

Table 2 Mean bias (absolute %-values, i.e. positive values) of estimated mean RLD ($RLD_{av,c}$) from reference mean RLD (RLD_{mo}) for 1:1 averaging (column "simple averaging"), averaging with a fixed 3:1 weighting factor (wf=3) and averaging with optimized wf values (optimized values of the wf for the three soil depths in parentheses); in the acronyms for the plots, "03" and "04" denote the year of monolith sampling (2003 and 2004), "d1" and "d2" denote the successive sampling date of the year, and "W" denotes wide and "N" narrow row spacing

Plot	Simple averaging	Averaging with 3:1 weighting	Averaging with optimized weighting factors (value of wf for each depth)
03-d1-W	11.2	11.6	8.3 (5; 0.47; 5)
03-d1-N	25.1	17.5	17.8 (3.4; 1.3; –)
04-d1-W	41.5	29.9	36.9 (2.2; 3.4; −0.25)
04-d1-N	20.1	18.1	18.2 (2.97; 5; 9.99)
04-d2-W	27.7	19.9	17.8 (2.3; 7.5; 28)
04-d2-N	21.6	16.7	20.4 (1.8; 0.2; 5)

Table 3 Ratio of RLD in the row to RLD between rows (RLD-RR); in parentheses: bias (%) between estimates of RLD-RR based on auger core sampling and monolith data; the column labeled "mono" contains values of RLD-RR obtained from data of the whole sampled monolith; "S1"…"S4" denote the four sampled soil slices perpendicular to the plant rows separately, "S1-S4" denotes the mean of the four soil slices; in the acronyms for the plots, "03" and "04" denote the year of monolith sampling (2003 and 2004), "d1" and "d2" denote the successive sampling date of the year, and "W" denotes wide and "N" narrow row spacing

Plot	Depth (cm)	Mono	S1	S2	S3	S4	S1–S4
03-d1-W	0–10	1.45	1.01 (−30)	1.30 (−11)	0.81 (−44)	1.74 (20)	1.16 (−20)
	10–20	1.14	2.38 (110)	0.99 (−13)	1.26 (11)	0.83 (−27)	1.20 (6)
	20–30	1.01	0.87 (−13)	1.62 (61)	1.01 (0)	0.87 (−13)	1.07 (6)
03-d1-N	0–10	1.30	1.53 (18)	1.54 (18)	1.2 (−8)	2.4 (87)	1.67 (29)
	10–20	1.27	1.38 (9)	1.28 (1)	0.97 (−23)	1.6 (27)	1.3 (3)
04-d1-W	0–10	5.7	5.8 (1)	7.0 (22)	11.2 (94)	9.1 (58)	8.6 (50)
	10–20	3.3	2.2 (−34)	1.3 (−62)	6.2 (88)	3.2 (2)	2.6 (−22)
	20–30	0.9	0.8(−18)	0.6 (−37)	1.6 (77)	0.87 (−4)	0.9 (−1)
04-d1-N	0–10	1.93	2.00 (3)	2.9 (48)	2.03 (5)	1.1 (−45)	1.96 (1)
	10–20	0.95	0.67 (−29)	2.3 (143)	0.46 (−51)	1.43 (51)	1.05 (11)
	20–30	1.01	1.08 (7)	0.83 (−18)	0.71 (−29)	2.2 (117)	12 (16)
04-d2-W	0–10	1.95	1.3 (−32)	1.1 (−44)	2.1 (5)	4.2 (112)	1.9 (−1)
	10–20	1.43	2.03 (42)	2.08 (45)	0.8 (−43)	1.7 (18)	1.47 (3)
	20–30	1.67	1.8 (7)	1.6 (−4)	1.45 (−14)	1.54 (−8)	1.62 (−3)
04-d2-N	0–10	1.95	3.1 (56)	2.3 (16)	1.7 (−13)	5.95 (205)	3.1 (59)
	10–20	1.13	1.3 (14)	1.4 (27)	1.57 (39)	0.8 (−27)	1.26 (12)
	20–30	1.1	1.46 (32)	1.11 (1)	1.27 (15)	0.79 (−29)	1.11 (1)

Table 4 Proportions of RD classes in the whole sampled monoliths (columns labelled "Mono") and bias (%) between proportions of RD classes from total root length estimated by auger core samplings (S1–S4) and whole sampled monolith; second sampling 2004; "S1"…"S4" denote the four sampled soil slices perpendicular to the plant rows separately, "S1–S4" denotes the mean of the four soil slices

RD class (mm)	Wide row spacing (04-d2-W)						Narrow row spacing (04-d2-N)					
	Mono	S1	S2	S3	S4	S1–S4	Mono	S1	S2	S3	S4	S1–S4
0–10 cm depth												
>3	2.1	−100	−84	205	−9	3.0	3.3	40	−78	−57	−33	−32
1.3–3	0.4	407	−16	−100	−100	48	0.6	−50	−1.2	−0.1	72	5.2
0.35–1.3 c	29.7	62	−100	46	62	18	69.8	36	−30	−31	39	3.3
0.35–1.3 f	52.8	−100	88	−100	−5.3	−29	26.3	−100	90	90	−100	−5.0
<0.35	15.0	234	−100	234	−100	67	0.0	–	–	–	–	–
10–20 cm depth												
>3	1.6	−18	146	−100	98	31	0.1	−100	990	311	−100	275
1.3–3	1.8	−49	−25	85	−100	−22	4.7	35	−10	5.7	−32	−0.2
0.35–1.3 c	51.5	−7.3	84	−8.6	−9.2	15	23.5	−100	−100	103	−100	−49
0.35–1.3 f	45.1	11	−100	10	11	−17	66.8	40	42	−30	−26	6.8
<0.35	0.0	–	–	–	–	–	4.9	−100	−100	−100	−100	−100
20–30 cm depth												
>3	0.0	–	–	–	–	–	0.0	–	–	–	–	–
1.3–3	4.0	−46	−42	−24	−6.5	−29	3.7	8.5	−12	31	−22	1.4
0.35–1.3 c	79.0	24	24	−37	22	8.1	69.2	−31	40	38	−100	−13
0.35–1.3 f	17.0	−100	−100	177	−100	−31	27.1	77	−100	−100	258	34
<0.35	0.0	–	–	–	–	–	0.0	–	–	–	–	–

c coarse, *f* fine

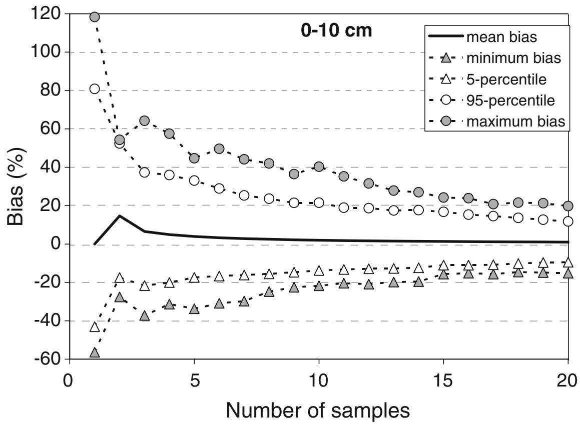

Fig. 3 Relation between bias of estimated total RLD of hypothetical auger samplings from RLD of the whole sampled monolith and number of core samples (for sampling 04-d2-W and 0–10 cm soil depth); *mean bias* is the mean of the bias values of all combinations (maximum 368 depending on number of samples) for the respective number of samples, whereas *5-percentile* and *95-percentile* delimit the range of bias values revealed by 90% of the combinations

different and erratic values between the separate slices when taking only two cores. In order to assess the potential magnitude of bias when taking more than two cores, bias values were calculated for several different random combinations of extracted soil cores (based on the sampling 04-d2-W), and increasing consecutively the number of cores, first for total RLD. Because the location of the extracted cores would be guided to a certain degree by the row structure of the crop, a totally free permutation regardless of location with every possible combination of positions within the soil monolith would not be realistic (cf. van Noordwijk et al. 1985). Therefore, for the case of two samples, it was assumed that one core was extracted within the row and one midway between the rows, whereas no restriction was imposed on the possible location parallel to the rows, resulting in 16 combinations. For the case of three samples, one core was extracted within the row, another midway between rows, and the third at a random location (cf. Ewel et al. 1982), excepting the within-row area and locations already sampled by the first two cores, resulting in 16×23=368 combinations. For all cases with more than three core samples, each additional core was chosen randomly, but avoiding duplication of locations where cores had already been extracted. For simplicity, the analysis was restricted to 350 random combinations for each number of core samples.

For 0–10 cm depth, the mean bias is always >0% and decreases with the number of samples (Fig. 3). This general overprediction is in line with bias values for defined sampling locations (Table 1). Since these mean bias values are based on multiple replications, upper and lower bounds of the calculated values may be important. When taking the five- and 95-percentile as practical indicators for the probability that 5% of the samplings are lower or higher than a certain bias, about ten samples would be necessary to attain a bias of the 95-percentile <20% for total RLD. The hypothetical random sampling procedure is applied similarly for estimating RLD proportions of separate RD classes. Again, for example for diameter class "0.35–1.3 mm fine" at 0–10 cm depth for sampling 04-d2-W (Fig. 4), the bias is found distinctly higher for any given number of samples as compared to estimation of total RLD (cf. Fig. 3). Since the smaller root diameter classes dominate the inter-row space, the bias for estimation of RD class "0.35–1.3 mm fine" (Fig. 4) is reflecting an underprediction for the case of using only two core samples. Based on only a few core samples, a representative assessment of the proportions of RD classes is hardly possible (Table 4), and even when extracting ten cores, the bias of the 95-percentile would still be 32% and for the five-percentile even −50%. For the other RD classes the bias is even higher (not shown here in detail).

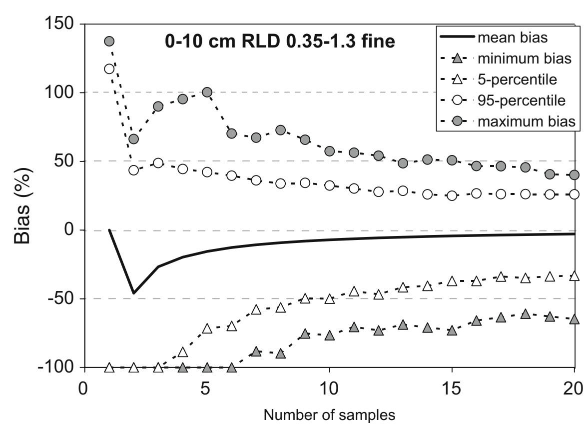

Fig. 4 Relation between bias of estimated RLD proportion of diameter class "0.35–1.3 mm fine" by hypothetical auger samplings from data of the whole sampled monolith and number of core samples (for sampling 04-d2-W and 0–10 cm soil depth); *mean bias* is the mean of the bias values of all combinations (maximum 368 depending on number of samples) for the respective number of samples, whereas *5-percentile* and *95-percentile* delimit the range of bias values revealed by 90% of the combinations

Discussion

Horizontally averaged RLD is overpredicted with a simple auger core sampling scheme consisting of only two cores, which is indicated by mostly positive bias values between $RLD_{av,c}$ and RLD_{mo} (Fig. 2). Such overprediction by simple averaging of samples collected from within and halfway between rows has been described analogously by van Noordwijk et al. (1985), albeit for other row crops (wheat, oat, rye) and RMD instead of RLD. These authors showed that bias is reduced by using a 1:3 weighting (within-row: between-row; i.e., wf=3 in Eq. 1) scheme when averaging RMD values of the two sampled positions. Van Noordwijk et al. (1985) further suggested calculating "ideal" weighting factors for cases where the detailed root distributions of row crops are known. Note that a zero bias as in van Noordwijk et al. (1985) was unattainable in our study due to the within-row variability (i.e., parallel to plant rows) of RLD; wf values were calculated such that the bias between RLD_{mo} and $RLD_{av,c}$, averaged for slices S1–S4, was minimized. The optimized wf values (Table 2) are strongly differing, and obviously no systematic trends are discernible with respect to date, row spacing, and soil depth among the wf values. These wf values would not be transferable from one sampling to another and it would be more practicable to use rather a 1:3 weighting scheme (wf=3) than to optimize *a posteriori* the weighting factors.

Estimates of 1D vertical RLD distributions are insufficient for more complex analyses (e.g., when using 2D vertical water flow and root uptake models with spatially distributed RLD), where horizontal variations of RLD are required. The estimation of the ratio of RLD in the plant row to RLD midway between rows by the auger core sampling scheme (Table 3)—as an approximation of the 2D vertical RLD distribution—revealed that albeit RLD-RR values are approximated only poorly by the assumed auger core sampling scheme in single slices when extracting only two samples (Table 3), in most cases the bias for the average of S1–S4 was sufficiently low to allow a reliable assessment of spatial variability of RLD. Consequently, an assessment of 2D RLD distribution by using an auger core sampling scheme with only two cores is at least as problematical as an assessment of mean RLD for each soil depth, whereas using eight soil cores yields in most cases somewhat reliable estimates (i.e., bias within ±20% of the reference dataset; cf. Fig. 1).

Estimates of horizontally averaged proportions of root diameter classes based on auger core samples and monolith data show (for the second sampling of 2004, 04-d2) that the root diameter distribution of the whole monolith is not well reflected by the auger core sampling scheme, both for wide and for narrow row spacing (Table 4). The distinctly higher bias when estimating RLD fractions pertaining to different RD classes from auger core sampling as compared to bulk RLD distribution may be explained by the more discontinuous occurrence and more pronounced spatial structure of different RD classes as compared to bulk RLD.

For total RLD, hypothetical random core samplings with increasing numbers of extracted samples indicated that about ten samples would be necessary to attain a bias of the 95-percentile <20%, whereas for estimation of RD classes, no reasonably low bias could be achieved with any number of cores. This suggest that for the assessment of RD classes in row crops, sampling of a complete soil monolith would be necessary.

The relatively large number of auger core samples necessary to obtain a representative estimate of the "true" mean RLD is in line with findings from previous studies: For instance, Schuurman and Goedewaagen (1971) suggested for cereals to take at least 24 cores, whereas according to Böhm (1979), at least five samples should be taken for each plot. Van Noordwijk et al. (1985) recommended taking at least ten auger core samples per plot, but they also found that this number increases with the variability of root distribution and could be higher when small differences between mean RLD values have to be discerned.

Conclusions

Data from a complete soil monolith sampling were used here as a reference data set for evaluating possible errors introduced by frequently reported auger coring for determination of RLD. When using only two auger core samples, one within the row and one midway between rows, total RLD was mostly overpredicted. Lower bias was attained by a 1:3 weighting of the two cores (i.e., giving more weight to the RLD from between the rows). However, due to variability of RLD parallel to the rows, no ideal weighting factors could be obtained by optimization for such a sampling scheme, and it seems appropriate to retain the 1:3 weighting scheme when estimating horizontally averaged RLD distributions of row crops.

Estimation of 2D vertical RLD distribution by calculating the ratio of RLD in the plant row to RLD midway between rows ($\mathrm{RLD\text{-}RR}=\mathrm{RLD}_{\mathrm{win}}/\mathrm{RLD}_{\mathrm{bet}}$) proved to be fraught with large errors when using only two cores per plot, but a lower bias could be attained when the average of eight cores was used. Consequently, we suggest that the 2D vertical RLD distribution of row crops can be approximated by the RLD-RR indicator when at least eight cores are used.

An assessment of the proportions of RD classes from total RLD yielded relatively high bias values, even when using the average of eight cores. Consequently, when taking samples for determination of root morphological parameters, more detailed and site-adapted sampling schemes are needed.

An analysis of sampling errors using successively more cores revealed that for total RLD, to attain a bias <20%, more than ten auger samples would be necessary. This suggest that the number of core samples taken in many studies (cf. literature review in the introduction) may limit the results. This problem seems even more serious when using core samples for estimating the proportions of RD classes. The results suggest that for studying RD class distributions, presumably a complete soil monolith should be sampled. When studying RMD instead of RLD distribution, results may be different and sampling schemes should be adapted. This analysis suggests also that root size classes and within-row variability should be accounted for when trying to reduce sampling effort, unless valid root growth models are available for predicting the space-time distribution of plant roots in soil.

References

Amato M, Ritchie JT (2002) Spatial distribution of roots and water uptake of Maize (*Zea mays* L.) as affected by soil structure. Crop Sci 42:773–780

Anderson EL (1987) Corn root growth and distribution as influenced by tillage and nitrogen fertilization. Agron J 79:544–549

Ball-Coelho BR, Roy RC, Swanton CJ (1998) Tillage alters corn root distribution in coarse-textured soil. Soil Tillage Res 45:237–249 doi:10.1016/S0167-1987(97)00086-X

Bengough AG, Castrignano A, Pages L, Van Noordwijk M (2000) Sampling strategies, scaling, statistics. In: Smit AL, Bengough AG, Engels C, Van Noordwijk M, Pellerin S, Van der Geijn SC (eds) Root methods, a handbook. Springer, Berlin, pp 147–173

Böhm W (1979) Methods of studying root systems. Ecological studies 33. Springer, Berlin, p 188

Chassot A, Stamp P, Richner W (2001) Root distribution and morphology of maize seedlings as affected by tillage and fertilizer placement. Plant Soil 231:123–135 doi:10.1023/A:1010335229111

Dwyer LM, Ma BL, Stewart DW, Hayhoe HN, Balchin D, Culley JLB et al (1996) Root mass distribution under conventional and conservation tillage. Can J Soil Sci 76:23–28

Ewel J, Gliessman S, Amador M, Benedict F, Berish C, Bermudez R et al (1982) Leaf area, light transmission, roots and leaf damage in nine tropical plant communities. Agro-ecosyst 7:305–326 doi:10.1016/0304-3746(82)90023-3

FAO (2006) World reference base for soil resources 2006. A framework for international classification, correlation and communication. World Soil Resources Report No. 103. 2006 edition, Rome.

Gajri PR, Arora VK, Kumar K (1994) A procedure for determining average root length density in row crops by single-site augering. Plant Soil 160:41–47 doi:10.1007/BF00150344

Gerke HH, Kuchenbuch RO (2007) Root effects on soil water and hydraulic properties. Biologia (Bratisl) 62(5):557–561 doi:10.2478/s11756-007-0110-8

Huang G, Zhao X-y, Su Y-g, Zhao H-l, Zhang T-h (2008) Vertical distribution, biomass, production and turnover of fine roots along a topographical gradient in a sandy shrubland. Plant Soil 308:201–212 doi:10.1007/s11104-008-9620-6

Kuchenbuch RO, Barber SA (1987) Yearly variation of root distribution with depth in relation to nutrient uptake and corn yield. Comm. Soil Sci Plant Anal 18:255–263

Kumar K, Prihar SS, Gajri PR (1993) Determination of root distribution of wheat by auger sampling. Plant Soil 143:245–253 doi:10.1007/BF00016615

Mengel DB, Barber SA (1974) Development and distribution of the corn root system under field conditions. Agron J 66:341–344

Oikeh SO, Kling JG, Horst WJ, Chude VO, Carsky RJ (1999) Growth and distribution of maize roots under nitrogen fertilization in plinthite soil. Field Crops Res 62:1–13 doi:10.1016/S0378-4290(98)00169-5

Pierret A, Moran CJ, Doussan C (2005) Conventional detection methodology is limiting our ability to understand the roles and functions of fine roots. New Phytol 166:967–980 doi:10.1111/j.1469-8137.2005.01389.x

Qin RJ, Stamp P, Richner W (2005) Impact of tillage and banded starter fertilizer on maize root growth in the top 25 centimeters of the soil. Agron J 97:674–683 doi:10.2134/agronj2004.0059

Schenk MK, Barber SA (1980) Potassium and phosphorus uptake by corn genotypes grown in the field as influenced by root characteristics. Plant Soil 54:65–76 doi:10.1007/BF02182000

Schuurman JJ, Goedewaagen MAJ (1971) Methods for the examination of root systems and roots. Pudoc, Wageningen, p 86

Sharratt BS, McWilliams DA (2005) Microclimatic and rooting characteristics of narrow-row versus conventional-row corn. Agron J 97:1129–1135 doi:10.2134/agronj2004.0292

Tennant D (1975) A test of a modified line intersect method of estimating root length. J Ecol 63:995–1001 doi:10.2307/2258617

van Noordwijk M, van de Geijn SC (1996) Root, shoot and soil parameters required for process-oriented models of crop growth limited by water or nutrients. Plant Soil 183:1–25 doi:10.1007/BF02185562

Van Noordwijk M, Floris J, de Jager A (1985) Sampling schemes for estimating root density distribution in cropped fields. Neth J Agric Sci 33:241–262

Wang EL, Smith CJ (2004) Modelling the growth and water uptake function of plant root systems: a review. Aust J Agric Res 55:501–523 doi:10.1071/AR03201

Wiesler F, Horst WJ (1994) Root growth of maize cultivars under field conditions as studied by the core and minirhizotron method and relationships to shoot growth. Z Pflanzenernahr Bodenk 157:351–358 doi:10.1002/jpln.19941570506

Zobel R (2003) Fine roots—discarding flawed assumptions. New Phytol 160:276–278 doi:10.1046/j.1469-8137.2003.00893.x