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REGULAR ARTICLE

Spatial distribution of maize roots by complete 3D soil monolith sampling

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Abstract The spatial distribution of root length density (RLD) is important for water and nutrient uptake by plants and biomass allocation in the soil. Experimental root assessment is, however, mostly based on methods that encompass only small fractions of the soil volume. The aim of this study was to characterize the three dimensional (3D) spatial distribution of RLD in the soil of a maize crop for plots of 37.5 and 75 cm row spacing. At each plot, a 3D soil monolith of 70×40×30 (=84,000) cm^3 was completely sampled in form of 84 cubic samples of 10 cm edge length. Roots were washed from the soil and RLD was determined using the line intersect method. In 2004, mean RLD values were 0.41 cm cm^{-3} for narrow and 0.34 cm cm^{-3} for wide row spacing at row closure (55 days after planting; DAP) and 0.74 cm cm^{-3} (1.37 cm cm^{-3} in 2003) for narrow and 0.77 cm cm^{-3} (0.96 cm cm^{-3} in 2003) for wide row spacing at tasseling (104 DAP). The CV values for RLD of 48% to 72% in 2004 were first higher for wide than for narrow row spacing but at the later growth stage (tasseling) lower for wide than for narrow. For individual vertical soil slices, CV values for RLD were about 40–60%, irrespective of the orientation of the slice. The results suggest that RLD was related mainly to the spatial location and the plant row structure, and not governed unambiguously by SBD or SWC. The spatially distributed maize root data suggest that variability of RLD parallel to plant rows is not negligible. Any simplified use of 1D or 2D vertical samples at separate locations may lead to erroneous estimations of RLD profiles.

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Keywords Corn · Line intersect method · Maize (*Zea mays* L.) · Root length density · Root mass · Row spacing · Soil bulk density · Soil volumetric sampling · Spatial variability

Abbreviations

CV	coefficient of variation (%)
DAP	days after planting
GDD	growing degree day (°C day)
RL	root length (cm)
RLD	root length density (cm cm^{-3} soil)
RFM	root fresh mass (g 1,000 cm^{-3} soil)
RM	root mass (g)
SBD	soil bulk density (g cm^{-3})
SRL	specific root length (cm g^{-1})
SWC	soil water content (cm^3 cm^{-3})

Introduction

The spatial distribution patterns of roots in soil have great impact on water and nutrient uptake by plants, and consequently also on plant growth and crop yields (e.g., Ehlers et al. 1991; Amato and Ritchie 2002; Doussan et al. 2006). Both root length density (RLD) and root mass density are pertinent parameters for characterizing root systems (Waisel and Eshel 2002). The spatial pattern of root systems, for instance of maize, may vary in a wide range depending on plant physiological parameters that determine root growth and architecture (Pagès et al. 2000), soil related parameters such as soil strength, soil bulk density (SBD), soil structure, soil water content, and soil temperature (e.g., Bengough and Mullins 1991; Kuchenbuch and Ingram 2004; Wang and Smith 2004; Kuchenbuch et al. 2006), external factors such as air temperature, precipitation and tillage (Kuchenbuch and Barber 1988; Kaspar et al. 1991; Chassot et al. 2001), and supply of nutrients (e.g., Jordan-Meille and Pellerin 2008). On the other hand, the root system affects soil hydraulic properties, for instance, with respect to soil structure or water content (e.g., Gerke and Kuchenbuch 2007; Pierret et al. 2007; Roulier et al. 2008).

Methods for characterizing the spatial distribution of root systems in soil (Böhm 1979) include root mapping (Pagès and Pellerin 1996), minirhizotron observations (Liedgens and Richner 2001), auger or core sampling (Chassot et al. 2001; Sharratt and McWilliams 2005), and soil monolith excavation (Buman et al. 1994; Gajri et al. 1994; Li et al. 2006). Most of the experimental studies considered 1D root distribution in vertical direction (i.e., soil depth) and 1D/2D in horizontal direction (i.e., perpendicular to plant rows), and soil water flow and crop growth models frequently assume simplified 1D vertical (e.g., Jones and Kiniry 1986; Jansson and Karlberg 2004) or 2D vertical RLD distributions (e.g., Heinen et al. 2003; Simunek et al. 1999).

However, if the distance between individual plants is relatively large, variability in the horizontal direction may be important not only in the perpendicular direction but also in that parallel to plant rows, such that root distribution shows an essentially 3D pattern (e.g., Van Noordwijk et al. 1985; Bengough et al. 2000). Several recent root growth models are based on 3D root system architecture (Pagès et al. 2000; Wang and Smith 2004; Wu et al. 2005), and some 3D soil water flow models contain a spatially distributed root water extraction term (e.g., Somma et al. 1998). On the other hand, experimental field data that could be used for testing such spatially distributed models are rarely available in 3D.

Previous monolith-type field samplings were restricted mostly to 2D vertical soil slices normal to the direction of plant rows (Buman et al. 1994; Gajri et al. 1994; Li et al. 2006). This restriction was mainly based on the prevailing simplifying assumption that variability parallel to the plant rows is negligible. However, a synthetic 3D sampling scheme based on a 3D architectural root growth simulation suggested that root growth patterns of maize show variability in all three spatial dimensions (Grabarnik et al. 1998).

Root distribution patterns of maize in 3D became an issue in recent years also in agronomy where narrower row spacing has been suggested to improve interception of light, uptake of nutrients, and utilization of soil water (e.g., Sharratt and McWilliams 2005). However, only few studies considered the effects of row spacing on root length (RL) and root mass (RM) distribution patterns. We are not aware of any complete 3D soil monolith investigation of the spatial distribution of RL and RM of maize.

The objective of this study is to characterize the 3D spatial distribution of RL and RM of maize for plots with different row spacing. The novelty is that the 3D data are obtained on a cubic volume basis from a complete soil monolith. The main questions are (1) how does variability of RL and RM depend on the direction with respect to plant rows, (2) what errors may be introduced when using lumped 1D or 2D vertical root distribution as compared to 3D, and (3) what is the impact of row spacing on root parameters and their spatial variability. It was not intended to compare row spacing effects on root systems in absolute terms but rather to analyze the intra-monolith spatial variability. For simplicity, a site with shallow groundwater with virtually all root growth in the upper cultivated 30 cm soil was selected.

Material and methods

Field site and experimental design

The field site Paulinenaue (52°41′ N; 12°42′ E) is located about 50 km west-north west of Berlin in the flat landscape called “Havelländisches Luch”. The soil is a Mollic Gleysol (FAO 2006) with predominantly sandy texture, originating from a degraded shallow fen lying on fluviatile sands. Organic carbon (C) contents in the cultivated topsoil (0–30 cm depth) amount to 21–22 g C kg^{-1} soil. Samples were taken once in 2003 and twice in 2004 from plots of 37.5 and 75 cm row spacing (Table 1). All plots were tilled in a conventional way with mouldboard ploughing in autumn. Fertilizer was applied at 140 kg N ha^{-1} as urea at the beginning of April, and 32 and 99 kg K ha^{-1} in March. In both years, silage maize (cv. Tassilo) was planted end of April (Table 1) with a density of 74,000 plants ha^{-1} irrespective of row spacing. The intra-row distance between plants was about 18 cm for wide and about 36 cm for narrow row spacing. Weather data (air temperature, wind speed, relative humidity, and global radiation) were recorded daily at a weather station in direct vicinity of the experimental plots. The first sampling date in 2004 was at the growth stage of ‘canopy closure’ of maize; the later samplings in 2003 and 2004 were at the time of ‘tasseling’ (Table 1). Growing degree days (GDD) were calculated based on daily median air temperatures, using a base temperature of 10°C (Kuchenbuch and Barber 1988).

Soil sampling

Samples were taken according to a three-dimensional (3D) spatially distributed monolith scheme (Böhm 1979), which is schematically depicted (Fig. 1) and illustrated by a photograph (Fig. 2). The soil monolith was 70 cm long (perpendicular to plant rows, *x*-direction), 40 cm wide (parallel to plant rows, *y*-direction) and 30 cm deep (*z*-direction). The soil volume of 0.084 m^3 in total was sampled completely in form of 84 cube-shaped 1000 cm^3 samples (Figs. 1 and 2) for each sampling time and row spacing.

Although maximum rooting depths of 150 cm have been described for maize at other sites in Germany (e.g., Wiesler and Horst 1994), here, in the sandy-peaty lowland soils at Paulinenaue with a controlled (neighbouring ditches) water table of about 60–70 cm below soil surface, root growth was restricted to the topsoil. Exploratory excavations revealed no roots in the white-bleached sand below 30 cm soil depth where signs of anoxic or hypoxic conditions indicated restricted root growth due to poor aeration. These exploratory excavations were carried out after a horizontal plane was cleaned at the bottom of the soil pit (30 cm depth). The soil underneath the plant rows and at more greyish spots with higher organic matter contents between the rows was excavated down to 40 cm depth using a spade and the soil was manually fractionised to look for roots. Not a single root was found for the early sampling date while for the later samplings, about three to five individual roots were found in the first 2 cm of the total subsoil area in the organic spots near the rows, which were not further considered here. Consequently, a sampling depth of 0–30 cm seemed to be sufficient to capture the major part of the root system at Paulinenaue. Similar studies conducted at other sites with deeper water tables reported that a major part of the root system of maize is found in 0–30 cm depth (e.g., Mengel and Barber 1974; Dwyer et al. 1996; Laboski et al. 1998; Chassot et al. 2001).

Prior to sampling, a trench was excavated perpendicular to the direction of the plant rows for documenting a soil profile and creating a starting point for the

Table 1 Field trials for the site Paulinenaue with sampling dates, row spacing, days after planting (DAP), cumulated growing degree days (GDD) and cumulated precipitation

Acronym	Planting date	Row spacing (cm)	Sampling date	DAP (days)	Cumulated GDD (°C days)	Cumulated precipitation (mm)
03-d1-W	23 April	75	10 July	78	574	74
03-d1-N	23 April	37.5	10 July	78	574	74
04-d1-W	28 April	75	22 June	55	256	67
04-d1-N	28 April	37.5	22 June	55	256	67
04-d2-W	28 April	75	10 August	104	656	214
04-d2-N	28 April	37.5	10 August	104	656	214

“03” and “04” refer to the year of the field trial (2003 and 2004), “d1” and “d2” refer to the number of the sampling date within the year (first and second), and “W” and “N” denote wide and narrow-row spacing, respectively

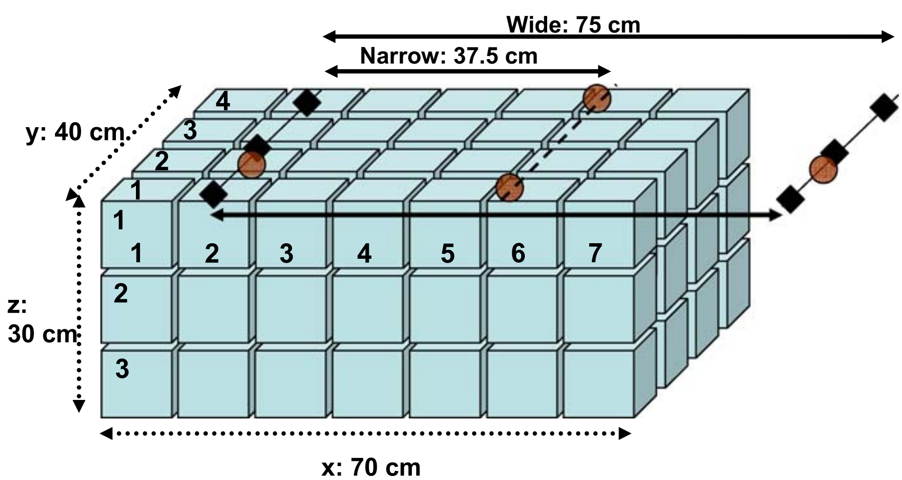

Fig. 1 Illustration of the 3D monolith sampling scheme. *Rhombic filled symbols* denote location of maize plants for wide row spacing; *circular symbols* denote the location of maize plants for narrow row spacing

monolith excavations. From the trench, separate cubic soil samples of 10 cm edge length (i.e., 1,000 cm^3) were obtained by gently pushing a metal frame horizontally into the soil (Fig. 2). The mass of the fresh soil samples was determined in the field, thus volume and mass distributions of both the soil and the root system were determined.

Laboratory methods

The soil water content (SWC) was determined from root-free sub-samples of approximately 50 g as the difference between field-moist and oven-dried (i.e., 105°C for 24 h) mass. Soil bulk density (SBD) was obtained from oven dry mass related to sample volume. After sub-sampling, the remaining soil was air-dried under ambient conditions in a greenhouse. Root measurements were carried out after washing out the roots from the soil. Before measurements, the total air-dried samples had been submerged in water for 24 h to re-hydrate the roots and to avoid root disruption. Washing was carried out manually using a nozzle and low water pressure on a stack of two sieves with mesh sizes of 1.0 and 0.4 mm. Special care was taken not to disrupt the original continuum of the roots. Photographical examples of the washed roots (Fig. 3) indicate that roots with diameters <0.4 mm were retained by the sieves. In fact, only few roots were visible on the 0.4 mm bottom sieve, and essentially 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. Similar results were reported, for instance, by Anderson (1988) who used a 1-mm screen to recover roots with diameters as small as 0.125 mm from the soil.

Fig. 2 Photograph of the monolith excavation from plot with wide row spacing

The elutriated roots were stored in 60% (volume-%) aqueous ethanol solution until 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 measured for size fractions representing significantly different root diameter classes as judged by eye. Root data are expressed as fresh instead of dry mass because the relative errors due to possibly adhering debris and soil particles are considered smaller for fresh as compared to dry mass.

Statistical analysis

One-way analysis of variance (ANOVA) was used to test for statistical significance of differences among

Fig. 3 Photograph of roots with different diameters after separation from the soil (illustrative example); ruler bar units are in cm

means of RLD, SBD and SWC, using the program SPSS (version 11.0.0). Comparisons between individual means were made using Fisher's least significant difference when the *F* value in the ANOVA was statistically significant. The null hypothesis of equal means was rejected at a probability of $p<0.05$.

Results

The total RL in the sampled soil volume of the first sampling in 2004 was higher for the plot with the narrow (04-d1-N) than for the plot with the wide (04-d1-W) row spacing (Table 2). For the second sampling of 2004 (04-d2), total RL was approximately equal (63,092 cm for wide vs. 62,321 cm for narrow row spacing) for both plots (note that the statistical significance of these differences could not be assessed since total RL values pertain to the sum of RL within the whole sampled soil volume for each plot). Compared with data from both sampling dates of 2004, total RL was higher in 2003 (especially for the narrow row spacing) and precipitation distinctly lower in 2003 (Table 1). Note that no samples at 20–30 cm soil depth could be obtained from the plot with the narrow row spacing (03-d1-N) in 2003 because the hard dry soil prevented undisturbed sampling.

For all three sampling dates, root and shoot dry mass per plant was higher for narrow than for wide row spacing plots; the differences between plots were larger for shoot than for root dry mass (Table 2). However, a quantitative analysis of row spacing effects on root and shoot parameters was not in the focus here, and the scope of statistical analyses based on data from three plants per monolith is restricted. The shoot dry mass values per plant were by 36% (03-d1), 70% (04-d1), and 20% (04-d2) larger for narrow than for wide row spacing. Thus, root/shoot ratios tended towards higher values for wide than for narrow, especially at the early growth stage in 2004.

Mean values of SBD were for a given depth interval and sampling date not significantly different except for the 10–20 cm depth in 2003 and the 20–30 cm depth at the first sampling in 2004 (Table 3). The soil of the selected plots was in general relatively homogeneous while the small differences in SBD are mainly reflecting soil moisture conditions and structural state of the soil at the particular sampling time. The SBD values were remarkably lower in 0–10 cm depth at tasseling in 2004 as those taken in 2003; the

Table 2 Root and shoot data and parameters related to the monolith

	03-d1-W	03-d1-N	04-d1-W	04-d1-N	04-d2-W	04-d2-N
Sum RL (cm)	80,233 (65,421[a])	76,643[a]	28,820	34,595	63,092	62,321
Sum RFM (g)	198 (164[a])	215[a]	73	87	215	244
Root dry mass (g) per plant	26.4	28.7	9.8	11.6	28.6	32.5
Sum shoot fresh mass (g)	2,340	1,900	243	348	1,777	2,099
Shoot dry mass (g) per plant	115.6	157.3	7.8	13.2	127.3	152.5
Root/shoot ratio	0.23	0.18	1.26	0.87	0.22	0.21

For the notation of the field trials see footnotes to Table 1.

RL root length, *RFM* root fresh mass

[a] Only for the 0–20 cm depth interval (20–30 cm depth of 03-d1-N was not sampled)

Table 3 Mean soil bulk density (SBD) values (g cm^{-3}) for each soil depth and plot; values in parentheses denote standard deviation; within each depth interval, values followed by the same superscript letter are not significantly different, whereas within each plot significance of differences in SBD between depth intervals was not analysed (for the notation of the field trials see footnotes to Table 1)

Soil depth (cm)	03-d1-W	03-d1-N	04-d1-W	04-d1-N	04-d2-W	04-d2-N
0–10	1.24^{ac} (0.09)	1.27^{c} (0.06)	1.20^{a} (0.11)	1.24^{ac} (0.09)	1.05^{b} (0.06)	1.08^{b} (0.08)
10–20	1.40^{a} (0.06)	1.47^{b} (0.06)	1.35^{c} (0.08)	1.33^{c} (0.05)	1.24^{d} (0.08)	1.24^{d} (0.07)
20–30	1.56^{a} (0.10)	–	1.40^{b} (0.08)	1.31^{c} (0.05)	1.24^{d} (0.08)	1.27^{d} (0.07)

latter were comparable with those of the first sampling in 2004. The spatial distribution of SBD suggests for 0–10 cm soil depth a relation to the distance perpendicular to the plant rows (Fig. 4), whereas below 10 cm soil depth, distinct differences in SBD between the intra- and the inter-row zones could not be found (not shown in detail). For the 0–10 cm depth, the intra-row SBD values (i.e., within the plant rows) were in general lower than SBD values in the inter-row zone, and consequently, significant positive correlations were found (for 03-d1-N, 04-d1-W, 04-d1-N, 04-d2-N) between SBD and distance to the plant row only for this depth. Correlations between SBD and RLD were not significant when the separate depth layers were considered (Fig. 5, shown exemplarily for the second sampling of 2004). Similar relationships were found between specific root length (SRL; i.e., the ratio of root length and root mass) and SBD (not shown here in detail). For all sampling dates, SWC was significantly higher for narrow than for wide

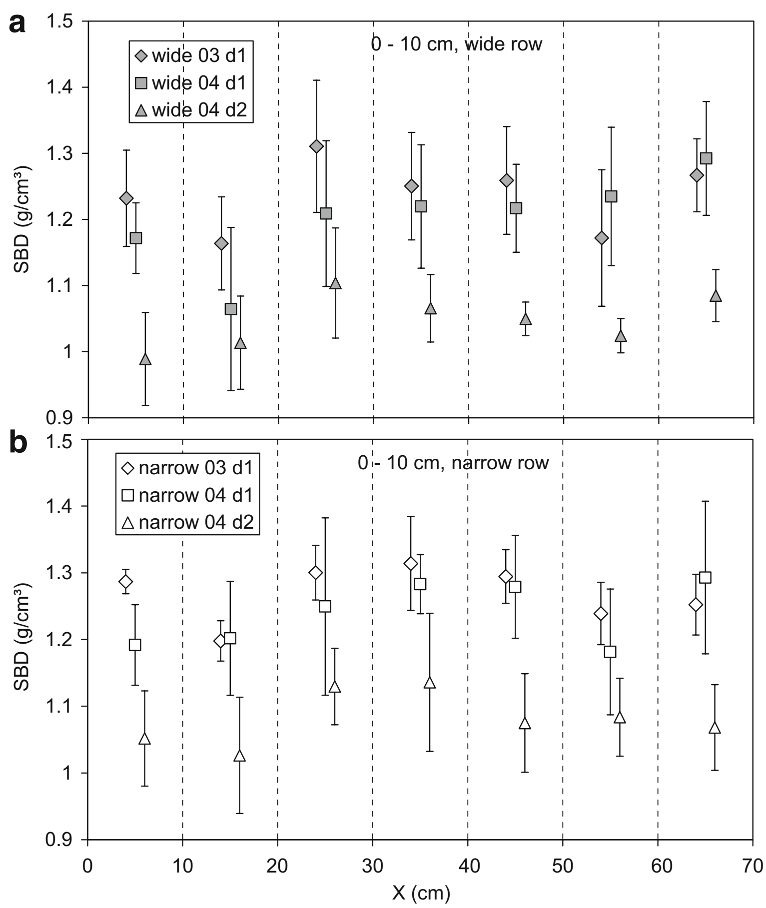

Fig. 4 Mean soil bulk density (*SBD*) perpendicular to plant rows (*X* direction) for 0–10 cm soil depth; **a** wide row spacing, **b** narrow row spacing. *Error bars* denote standard deviations (n=4). *Symbols* within a given *X* interval bounded by *vertical lines* pertain to the same monolith position in *X* direction and were shifted relative to each other only for better visibility

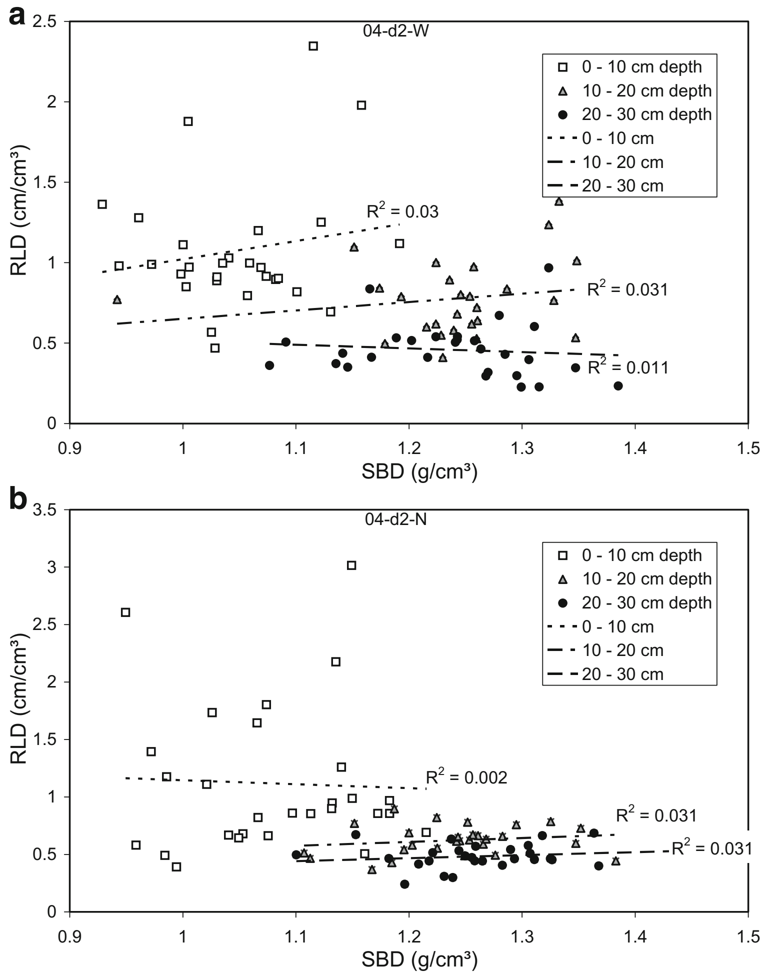

Fig. 5 Relation between soil bulk density (*SBD*) and root length density (*RLD*) for the second sampling of 2004 (04-d2); **a** wide row spacing, **b** narrow row spacing

row spacing in the 0–10 cm soil layer but not deeper in the profile (Table 4). The SWC was distinctly drier in 2003 than in 2004, especially below 10 cm soil depth. The variability of SWC (Table 4) in terms of CV values was less than 10%. The correlation between SWC and RLD was ambiguous: whereas for 03-d1-W, 03-d1-N and 04-d1-W, the overall correlation was negative, for 04-d1-N, 04-d2-W and 04-d2-N it was in general positive (not shown here in detail).

The spatial distributions of RLD and RFM of the 1,000 cm^3 samples within the soil monoliths are shown as cross sections perpendicular to the plant rows (Figs. 6, 7 and 8). The symbols for RLD represent mean values of four samples with the same *x*- and *z*-coordinates, but differing in location along the *y*-axis parallel to the plant rows (compare Fig. 1). In contrast, for RFM, median and minimum/maximum values are given for the *x*- and *z*-coordinates in

Table 4 Mean soil water content (SWC, $cm^3\ cm^{-3}$) for each soil depth and plot; values in parentheses denote standard deviation; values within a depth interval followed by the same superscript letter are not significantly different (for the notation of the field trials see footnotes to Table 1)

Soil depth (cm)	03-d1-W	03-d1-N	04-d1-W	04-d1-N	04-d2-W	04-d2-N
0–10	0.171^{a} (0.08)	0.234^{abcd} (0.184)	0.190^{a} (0.023)	0.219^{b} (0.025)	0.248^{c} (0.037)	0.267^{d} (0.027)
10–20	0.213^{a} (0.062)	0.164^{b} (0.109)	0.263^{c} (0.021)	0.269^{cd} (0.013)	0.288^{e} (0.026)	0.275^{d} (0.014)
20–30	0.120^{a} (0.028)		0.264^{b} (0.014)	0.258^{b} (0.015)	0.225^{c} (0.028)	0.227^{c} (0.014)

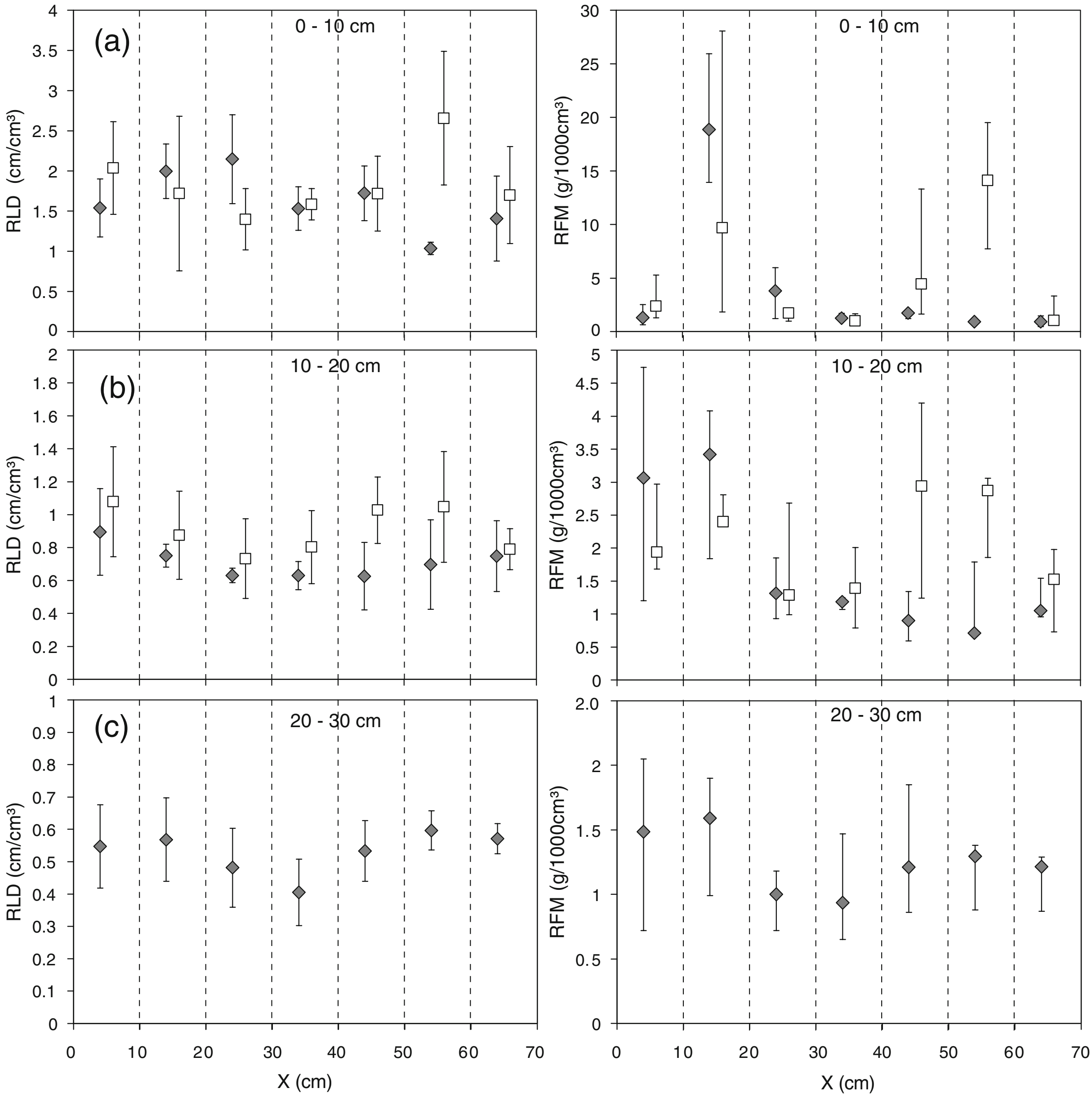

Fig. 6 Root length density (*RLD*; *left side*) and root fresh mass (*RFM*; *right side*) in **a** 0–10 cm, **b** 10–20 cm and **c** 20–30 cm soil depth, perpendicular to the plant rows (*X* direction). Sampling date 2003 (*03-d1*), wide (*filled rhombs*) and narrow (*hollow squares*) row spacing. *Error bars* denote standard deviation (n=4) for RLD and minimum/maximum values for RFM. *Symbols* within a given *X* interval bounded by *vertical lines* pertain to the same position in *X* direction and were shifted relative to each other only for better visibility

Figs. 6, 7, and 8, to account for the highly skewed and non-normal distribution of RFM values. Mean RLD data for separate 2D soil slices of different orientation are compiled in Tables 5, 6 and 7. The individual RLD, RFM and SBD data of all samples are given in the Appendix.

For plots of both row spacings, RLD and RFM values in 0–10 cm depth were in general highest in the rows and lowest between the plant rows (Figs. 6, 7 and 8). However, for RLD, small deviations from this pattern did occur: for instance, in the plot 03-d1-W, highest RLD values were found at the lateral

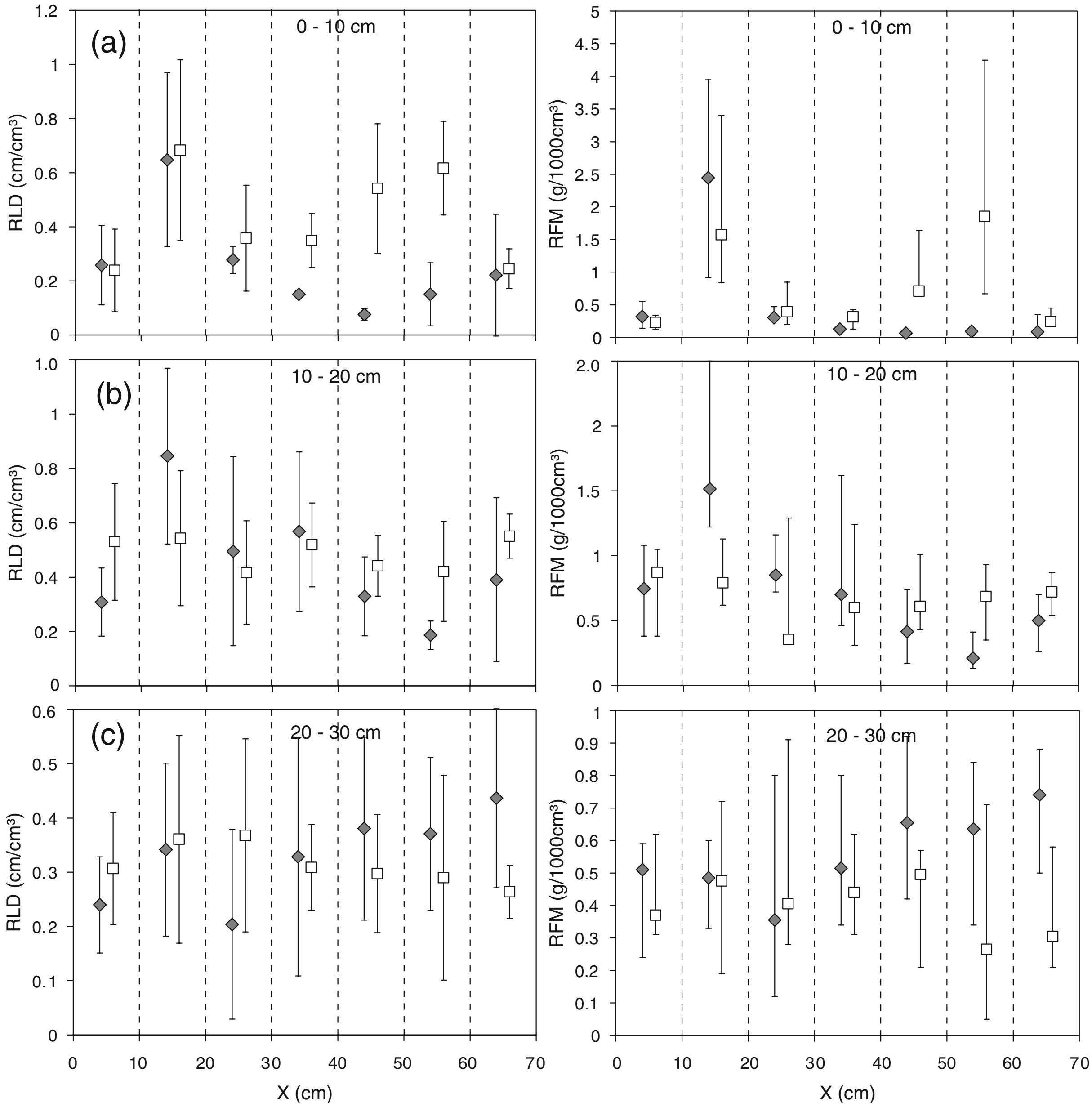

Fig. 7 Root length density (*RLD*; *left side*) and root fresh mass (*RFM*; *right side*) in **a** 0–10 cm, **b** 10–20 cm and **c** 20–30 cm soil depth perpendicular to the plant rows. Sampling date 04-d1, wide (*filled rhombs*) and narrow (*hollow squares*) row spacing. *Error bars* denote standard deviation (n=4) for RLD and minimum/maximum values for RFM. *Symbols* within a given X interval bounded by *vertical lines* pertain to the same position in X direction and were shifted relative to each other only for better visibility

position x=20–30 cm rather than at x=10–20 cm. On the other hand, RFM values exhibited large differences between intra- and inter-row positions, especially in 0–10 cm depth. For 20–30 cm depth, RLD and RFM values in the inter- and intra-row zones were largely equal. For some sampling positions, values in the inter-row zone were even larger than below the plant rows, for instance at the time of row closure in 2004 (04-d1). The most distinct dependence of RLD and RFM values on the distance to the plant row was observed for the samples taken at the second date in 2004 (tasseling, 04-d2; Fig. 8), with

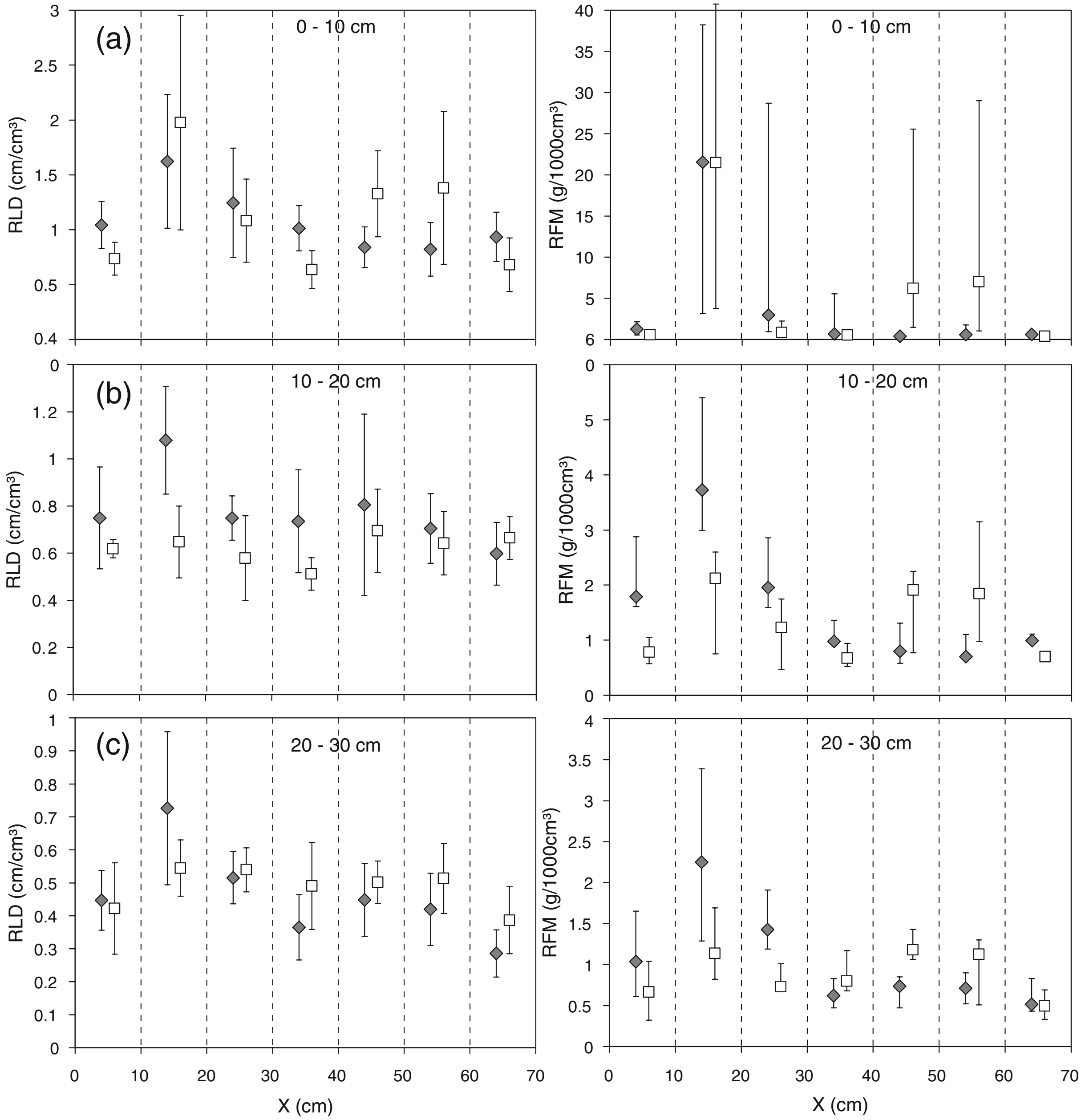

Fig. 8 Root length density (*RLD*; *left side*) and root fresh mass (*RFM*; *right side*) in **a** 0–10 cm, **b** 10–20 cm and **c** 20–30 cm soil depth perpendicular to the plant rows. Sampling date 04-d2, wide (*filled rhombs*) and narrow (*hollow squares*) row spacing. *Error bars* denote standard deviation (n=4) for RLD and minimum/maximum values for RFM. *Symbols* within a given X interval bounded by *vertical lines* pertain to the same position in X direction and were shifted relative to each other only for better visibility

highest values at x=10–20 cm. In line with this, correlation coefficients between RLD and distance to the plant rows were consistently significantly (p< 0.05) negative for 0–10 cm depth, whereas no significant correlations were found for soil depths below 10 cm (with the exception of 04-d2-W). On the other hand, the correlation of RFM and SRL with distance to the plant rows was better, but showed also a decrease with soil depth (not shown here in detail).

Table 5 Mean values and coefficient of variation (CV, %, in parentheses) of root length density (RLD) for vertical soil slices parallel to plant rows; mean values followed by the same index are not significantly different ($p<0.05$); compared are values among the different vertical soil slices within a plot (comparison of values within a column; for the notation of the field trials see footnotes to Table 1)

Slice (*x*-direction)	Plot					
	03-d1-W	03-d1-N	04-d1-W	04-d1-N	04-d2-W	04-d2-N
1	0.99^{a} (50)	1.56^{a} (43)	0.27^{a} (43)	0.36^{a} (55)	0.75^{b} (41)	0.59^{ab} (29)
2	1.11^{a} (62)	1.30^{a} (61)	0.61^{b} (54)	0.53^{a} (52)	1.14^{a} (46)	1.06^{ab} (81)
3	1.09^{a} (77)	1.07^{a} (43)	0.33^{a} (74)	0.38^{a} (45)	0.84^{ab} (50)	0.73^{ab} (46)
4	0.86^{a} (62)	1.19^{a} (39)	0.35^{a} (75)	0.39^{a} (36)	0.70^{b} (46)	0.55^{a} (25)
5	0.96^{a} (63)	1.37^{a} (36)	0.26^{a} (69)	0.43^{a} (43)	0.69^{b} (41)	0.84^{b} (51)
6	0.78^{a} (32)	1.85^{a} (56)	0.24^{a} (60)	0.44^{a} (49)	0.64^{b} (38)	0.85^{ab} (65)
7	0.91^{a} (53)	1.24^{a} (51)	0.35^{a} (67)	0.35^{a} (45)	0.61^{b} (51)	0.58^{ab} (35)
Mean CV	57	47	63	46	45	48

In accordance with these findings, vertically (0–30 cm) averaged RLD values, denoted as vertical slices (Table 5), are in general higher in the intra-row (i.e., slice 2 for wide and slices 2 and 6 for narrow row spacing) than in the inter-row zones. The CV values for the slices indicate a relatively large horizontal spatial variability of RLD and RFM. For the two spatial orientations parallel and perpendicular to the rows, mean CV values of RLD within the vertical slices are in a similar range (45–65%, Tables 5 and 6). For the horizontally (40×70 cm) averaged values (Table 7), RLD values generally decrease with soil depth except for the early development stage in 2004 (04-d1). Here, the values were largest in the 10–20 cm depth interval. This effect was most pronounced for the plot with wide row spacing (04-d1-W). The CV values of RLD of horizontal planes are highest in 0–10 cm and decrease with depth (Table 7). Compared to vertical slices, the range of CV values (i.e., 20–90%) is higher for horizontal planes.

Discussion

Root and shoot parameters

Although we did not intend to compare plant parameters of plots with wide and narrow row spacing in absolute terms, we notice particularly the difference in RL and shoot dry mass per plant for the first sampling date (Table 2; 04-d1). These data may reflect the effect of the distance between individual maize plants in relation to the size of the above-ground shoot and below-ground root system at the early growth stage. At later growth stages (03-d1, 04-d2), the degree of overlapping of shoot and root spheres of individual plants is presumably similar for wide and narrow rows (cf. Sharratt and McWilliams 2005). The stimulating effect of higher air temperatures on root growth is indicated by the sum of GDD (Table 1). The GDD may help explaining that root biomass values found in 2003 are so much larger than

Table 6 Mean values and coefficient of variation (CV, %, in parentheses) of root length density (RLD) for vertical soil slices perpendicular to plant rows; mean values followed by the same index are not significantly different ($p<0.05$); compared are values among the different vertical soil slices within a plot (comparison of values within a column) (for the notation of the field trials see footnotes to Table 1)

Slice (*y*-direction)	Plot					
	03-d1-W	03-d1-N	04-d1-W	04-d1-N	04-d2-W	04-d2-N
1	0.92^{a} (62)	1.54^{a} (45)	0.29^{a} (73)	0.35^{a} (45)	0.82^{a} (46)	0.84^{a} (67)
2	0.94^{a} (51)	1.34^{a} (42)	0.27^{a} (57)	0.42^{ab} (63)	0.71^{a} (42)	0.59^{a} (30)
3	0.91^{a} (62)	1.16^{a} (34)	0.28^{a} (73)	0.40^{ab} (38)	0.79^{a} (53)	0.76^{a} (61)
4	1.05^{a} (65)	1.42^{a} (68)	0.54^{b} (57)	0.48^{b} (38)	0.76^{a} (58)	0.78^{a} (72)
Mean CV	60	47	65	46	50	57

Table 7 Mean values and coefficient of variation (CV, %, in parentheses) of RLD (root length density) for horizontal planes for different sampling depths; mean values followed by the same index are not significantly different ($p<0.05$); compared are values among plots (comparison of values within a line; for the notation of the field trials see footnotes to Table 1)

Depth	Plot					
	03-d1-W	03-d1-N	04-d1-W	04-d1-N	04-d2-W	04-d2-N
0–10 cm	1.63^{a} (30)	1.83^{a} (37)	0.25^{b} (90)	0.43^{c} (56)	1.07^{d} (38)	1.12^{d} (58)
10–20 cm	0.71^{a} (27)	0.91^{b} (29)	0.45^{c} (67)	0.49^{c} (34)	0.78^{a} (30)	0.62^{d} (21)
20–30 cm	0.53^{a} (21)	–	0.33^{b} (50)	0.31^{b} (41)	0.46^{a} (37)	0.49^{a} (22)
Mean CV	26	33	69	44	35	33
Soil monolith	0.96^{a} (60)	1.37^{b} (50)	0.34^{c} (72)	0.41^{d} (48)	0.77^{e} (50)	0.74^{e} (63)

those in 2004 although explanations that are based only on temperature are insufficient (Kuchenbuch and Barber 1988). The values for root dry mass per plant correspond largely with those reported elsewhere (see review in Amos and Walters 2006), although the conditions at the Paulinenaue site differ slightly from other, more typical maize growing areas (high groundwater table, soil type influenced by groundwater, relatively cool climate). The correspondence corroborates the assertion that the root system was captured, although sampling was restricted here to the topsoil. The temporally decreasing root/shoot ratios (Table 2) indicate a preferential partitioning of photosynthetic products towards the root during the early stages of maize development (Amos and Walters 2006). The root/shoot ratios approach final values at tasseling of about 0.2 that are relatively similar for all plots and comparable with those reported elsewhere (Amos and Walters 2006).

Root mass and length distribution

Relatively high concentrations of root mass (i.e., RFM) can be found in soil regions where maize plants develop adventitious and nodal roots, as in the topsoil and in the intra-rows. The different distributions for the RLD, for which relatively high values were observed in the inter-row zone, may be explained by relatively smaller diameters of the roots in the outer spheres and by overlapping of roots from neighbouring plants (e.g., Kovar et al. 1992; Gajri et al. 1994). Compared with RLD, the RFM seems to vary more strongly parallel to the plant rows, especially in the 0–10 cm layer. Note that the error bars (Figs. 6, 7 and 8) denote maximal and minimal values for RFM but standard deviation for RLD. Below 20 cm soil depth, both RLD and RFM values are largely independent of plant row position. Accordingly, correlation coefficients of RLD and RFM vs. distance to the rows were not significant for 20–30 cm depth.

The spatial patterns of SBD (Figs. 4), RLD and RFM (Figs. 6, 7 and 8) suggest a negative correlation between SBD and root parameters, especially in 0–10 cm depth, since SBD is lower at intra- and higher at inter-row positions, whereas RLD and RFM values show an opposite trend. However, significant ($p<0.05$) negative correlation coefficients between RLD or RFM and SBD were observed only when data for all soil depths were pooled (for 03-d1 and 04-d2, and negative but not statistically significant for 04-d1; not shown here in detail). When separate depth layers were considered, no significant correlations were found (Fig. 5). Presumably, the clear negative correlation between SBD and RLD when all soil depth are pooled is enhanced by the distinct decrease of RLD and increase of SBD with soil depth. These depth trends are much more distinct than the relation of both RLD (Figs. 6, 7 and 8) and SBD (Fig. 4) with horizontal distance to the plant rows.

The analogous negative correlations between SRL and SBD imply that the root diameter in general increases with increasing SBD, which has been described in several previous studies (e.g. Kuchenbuch and Ingram 2004).

Spatial variability of RLD

The RLD maxima in vertical distributions as observed here (for 04-d1) in the second soil layer were also described before (e.g., Barber 1971; Chassot et al. 2001; Sharratt and McWilliams 2005). More intense rooting patterns in deeper layers may be explained by the timing of fertilization (Chassot et al. 2001), by the temporal pattern of precipitation (Sharratt and

McWilliams 2005), or by drying of the surface soil layer. The relatively low mean RLD in the uppermost layer (0–10 cm) of the early sampling in 2004 seems to correspond with low SWC in this layer (Table 4), although the spatial distributions of RLD and SWC are completely different, and no clear correlations between both have been found. Although SWC is here expressed without the contribution of water contained in the roots, in a more general sense, the SWC can mostly not be sampled for water in soil pores and roots independently. If the SWC includes both water in soil pores and water in roots, soil drying mostly reduces the fraction of water in soil pores, such that in sandy soils and intensively rooted regions, a significant fraction of SWC consists of water in roots (Gerke and Kuchenbuch 2007). Thus, SWC values cannot be independently used for interpretation of spatial RLD distributions.

For the early stage (04-d1), overall spatial variability of RLD is relatively large, and larger for the wide than for narrow row spacing. At the later growth stage, RLD variability is smaller for wide as compared to narrow row spacing (Tables 5, 6 and 7).

The similar CV values for RLD within vertical soil slices of different spatial orientation (parallel and perpendicular to the rows, Tables 5 and 6) suggest that variability of RLD is important both perpendicularly to the plant rows, but also parallel to the plant rows.

For horizontal slices, the decrease in CV values of RLD with depth (Table 7) suggests a greater structural soil heterogeneity close to the soil surface, whereas at greater depth, the “fan”-like shape and overlapping of the root systems between neighbouring plants cause a more continuous distribution of roots. Since effects of a greater soil structural heterogeneity close to the soil surface (Bengough et al. 2000) can largely be neglected here, merely the gradually increasing overlapping of the individual root systems with depth can be used to explain the decreasing spatial variability of RLD with depth as observed in some studies (e.g., Yu et al. 2007), whereas others do not report such trend (e.g., Gajri et al. 1994). The relatively high CV values of RLD within horizontal layers indicate that assuming simplified 1D distribution would be fraught with errors. The estimation error would be highest for RLD values of the uppermost soil layer.

For the more complex 2D vertical distributions of RLD perpendicular to the rows, the potential error induced by spatial variability parallel to the rows can be estimated from the variability in the direction parallel to the plant rows (Figs. 6, 7 and 8). Our results suggest that RLD data obtained from a single 2D vertical soil slice (e.g., Li et al. 2006) incur a relatively large uncertainty. For simulations of root water extraction with 2D vertical model approaches, this uncertainty in root parameters for a given position in the x–z plane should be accounted for. Also, when sampling soil for RLD determination, the focus should not be only on the variation in RLD perpendicular to the rows as it is commonly the case for both auger sampling (Gajri et al. 1994) and monolith sampling schemes (Li et al. 2006), but also on the variation in RLD parallel to plant rows (intra-row variability).

Conclusions

In this study, the 3D spatial variability of root length (RL) and root mass (RM) distribution of maize in 2 years and at two growth stages for wide and narrow row spacing was characterized. The experimental data are based on a complete volumetric soil monolith sampling (0–30 cm depth) of 84 soil samples of 1,000 cm^3 each. The roots of 504 soil samples were washed out from a total sampled soil volume of 0.504 m^3. The results suggest that the 3D spatial variability of the maize roots systems for the growth stages ‘row closure’ and ‘tasseling’ corresponds with absolute plot-related values of root mass and root-to-shoot ratios. The root to shoot mass ratios confirm a decreasing difference in assimilate partitioning for wide compared with narrow row spacing with increasing DAP. The results suggest a clear trend of decreasing horizontally averaged RLD values with depth at maize tasseling that corresponds with standard lumped root density distribution models. However, data obtained at the (earlier) stage of maize canopy closure indicate other patterns of root spatial variability that cannot be lumped in a standard 1D vertical approach. Data of RLD within 2D soil slices suggest that root spatial variation parallel to plant rows is not negligible and needs attention, in particular for experiments with larger intra-row distances between individual plants. Any simplified use of 1D or 2D vertical samples at separate locations may lead to erroneous estimations of RLD profiles. The data obtained in this study may be utilized for testing and further development of 3D root growth models based on root architecture (as cited in

"Introduction"). Further analyses of RL and RM ratios and the spatial distribution of different root diameter classes could help to better interpret the impact of the observed root distributions on the spatial pattern of water and nutrient uptake, which, however, was beyond the scope of this paper.

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Appendix

Table 8 RLD, RFM, SBD, individual data of the total soil monolith; sampling at tasseling in 2003 (03-d1; n.d., not determined; n.a., not available; m.v., missing value)

03-d1			Wide							Narrow						
	Depth (Z)	Row (Y)	*X*-position							*X*-position						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7
RLD (cm/cm^3)	0–10	1	1.04	1.83	2.44	1.18	1.80	1.12	1.73	2.85	0.99	1.20	1.77	1.77	2.70	2.56
		2	1.89	1.92	1.38	1.70	1.48	1.01	1.24	1.50	1.18	1.97	1.72	2.00	2.65	1.22
		3	1.55	1.75	2.12	1.47	2.17	0.94	0.74	1.95	1.60	1.17	1.35	1.04	1.62	1.35
		4	1.68	2.49	2.64	1.78	1.44	1.07	1.92	1.84	3.11	1.26	1.50	2.05	3.65	1.66
	10–20	1	0.80	0.83	0.67	0.60	0.35	0.54	0.54	1.48	0.80	1.05	1.04	1.16	1.43	0.81
		2	0.59	0.76	0.67	0.75	0.76	0.87	0.86	1.21	0.82	0.55	0.94	0.88	1.20	0.96
		3	1.00	0.75	0.59	0.63	0.59	0.40	0.99	0.90	1.25	0.80	0.69	1.24	0.67	0.67
		4	1.20	0.66	0.60	0.55	0.80	0.98	0.60	0.72	0.62	0.54	0.55	0.83	0.89	0.72
	20–30	1	0.71	0.58	0.59	0.29	0.67	0.55	0.57	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		2	0.39	0.74	0.58	0.45	0.45	0.61	0.55	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		3	0.53	0.52	0.37	0.36	0.52	0.55	0.64	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		4	0.56	0.43	0.38	0.53	0.49	0.68	0.53	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
RFM (g/1,000 cm^3)	0–10	1	0.63	17.5	5.09	1.03	2.02	1.07	1.17	3.40	14.4	1.86	1.09	6.94	19.5	3.32
		2	1.51	25.9	1.20	1.71	1.47	0.86	0.67	1.28	1.82	1.61	1.66	1.64	9.2	0.98
		3	1.10	13.9	2.49	1.10	1.99	0.91	0.47	1.36	5.02	0.97	0.73	1.96	7.73	0.96
		4	2.52	20.2	5.96	1.44	1.22	0.95	1.47	5.27	28.1	2.20	0.89	13.3	19.0	1.13
	10–20	1	2.59	3.67	1.41	1.19	0.59	0.71	0.96	2.97	2.45	2.68	1.55	4.20	3.06	1.98
		2	1.20	1.84	1.22	1.25	0.99	1.79	1.09	1.68	2.34	0.99	2.01	1.24	1.86	1.93
		3	4.74	3.17	0.93	1.18	0.81	0.68	1.54	1.80	2.81	1.39	1.23	1.84	2.88	0.73
		4	3.54	4.08	1.85	1.07	1.34	m.v.	1.01	2.08	2.35	1.18	0.79	4.04	2.86	1.12
	20–30	1	1.64	0.99	1.18	0.65	1.85	0.88	1.29	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		2	0.72	1.34	1.17	0.89	0.86	1.26	1.17	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		3	1.33	1.84	0.72	0.98	1.02	1.38	0.87	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		4	2.05	1.90	0.83	1.47	1.40	1.33	1.26	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
SBD (g/cm^3)	0–10	1	1.32	1.23	1.38	1.34	1.28	1.15	1.21	1.27	1.17	1.27	1.40	1.34	1.23	1.31
		2	1.26	m.v.	1.41	1.29	1.36	1.24	1.31	1.28	1.17	1.29	1.33	1.27	1.25	1.24
		3	1.18	1.18	1.22	1.17	1.24	1.26	1.28	1.31	1.23	1.28	1.23	1.31	1.29	1.27
		4	1.17	1.09	1.23	1.19	1.16	1.04	m.v.	m.v.	1.21	1.36	1.29	1.26	1.18	1.20
	10–20	1	1.50	1.43	1.45	1.45	1.42	1.31	1.44	1.62	1.54	1.52	1.47	1.54	1.42	1.40
		2	1.44	1.32	1.36	1.39	1.43	1.42	1.44	1.53	m.v.	1.39	1.43	1.48	1.39	1.42
		3	1.43	1.34	1.40	1.47	1.42	1.41	1.39	1.46	1.44	1.47	1.50	1.46	1.50	1.34
		4	1.52	1.31	1.36	1.38	1.39	1.40	1.25	1.46	n.d.	n.d.	n.d.	1.47	1.49	n.d.
	20–30	1	1.55	1.49	1.49	1.50	1.52	1.52	1.72	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		2	1.57	1.49	1.50	1.49	1.65	1.59	1.65	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		3	1.88	1.68	1.46	1.42	1.45	1.51	1.62	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		4	1.45	1.47	1.61	1.53	1.64	1.59	1.67	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

Table 9 RLD, RFM, SBD, individual data of the total soil monolith; first sampling in 2004 (04-d1)

04-d1			Wide row							Narrow row						
	Depth (Z)	Row (Y)	*X*-position							*X*-position						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7
RLD (cm/cm^3)	0–10	1	0.10	0.37	0.28	0.14	0.06	0.09	0.16	0.12	0.48	0.13	0.24	0.20	0.53	0.21
		2	0.44	0.37	0.21	0.15	0.05	0.04	0.04	0.24	1.18	0.51	0.41	0.65	0.44	0.16
		3	0.29	0.94	0.28	0.16	0.08	0.16	0.13	0.45	0.59	0.53	0.29	0.56	0.64	0.29
		4	0.20	0.91	0.34	0.15	0.10	0.31	0.55	0.15	0.48	0.26	0.45	0.75	0.85	0.32
	10–20	1	0.22	0.97	0.36	0.66	0.45	0.25	0.22	0.60	0.39	0.35	0.58	0.44	0.31	0.64
		2	0.32	0.47	0.38	0.32	0.37	0.12	0.16	0.65	0.88	0.25	0.38	0.57	0.55	0.60
		3	0.21	0.73	0.23	0.34	0.12	0.18	0.34	0.21	0.33	0.38	0.71	0.45	0.22	0.51
		4	0.48	1.22	1.01	0.94	0.38	0.19	0.83	0.66	0.57	0.69	0.40	0.30	0.60	0.46
	20–30	1	0.18	0.26	0.12	0.15	0.35	0.28	0.36	0.43	0.32	0.20	0.30	0.38	0.17	0.31
		2	0.34	0.18	0.13	0.17	0.31	0.49	0.54	0.22	0.19	0.23	0.23	0.15	0.15	0.25
		3	0.15	0.38	0.10	0.37	0.24	0.22	0.25	0.23	0.30	0.49	0.42	0.28	0.28	0.20
		4	0.29	0.54	0.47	0.62	0.62	0.49	0.61	0.34	0.64	0.55	0.29	0.38	0.56	0.30
RFM	0–10	1	0.14	2.34	0.27	0.12	0.07	0.10	0.35	0.15	1.23	0.26	0.13	0.70	2.75	0.22
($g/1,000\ cm^3$)		2	0.23	0.92	0.29	0.16	0.05	0.03	0.05	0.31	3.40	0.53	0.33	0.72	0.67	0.18
		3	0.55	2.55	0.47	0.14	0.10	0.10	0.08	0.34	0.84	0.85	0.30	0.68	0.96	0.26
		4	0.41	3.95	0.32	0.07	0.06	0.09	0.09	0.13	1.92	0.20	0.43	1.64	4.25	0.45
	10–20	1	0.64	1.74	0.76	1.62	0.74	0.41	0.26	0.82	0.75	0.36	0.72	1.01	0.63	0.75
		2	1.08	1.22	0.94	0.71	0.58	0.27	0.35	1.05	1.13	0.32	0.31	0.62	0.93	0.69
		3	0.38	2.50	0.72	0.46	0.25	0.15	0.65	0.38	0.62	0.35	1.24	0.60	0.35	0.87
		4	0.85	1.29	1.16	0.69	0.17	0.13	0.70	0.92	0.83	1.29	0.48	0.43	0.74	0.54
	20–30	1	0.46	0.60	0.15	0.34	0.54	0.75	0.62	0.62	0.23	0.28	0.38	0.43	0.05	0.30
		2	0.59	0.33	0.56	0.40	0.77	0.84	0.88	0.39	0.19	0.40	0.50	0.56	0.21	0.31
		3	0.24	0.53	0.12	0.63	0.92	0.52	0.50	0.31	0.72	0.41	0.62	0.21	0.32	0.21
		4	0.56	0.44	0.80	0.80	0.42	0.34	0.86	0.35	0.72	0.91	0.31	0.57	0.71	0.58
SBD (g/cm^3)	0–10	1	1.10	0.88	1.07	1.13	1.14	1.10	1.18	1.27	1.30	1.35	1.26	1.23	1.07	1.21
		2	1.16	1.12	1.32	1.31	1.28	1.35	1.38	1.16	1.13	1.15	1.25	1.19	1.20	1.24
		3	1.22	1.13	1.27	1.28	1.26	1.26	1.33	1.20	1.25	1.37	1.35	1.35	1.16	1.26
		4	1.21	1.13	1.17	1.15	1.19	1.23	1.28	1.13	1.13	1.12	1.27	1.34	1.30	1.46
	10–20	1	1.48	1.44	1.35	1.48	1.40	1.49	1.51	1.42	1.34	1.39	1.42	1.36	1.33	1.30
		2	1.40	1.35	1.35	1.36	1.38	1.37	1.28	1.31	1.24	1.29	1.28	1.27	1.36	1.26
		3	1.37	1.38	1.36	1.31	1.28	1.30	1.29	1.33	1.39	1.31	1.36	1.32	1.38	1.38
		4	1.28	1.27	1.26	1.27	1.25	1.22	1.23	1.32	1.35	1.41	1.36	1.21	1.32	1.32
	20–30	1	1.47	1.42	1.39	1.42	1.51	1.44	1.48	1.27	1.33	1.32	1.29	1.32	1.31	1.34
		2	1.38	1.41	1.36	1.36	1.38	1.47	1.43	1.39	1.31	1.33	1.30	1.27	1.25	1.20
		3	1.38	1.40	1.50	1.52	1.46	1.46	1.46	1.27	1.34	1.31	1.40	1.31	1.28	1.22
		4	1.28	1.38	1.29	1.20	1.26	1.31	1.31	1.33	1.35	1.33	1.33	1.40	1.34	1.30

Table 10 RLD, RFM, SBD, individual data of the total soil monolith; second sampling in 2004 (04-d2)

04-d2			Wide row							Narrow row						
	Depth (*Z*)	Row (*Y*)	*X*-position							*X*-position						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7
RLD (cm/cm^3)	0–10	1	0.90	1.28	1.98	0.90	0.97	1.00	0.82	0.58	2.61	1.64	0.86	1.39	1.73	0.39
		2	0.98	0.99	0.89	1.11	0.91	0.85	1.20	0.64	1.11	0.86	0.49	0.86	0.67	0.68
		3	0.93	1.88	1.12	1.25	0.91	0.97	1.03	0.82	1.18	0.86	0.69	1.80	2.18	0.66
		4	1.36	2.35	1.00	0.80	0.57	0.47	0.69	0.90	3.02	0.97	0.51	1.26	0.95	0.99
	10–20	1	0.55	1.38	0.77	0.60	0.68	0.79	0.62	0.67	0.76	0.79	0.59	0.73	0.62	0.66
		2	0.58	1.10	0.62	0.53	m.v.	m.v.	0.41	0.63	0.62	0.51	0.43	0.47	0.49	0.66
		3	0.89	1.00	0.77	1.01	1.24	0.53	0.64	0.58	0.77	0.65	0.49	0.69	0.82	0.56
		4	0.98	0.84	0.84	0.80	0.50	0.79	0.72	0.60	0.44	0.37	0.54	0.90	0.63	0.78
	20–30	1	0.54	0.97	0.60	0.46	0.54	0.52	0.32	0.31	0.66	0.63	0.46	0.58	0.44	0.46
		2	0.35	0.84	0.53	0.41	0.52	0.36	0.23	0.57	0.46	0.50	0.42	0.44	0.47	0.44
		3	0.40	0.43	0.51	0.23	0.30	0.30	0.23	0.30	0.52	0.49	0.41	0.53	0.67	0.24
		4	0.50	0.67	0.41	0.35	0.44	0.51	0.37	0.51	0.54	0.54	0.69	0.45	0.46	0.40
RFM ($g/1,000\ cm^3$)	0–10	1	0.56	3.15	28.7	5.54	0.34	0.54	0.89	0.68	40.8	2.23	1.23	7.70	12.1	0.39
		2	2.16	8.62	0.95	0.62	0.42	0.65	0.57	0.48	3.76	0.63	0.42	1.48	1.04	0.42
		3	0.58	34.5	3.79	0.74	0.49	1.79	0.67	0.51	5.43	0.71	0.69	25.6	29.0	0.32
		4	1.96	38.2	2.18	0.40	0.39	0.26	0.39	1.16	37.5	0.99	0.41	4.75	1.96	0.63
	10–20	1	1.81	3.78	1.77	0.94	0.80	1.10	0.93	0.86	2.58	1.75	0.94	1.93	2.37	0.72
		2	1.61	5.40	2.14	0.90	m.v.	m.v.	m.v.	0.57	1.66	0.47	0.52	0.77	0.98	0.68
		3	2.88	2.99	2.86	1.36	1.31	0.68	0.99	0.71	2.60	1.27	0.81	2.25	3.15	0.64
		4	1.77	3.67	1.59	1.02	0.58	0.70	1.11	1.05	0.75	1.19	0.54	1.89	1.32	0.78
	20–30	1	0.61	3.39	1.42	0.65	0.74	0.82	0.47	0.32	1.69	1.01	0.90	1.06	1.13	0.52
		2	0.65	2.74	1.43	0.59	0.73	0.52	0.56	0.83	0.85	0.73	0.68	1.12	1.12	0.69
		3	1.42	1.29	1.91	0.47	0.47	0.60	0.43	0.50	1.42	0.73	0.70	1.24	1.30	0.33
		4	1.65	1.76	1.19	0.83	0.85	0.90	0.83	1.04	0.82	0.67	1.17	1.43	0.51	0.47
SBD (g/cm^3)	0–10	1	1.08	0.96	1.16	1.08	1.07	1.06	1.10	0.96	0.95	1.07	1.18	0.97	1.03	0.99
		2	0.94	0.97	1.03	1.00	1.03	1.00	1.07	1.05	1.02	1.10	0.98	1.11	1.04	1.05
		3	1.00	1.00	1.19	1.12	1.07	1.01	1.04	1.07	0.99	1.17	1.22	1.07	1.14	1.08
		4	0.93	1.12	1.04	1.06	1.03	1.03	1.13	1.13	1.15	1.18	1.16	1.14	1.13	1.15
	10–20	1	1.23	1.33	0.94	1.22	1.24	1.25	1.22	1.26	1.29	1.33	1.27	1.35	1.24	1.26
		2	1.24	1.15	1.26	1.26	1.20	1.24	1.23	1.25	1.24	1.11	1.18	1.11	1.28	1.28
		3	1.24	1.22	1.33	1.35	1.32	1.35	1.26	1.20	1.15	1.24	1.25	1.20	1.22	1.23
		4	1.26	1.29	1.17	1.25	1.18	1.19	1.26	1.35	1.38	1.17	1.20	1.19	1.27	1.25
	20–30	1	1.24	1.32	1.31	1.26	1.22	1.20	1.27	1.23	1.32	1.24	1.31	1.31	1.26	1.18
		2	1.35	1.17	1.19	1.17	1.24	1.08	1.30	1.26	1.29	1.10	1.21	1.22	1.26	1.26
		3	1.31	1.28	1.26	1.39	1.30	1.27	1.32	1.24	1.22	1.25	1.28	1.24	1.15	1.20
		4	1.24	1.28	1.22	1.15	1.14	1.09	1.14	1.31	1.47	1.29	1.36	1.33	1.32	1.37

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