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Root distribution and morphology of maize seedlings as affected by tillage and fertilizer placement

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Abstract

Suboptimal soil conditions are known to result in poor early growth of maize (*Zea mays* L.) in no-tillage (NT) systems in contrast with conventional tillage (CT) systems. However, most studies have generally focused on maize roots at later growth stages and/or do not give details on root morphology. In a 2-year field study at two locations (silt loam and loam soils) in the Swiss midlands, we investigated the impacts of tillage intensity, NT vs. CT, and NP-fertilizer sidebanding on the morphology, vertical and horizontal distribution, and nutrient uptake of maize roots at the V6 growth stage. The length density (RLD) and the length per diameter-class distribution (LDD) of the roots were determined from soil cores taken to a depth of 0.5 m and at distances of 0.05 and 0.15 m from both sides of the maize row. The temperature of the topsoil was lower, and the bulk density and penetration resistance were greater in the topsoil of NT compared with CT. The growth and the development of the shoot were slower in NT. RLD was greater and the mean root diameter smaller in CT than in NT, while the vertical and horizontal distribution of roots did not differ between CT and NT. RLD increased in the zone enriched by the sidebanded fertilizer, independent of the tillage system, but LDD did not change. The poorer growth of the roots and shoots of maize seedlings was presumably caused by the lower topsoil temperature in NT rather than by mechanical impedance. The placement of a starter fertilizer at planting under NT is emphasized.

Abbreviations: NT – no-tillage; CT – conventional tillage; RLD – root length density; LDD – length per diameter-class distribution; BD – soil bulk density; PR – soil penetration resistance

Introduction

No-tillage (NT) systems are widely accepted as means of reducing some of the negative impacts (such as soil erosion, energy use, leaching and runoff of agricultural chemicals) associated with conventional tillage (CT) systems (Uri et al., 1998). NT systems are particularly beneficial for a row crop like maize (*Zea mays* L.), which is susceptible to the leaching of agrochemicals and to soil loss and degradation because of the large distance between the rows and its slow initial growth in cold wet climates.

However, NT systems have disadvantages. Slower seed zone warming can occur in the spring during early maize growth because most of the residues of the previous crop are left on the soil surface (Azooz et al., 1995) and because of a higher thermal conductivity of untilled soils (Azooz and Arshad, 1995). In a review of the effects of conservation tillage systems on soil properties, Cannell et al. (1994) reported that the topsoil bulk density in NT systems usually is greater than in tilled soils; this greater soil density is often associated with increased penetration resistance but the soil water content is not usually affected or even increases.

The effects of tillage-induced changes in soil temperature and bulk density on plant growth are mediated through the growth and function of the roots. There is

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also a direct effect of soil temperature on the shoots of maize seedlings, because the shoot apex remains below the surface of the soil until about the V6 growth stage (Beauchamp and Lathwell, 1967; Ritchie et al., 1996). According to Richner et al. (1996), fluctuations in the topsoil temperature (as small as 2–3 °C around 15 °C) can adversely affect the growth of roots and shoots of maize seedlings. This can have long-term effects; at silking, maize root length density below the 0.30-m soil depth was correlated with the growing degree days for the 2 weeks following planting (Kuchenbuch and Barber, 1988). This may explain why the lower topsoil temperature is one of the main factors that hinders the emergence of maize and the growth and development of seedlings in NT systems (Al-Darby and Lowery, 1987). In contrast, there is no consensus about the effects of bulk density on the distribution and function of roots, because of the formation of vertically oriented biopores that are suitable for preferential root growth in NT systems (Ehlers et al., 1983; Martino and Shaykewich, 1994); these biopores may counteract the possible negative effect of increased bulk density on roots.

The combination of reduced soil temperature and increased soil strength may be responsible for the poor early growth of maize in NT systems, which may have an adverse affect on the final yield (Gavito and Miller, 1998; Janovicek et al., 1997). The exact causes of this early decrease in growth rate, however, have not yet been determined. Gavito and Miller (1998) and Miller et al. (1995) mentioned the possibility of an ‘unknown factor’, such as altered soil density, temperature, moisture, or their combined effects. Data on maize roots that were affected by tillage systems are often based on later sampling times around anthesis. They generally focus on vertical root length density gradients rather than on horizontal gradients. Root mass is usually assessed, but precise information about root morphology is rarely given. Furthermore, the effect of tillage on root proliferation differs from site to site owing to the wide range of potential effects of tillage on soil conditions (Dwyer et al., 1996).

The objectives of this study were to characterize the lateral and vertical distribution and the morphology of the root system of maize at an early growth stage as affected by tillage intensity and to determine whether differences in soil temperature and strength between the tillage systems affect the distribution, morphology and function of maize roots and, ultimately, the growth of the shoots. Furthermore, Mallarino et al. (1999) reported that the sidebanding of NP fertilizer promotes the early growth of maize, this study, therefore, focused on the effect of the sidebanding of NP fertilizer on the distribution and morphology of roots.

Table 1. Monthly precipitation and mean air temperature in Schafisheim and Zollikofen in April, May, and June in 1997 and 1998

Month	Precipitation		Mean air temperature	
	1997	1998	1997	1998
	mm		°C	
		Schafisheim		
April	71	81	7.6	8.3
May	40	35	13.2	14.8
June	139	109	16.0	17.1
		Zollikofen		
April	68	115	7.4	7.5
May	55	41	13.3	13.9
June	144	49	15.8	16.9

Materials and methods

Experimental sites

A field experiment was carried out in 1997 and 1998 at two sites in the Swiss midlands: In Schafisheim (47° 23′ N, 8° 09′ E, 429 m above sea level) on an Orthic Luvisol (FAO classification) and in Zollikofen (47° 00′ N, 7° 28′ E, 555 m above sea level) on a Gleyic Cambisol (FAO classification). Soil characteristics at Schafisheim were 15% clay, 35% silt, 50% sand, 3.3% organic matter and pH 6.7, and at Zollikofen 14% clay, 51% silt, 36% sand, 2.7% organic matter and pH 6.3. Precipitation and the daily mean air temperatures were measured at each site (Table 1). The 1998 growing season was characterized by a dry period without rain for the first three 3 weeks after planting. The nutrient and water contents of the experimental plots at the V6 growth stage of maize are given in Table 2.

Experimental treatments

This study was conducted in 1997 and 1998 within the scope of a tillage experiment initiated in 1995 in Zollikofen and in 1996 in Schafisheim. The study was based on a 4 year rotation of winter wheat, oilseed rape, winter wheat, and maize; white mustard

Table 2. Effect of tillage on soil contents of P and K, mineral nitrogen concentration in the soil solution within the row (N_{min}), and gravimetric water content (θ_g) of the soil (0 – 0.30 m) at the V6 stage of maize at two sites in the Swiss midlands in 1997 and 1998

Year	Site	Tillage	P	K	N_{min}	θ_g
			mg kg^{-1}	mg kg^{-1}	mg L^{-1}	kg kg^{-1}
				0 – 0.15 m		
1997	Schafisheim	CT	15.5	70.8	20	0.20
		NT	14.9	102.9	30	0.21
	Zollikofen	CT	3.4	22.4	8	0.22
		NT	3.7	24.3	3	0.21
1998	Schafisheim	CT	16.0	65.8	37	0.25
		NT	16.3	82.7	19	0.28
	Zollikofen	CT	4.9	28.8	14	0.18
		NT	4.4	27.1	14	0.22
				0.15 – 0.30 m		
1997	Schafisheim	CT	9.9	46.8	10	0.22
		NT	8.9	61.1	10	0.19
	Zollikofen	CT	2.8	18.0	4	0.24
		NT	2.8	18.0	7	0.21
1998	Schafisheim	CT	12.1	43.7	8	0.25
		NT	9.9	45.4	14	0.23
	Zollikofen	CT	3.5	15.2	9	0.23
		NT	2.5	12.7	8	0.21

(*Brassica alba* L. cv. Martigena) was included as a cover crop between winter wheat and maize. The plots were arranged so that four rotation crops were grown each year. The tillage treatments described in this study were CT and NT. Throughout the crop rotation, all crop residues were left on the soil surface. The tillage of the individual plots was the same each year. The CT treatment was moldboard plowed to a depth of 0.25 m and rototilled to a depth of 0.10 m immediately prior to planting with a conventional planter with double-disk openers (Kuhn Nodet Planter II, Montereau, France). The NT plots were sown without any prior tillage using a no-till planter with a double-disk opener assembly following a ripple coulter (Kinze 2000, Kinze, Williamsburg, IA, USA). Maize (cv. Granat) was planted at 100 000 plants ha^{-1} in 0.75-m rows and at 105 000 plants ha^{-1} in 0.78-m rows in CT and NT, respectively. The planting dates were 3 May 1997 and 8 May 1998. A mixture of dry fertilizer (diammonium phosphate and NH_4NO_3, 30 and 17 kg ha^{-1} of N and P, respectively) was banded on one side of each row, 0.05 m to the side and 0.05 m below the seeds at planting. The rates of N and P applied at planting were made up by a side-dressing application at the V4 growth stage and by a broadcast application before planting, respectively. The fertilizer rates applied with basal dressing and starter fertilization, which were based on local recommendations, were the same for both tillage systems, whereas the N side-dressing at V4 was measured on a per-plot-basis according to a soil N_{min} test (Wehrmann and Scharpf, 1979). The basal dressing included 35 kg ha^{-1} P, 133 kg ha^{-1} K, and 18 kg ha^{-1} Mg. Calculated side-dressing N rates did, on average, not differ among tillage systems; averaged across all years, sites, and tillage systems, 107 kg N ha^{-1} were applied. Weeds were controlled by spraying 1.500 kg ha^{-1} a.i. atrazine [6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine] and 1.920 kg ha^{-1} a.i. metolachlor [(S)-2-chloro-N-(2-ethyl-6-methyl-phenyl)-N-(2-methoxy-1-methyl-ethyl)-acetamide)] premergence on all plots. Glyphosate (*N*-[phosphonomethyl] glycine) and ammonium sulfate were applied (1.08 and 10 kg ha^{-1} a.i., respectively) before planting in the NT plots.

Table 3. Means of the daily mean (T), maximal (T_{max}), and minimal (T_{min}) soil temperature at a depth of 5 cm and cumulative growing degree days (GDD) in two periods of measurement as a function of tillage at two sites in the Swiss midlands; data averaged over 1997 and 1998

Site	Period of measurement[a]	Tillage	Soil temperature variables (°C)			
			T	T_{max}	T_{min}	GDD[b]
Schafisheim	17–31 May	CT	18.3 a[c]	23.6 a	13.3 a	150 a
		NT	17.2 b	22.0 b	13.2 a	129 b
	1–15 June	CT	19.7 a	24.0 a	15.9 a	175 a
		NT	19.4 a	23.2 a	16.1 a	172 a
Zollikofen	17–31 May	CT	17.2 a	22.1 a	12.9 a	129 a
		NT	16.1 b	19.7 b	12.9 a	113 b
	1–15 June	CT	19.6 a	23.6 a	16.0 a	171 a
		NT	19.2 a	22.6 a	16.3 a	164 a

[a] 17 May, 1 June, and 15 June correspond approximately to VE, V3, and V6 growth stages (Ritchie et al., 1996), respectively, in the CT treatment.

[b] GDD were computed from hourly soil temperature using a base temperature of 8 °C (Jones and Kiniry, 1986).

[c] Means followed by the same letter in the same growth period do not differ significantly at α=0.05.

Measurements

The temperature of the soil was measured hourly at a depth of 0.05 m with one in-row temperature probe in each plot and recorded with a data logger (Hobo H8 Temp Logger, Onset Computer Corporation, Bourne, MA, USA). Daily growing degree days (GDD) were computed from hourly soil temperature using a base temperature of 8 °C (Jones and Kiniry, 1986).

The bulk density (BD) of the soil was measured to a depth of 0.30 m in 0.05-m increments in all plots at the time of root sampling, using a steel sampler (0.109 m inner diameter and 0.05 m height). Three in-row-subsamples per plots were taken next to the locations of root sampling (see below). The soil cores were weighed and their moisture content determined after drying in an oven (105 °C) to constant mass.

Penetration resistance (PR) was measured at the time of root sampling at 10 random locations in each plot using a hand-held recording cone penetrometer (Anderson et al., 1980). The measurements were made in the row at intervals of 0.035 m to a depth of 0.49 m. The semi-angle of the cone was 15° and the diameter 0.013 m. The penetration rate was approximately 0.03 m s^{-1}. Measurements were made at Zollikofen because of the large number of stones in the soil at Schafisheim, which would have made interpretation difficult (Anderson et al., 1980).

Before sampling the roots, the shoots of the center plant, where root sampling was to occur, and of its two adjacent plants in the row were cut at ground level and their growth stages determined. The leaf area of the visible leaf blades and of the parts of partially expanded leaves of the center plants was measured with a leaf area meter (LI-COR 3100, Lincoln, NE, USA). The plant material of all three plants was oven-dried for 48 h at 65 °C and ground using a sample mill (Cyclotec 1093, Tecator AB, Höganäs, Sweden). The total N concentration of 50 mg of plant material was determined using an elemental analyzer (LECO CHN-1000, LECO Instrumente GmbH, Kirchheim bei München, Germany). The total P concentration of 50 mg of plant material was determined after dry ashing the samples at 550 °C for 6 h and then dissolving the ash with 1 l HCl 20% kg^{-1} dry matter. Phosphorus in the solution was measured by colorimetry.

Root sampling was done using the soil-core method (Böhm, 1979) when 50% of the plants in the CT plots had reached the V6 growth stage. This growth stage was reached 38 and 47 days after planting in 1997, and 32 and 41 days after planting in 1998 at Schafisheim and Zollikofen, respectively. The soil cores were taken to a depth of 0.5 m at three locations per plot using an auger (0.050 m inner diameter and 0.25 m length) attached to a hand-held, power-driven sampler. At each sampling location, cores

Table 4. Means and analysis of variance for shoot dry weight (SDW) and number of fully expanded leaves (NLF) of maize at the V6 stage as a function of tillage at two sites in the Swiss midlands

Year	Site	Tillage	SDW	NLF
			g	
1997	Schafisheim	CT	5.1 a[a]	5.4 a
		NT	3.4 b	4.7 b
	Zollikofen	CT	9.4 a	6.0 a
		NT	5.8 b	5.0 b
1998	Schafisheim	CT	11.2 a	5.4 a
		NT	8.6 b	4.9 b
	Zollikofen	CT	9.6 a	5.4 a
		NT	9.9 a	5.0 b

Source of variation	df	SDW	NLF
Year (Y)	1	**	NS
Site (S)	1	NS	NS
Y × S	1	*	NS
Reps within Y × S	8		
Tillage (T)	1	***	***
T × Y	1	*	*
T × S	1	NS	NS
T × Y × S	1	NS	NS
Error	8		
Total	23		
R^2		0.87	0.83
CV (%)		11.1	2.1

[a] Means followed by the same letter within a year x site combination do not differ significantly at $\alpha = 0.05$.

*, **, *** Significant at the α = 0.05, 0.01, and 0.001 levels, respectively; NS is not significant.

were taken at distances of 0.05 and 0.15 m from a plant on each side of the row. In 1997, cores were taken additionally from mid-way between crop rows (0.375 m from the row). No roots were found (data not shown) and this position was omitted from the sampling in 1998. Only non-wheel track interrows were sampled, because wheel traffic affects the growth and distribution of roots (Kaspar et al., 1991). The soil cores were divided into 0.05 m sections down to 0.30 m and into 0.10 m sections down to 0.50 m. These segments were washed using a semiautomatic hydropneumatic elutriation system (Gillison's Variety Fabrication Inc., Benzonia, MI, USA) equipped with a 290-μm sieve (Smucker et al., 1982). Live (white) roots were separated from the rest of the organic matter and stained with fuchsin dye (Pararosaniline P-1528, Sigma Chemical Co., St. Louis, MO, USA) for at least 12 h at 4 °C. They were rinsed under running tap water, suspended in a thin layer of water, and uniformly distributed on a glass tray, which was placed on a scanner to obtain grayscale images (resolution 600 × 600 dpi). Because a root must be at least three pixels (dots) wide to be detected by the used image-analysis program (see below), the theoretical lower size limit of resolution was 127 μm, which is three times the pixel size of the scanner (42.33 μm at a resolution of 600 dpi). The root images were analyzed to determine the length and diameter of the roots using the computer program ROOT DETECTOR (Walter and Bürgi, 1996). The program is based on an algorithm for the segmentation and local description of elongated, symmetric line-like structures developed by Koller et al. (1995). The length and the mean diameter are computed separately for each measured root segment. Thus, the total measured root length can be sorted into user-defined diameter classes, which yields the length per diameter-class distribution (LDD) of the roots. In this study, we used the following diameter classes: 0–200, 200–400, 400–800, 800–1600 and 1600–3200 10^{-6} m. Root length density (RLD) was calculated by dividing the root length by the volume of the core segment. The roots were dried in an oven for 48 h at 65 °C and the dry weight determined.

Experimental design and statistics

The experiment was designed as a randomized complete block with three replicates. BD and PR were analyzed according to a split-plot design with tillage as the main plot factor and soil depth as the subplot factor. RLD data were analyzed according to a split–split–split plot design with tillage as the main plot, NP-fertilizer banding as the subplot, horizontal distance from the plant as the sub-subplot, and depth as the sub–sub–subplot. To analyze the LDD, the median diameter and the percentage of total measured root length in the 0–200 10^{-6} m diameter class (pRL_{200}) were analyzed according to the above ANOVA model. The median root diameter was determined for each sample by taking the upper limit of the diameter class in which 50% of total measured root length was reached. Based on exploratory analysis, the 0–200 10^{-6} m diameter class was selected. In this class, most of the variability was due to the experimental treatments.

If subsamples were taken within plots, they were pooled before statistical analysis. The plot averages

Table 5. Percentage of total measured root length as a function of depth and distance from the row. Data are averaged over all treatments

Depth (cm)	Distance (cm)		
	5	15	Total
		%	
0–5	17	2	19
5–15	53	7	60
15–30	13	5	18
30–50	1	2	3
Total	84	16	100

were subjected to ANOVA, and significant differences were separated by orthogonal contrasts or Fisher protected LSD tests when appropriate. Some data sets were transformed in order to meet assumptions for ANOVA. However, all the results are presented in their original scale of measurement. Significant differences were accepted at $P \leq 0.05$, unless otherwise stated.

Results

Soil physical parameters

The temperature of the topsoil (at a depth of 0.05 m) was significantly lower in the NT treatment compared with CT during early maize growth (Table 3); across all environments, mean daily soil temperature (T), maximum daily soil temperature (T_{max}), and growing degree days (GDD) based on T (T_b = 8 °C) were reduced by 0.9, 1.6 and 13.1 °C, respectively, under NT as compared with CT in the earlier period of measurement, but were similar thereafter, while the daily minimum soil temperature (T_{min}) was not affected. The interaction between the site and the measurement period was significant for T, T_{max}, and GDD. These values were lower at Zollikofen than at Schafisheim in the earlier measurement period, but about the same thereafter. Only in 1998 was the mean daily soil temperature lower in the first half of June as well (data not shown).

BD was significantly lower under CT than under NT ($P \leq 0.001$) from 0 m to a depth of 0.25 m (Figure 1). From 0.30 to 0.50 m, there was no difference in BD between CT and NT (data not shown). The sum of squares for depth was partitioned into orthogonal

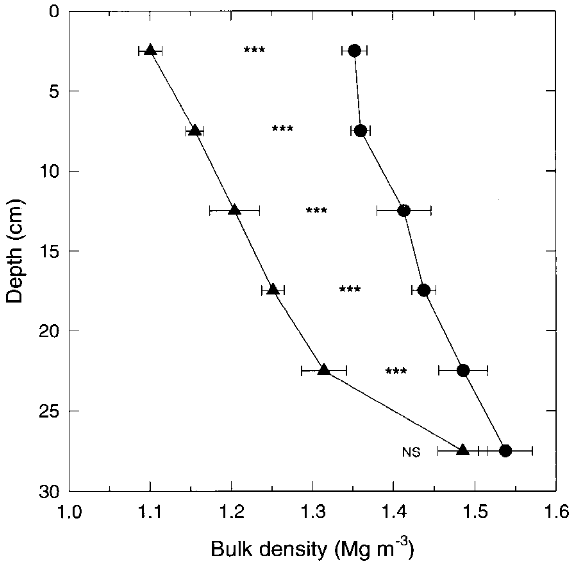

Figure 1. Soil bulk density as a function of depth and tillage at the V6 stage of maize, averaged over two years and 2 sites. ▲ CT; ● NT; *** Significant at the α = 0.001 level; NS is not significant. Horizontal bars are standard errors.

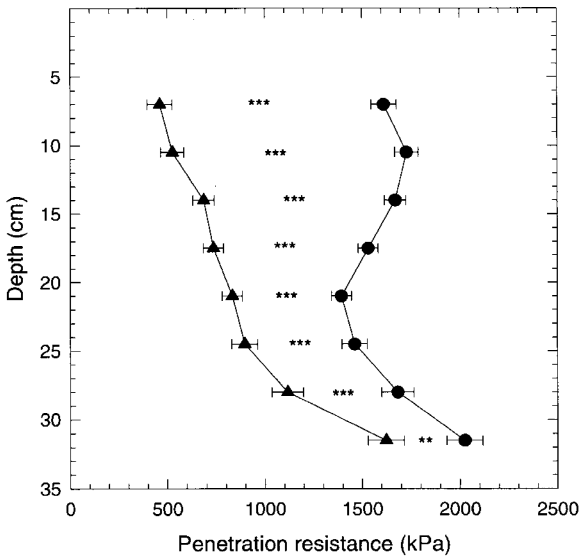

Figure 2. Soil penetration resistance as a function of depth and tillage at the V6 stage of maize at Zollikofen, averaged over two years. ▲ CT; ● NT; **, *** Significant at the α = 0.01 and 0.001 levels, respectively; NS is not significant. Horizontal bars are standard errors.

Table 6. Analysis of variance for root length density of maize at the V6 growth stage for two years at two sites in the Swiss midlands

Source of variation	df	1997		1998	
		Schafisheim	Zollikofen	Schafisheim	Zollikofen
			5 cm from the plant row		
Replication	2				
Tillage (T)	1	NS	NS	NS	*
Error a	2				
Fertilizer band (F)	1	**	**	***	NS
T × F	1	NS	NS	*	NS
Error b	4				
Depth (D)	7	***	***	***	***
T × D	7	NS	**	NS	**
F × D	7	*	***	***	***
T × F × D	7	NS	NS	**	NS
Experimental error	56				
Total	95				
R^2		0.65	0.64	0.77	0.67
CV (%)		114	123	105	126
			15 cm from the plant row		
Replication	2				
Tillage (T)	1	NS	NS	NS	NS
Error a	2				
Fertilizer band (F)	1	NS	NS	NS	NS
T × F	1	NS	NS	NS	NS
Error b	4				
Depth (D)	7	*	***	***	***
T × D	7	NS	**	***	NS
F × D	7	NS	NS	*	NS
T × F × D	7	NS	NS	NS	NS
Experimental error	56				
Total	95				
R^2		0.59	0.68	0.56	0.47
CV (%)		177	119	142	143

*, **, *** Significant at the α = 0.05, 0.01, and 0.001 levels, respectively; NS is not significant.

polynomial contrasts. Bulk density increased linearly ($P \leq 0.001$) with depth in CT and NT, and the quadratic component was significant in CT only.

PR followed a pattern similar to that of BD. The interaction between tillage and depth was highly significant ($P \leq 0.001$). From 0 to 0.32 m, CT showed a significantly reduced penetration resistance compared with NT (Figure 2). Below that depth there was no significant difference between CT and NT with little further change of PR values (data not shown).

Shoot parameters

Tillage had a strong effect on SDW which was higher in 1997 than in 1998. Averaged across both sites, SDW under NT was reduced by 36% compared with CT in 1997 ($P \leq 0.01$) (Table 4). In 1998, a significant reduction (23%) in SDW in NT was observed in Schafisheim. Plants under NT showed a significantly delayed development. The difference between the tillage treatments was larger in 1997 ($P \leq 0.001$) than in 1998 ($P \leq 0.01$), with fewer fully expanded leaves under NT in 1997 and 1998 (0.8 and 0.4, respectively).

Root parameters

Growth and distribution of roots

RLD was mainly affected by distance from the plant row and by depth. Averaged across all treatments, the highest RLD was found close to the young plant, i.e. between depths of 0.05 and 0.15 m at 0.05 m from the plant row (Table 5). RLD decreased strongly with increasing depth and horizontal distance from the plant row. There was a highly significant ($P \leq 0.001$) interaction among year, site, tillage, fertilizer banding, distance from the plant, and depth on RLD. Therefore, an individual ANOVA was performed for each year-site combination and for each distance from the plant row (Table 6).

At Zollikofen, RLD decreased by 55 and 33% under NT compared with CT in the 0.05 to 0.15 m soil layer, in the position closest to the plant row, in 1997 and 1998, respectively (Figures 3 and 4). The tillage effect on RLD did not depend on fertilization status. At Schafisheim, there was no significant tillage effect on RLD in 1997. In 1998, the RLD of the topsoil was higher under NT than under CT on the fertilized side of the row and lower on the unfertilized side of the row. The effect of tillage was higher and more consistent at Zollikofen than at Schafisheim in both years. At Zollikofen, RLD under CT tended to be higher than under NT at nearly all depths and positions. No significant differences in RLD between the tillage treatments were found in soil layers below 0.20 m.

The effect of the NP starter fertilizer on RLD was significant only in soil layers from 0.05 to 0.15 m, at a distance of 0.05 m from the plant row (Figures 3 and 4). The RLD was as much as three times higher on the fertilized side of the row compared to the unfertilized side of the row. At 0.15 m from the plant row, the RLD was generally the same on both sides of the row. The effect of fertilizer, as described above, was weaker at Schafisheim in 1997 compared with the other three environments. The relative distribution of RLD along the soil profile was drastically altered by the placement of the starter fertilizer, with a larger portion of roots in the 0.05–0.10 m soil layer on the fertilized side of the row than on the unfertilized side of the row.

Root morphology

The interaction between tillage and the distance from the plant had a significant effect on LDD. At 0.05 and 0.15 m from the row, the median root diameter was lower, and pRL_{200} was higher under CT than under NT (Table 7). The differences in the median diameter and pRL_{200} between the tillage systems were larger 0.15 m from the row than they were 0.05 m from the row. There was no significant effect of fertilizer banding on root morphology (data not shown). LDD was similar at all depths (Figure 5).

Table 7. Root morphological characteristics of maize at the V6 growth stage in the 0–50 cm deep layer as a function of distance from the plant row and tillage. Data are averaged over two years and two sites in the Swiss midlands

Distance from the row (cm)	Tillage	Root morphological characteristics: Median root diameter[a]	pRL$_{200}$[b]
		10^{-6} m	%
5	CT	317 a[c]	36 a
	NT	348 b	31 b
15	CT	344 a	31 a
	NT	447 b	23 b

[a] The median diameter is the upper limit of the diameter class in which 50% of total root length was reached.

[b] pRL_{200} is the length of roots thinner than 200 10^{-6} m, as a percentage of the total measured root length.

[c] Means followed by different letters within a tillage system x distance combination differ significantly at $\alpha = 0.05$.

Nutrient supply to the shoot

The content of nitrogen in shoot dry matter (N_c) was not significantly affected by tillage, but it was significantly affected by year ($P \leq 0.001$). N_c was 3.6% in 1997 and 4.3% in 1998 across all treatments (Table 8). The content of phosphorus in shoot dry matter (P_c) responded to tillage dependent on the year. In 1997, P_c was lower under NT than under CT, the difference was significant ($P \leq 0.001$) at Schafisheim only. In 1998, the opposite occurred with a significantly higher P_c under NT than under CT at both sites. P_c was higher in 1998 than in 1997 and higher at Schafisheim than at Zollikofen.

Discussion

Nearly all the root length (97%) was found in the A_p-horizon, as measured here; differences in root growth, distribution or morphology between the tillage treatments can be explained by changes in the rooting environment as caused by tillage. Mengel and Barber (1974) observed, at a similar maize growth stage, that about 20% of the total measured root length was found in layers below 0.30 m. The discrepancy between those results and ours might be due to the fact that

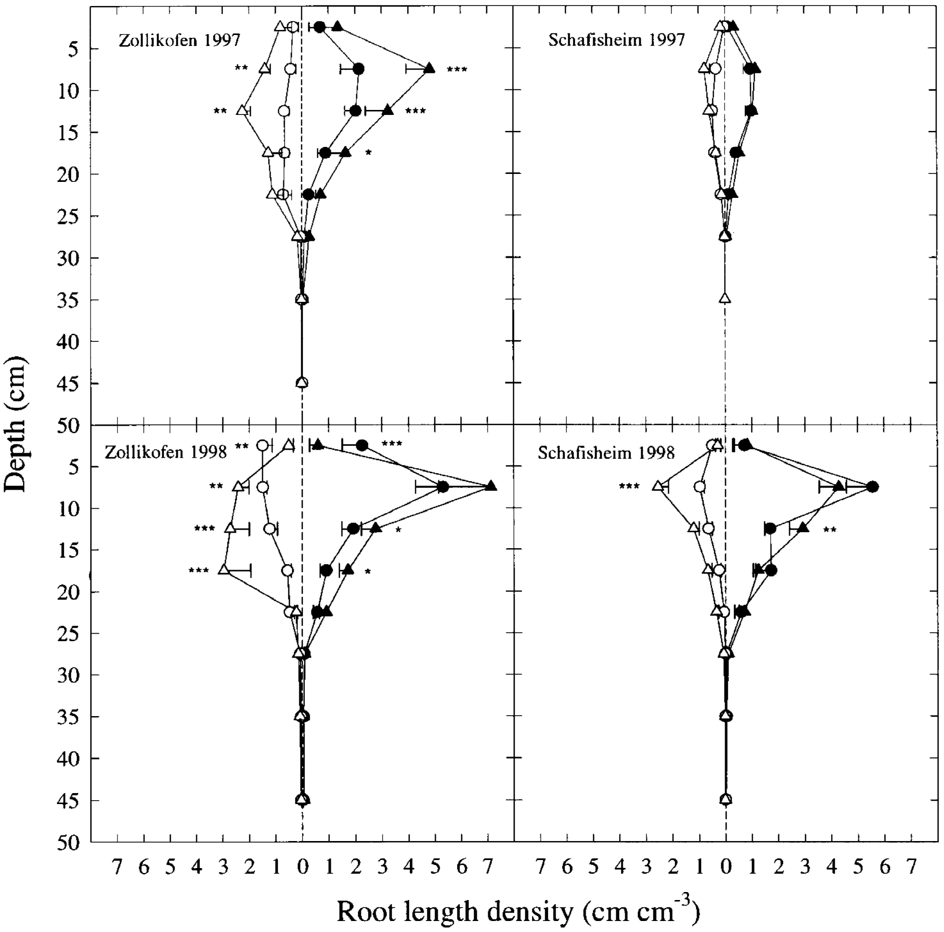

Figure 3. Root length density at the V6 stage of maize as a function of depth, tillage, and NP-fertilizer placement at 5 cm from the plant row at Zollikofen and Schafisheim in 1997 and 1998. ▲ CT; ● NT; open symbols: unfertilized row side; filled symbols: fertilized row side; *, **, *** Significant at the α = 0.05, 0.01 and 0.001 levels, respectively; blank is not significant. Horizontal bars are standard errors.

their sampling was done directly over the plant and, thus, included mainly the vertically growing seminal roots.

There were large differences in BD and PR of the topsoil between the tillage treatments, whereas there were hardly any differences between sites and years. Nevertheless, the effect of tillage intensity on the roots varied greatly among the environments (site by year combinations), indicating that factors other than BD and PR were involved. The soil water content is known to modify the bulk density and penetration resistance. The resistance to penetration (RP) decreases with increasing WT independently of soil type (Busscher et al., 1997). The predominantly moist soil conditions and the generally higher topsoil water contents in NT compared with CT during our study could have alleviated the detrimental impacts of increased BD and PR in NT to some extent.

The reduction in the temperature of the topsoil in NT, as found in this and many other studies, can be related to the residues that covered the soil surface and perhaps to higher contents of water in the topsoil (Anderson, 1987; Khakural et al., 1992) which increases the thermal conductivity of the soil. The maize shoot apex remains below the soil surface until about the V6 stage (Swan et al., 1996); thus, the lower soil temperature observed in all environments in NT was a major factor causing a delay in the development of the plant as well as a slower shoot growth. The soil temperature in the early part of the growing season has been considered to be one of the major factors affecting the emergence of maize and seedling growth and devel-

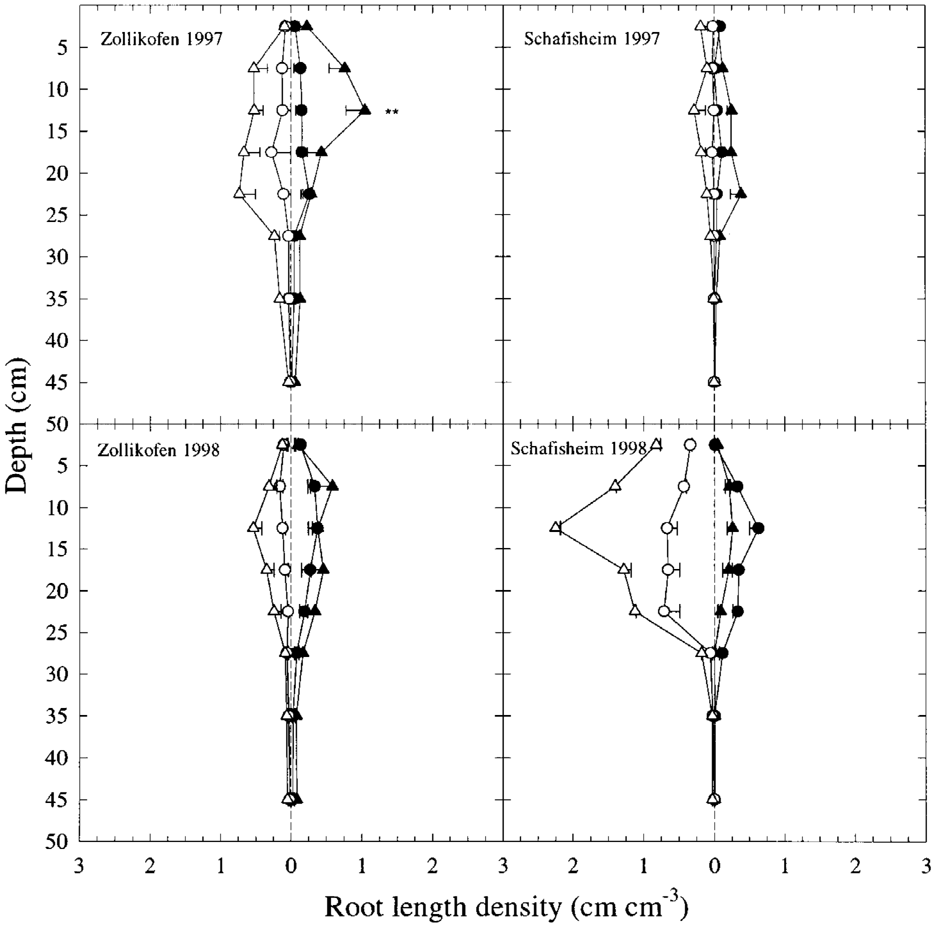

Figure 4. Root length density at the V6 stage of maize as a function of depth, tillage, and NP-fertilizer placement at 15 cm from the plant row at Zollikofen and Schafisheim in 1997 and 1998. ▲ CT; ● NT; open symbols: unfertilized row side; filled symbols: fertilized row side; *, **, *** Significant at the $\alpha = 0.05$, 0.01 and 0.001 levels, respectively; blank is not significant. Horizontal bars are standard errors.

opment (Al-Darby and Lowery, 1987; Hayhoe et al., 1996; Tardieu and Pellerin, 1991).

The reductions in RLD, especially at Zollikofen, and the greater root diameters observed under NT are probably typical responses of roots to a reduced soil temperature (Bowen, 1991) as well as to increased soil mechanical impedance (Bennie, 1996). The difference in the mean root diameter, which reflects the degree of root branching, between the tillage systems increased with distance from the plant row, indicating that it was associated with a delay in development and/or growth. This is probably also due to the reduced topsoil temperature. At Zollikofen, the effect of tillage on root growth and morphology was more consistent than at Schafisheim. In general, root length and weight were reduced in NT compared with CT at all sampling positions and depths. The soil at Zollikofen is finely textured (silt loam) and poorly drained, a soil that usually needs to be tilled (Cannell et al., 1994; Carter, 1994). Based on experiments conducted on a soil with a texture similar to that of the soil at Zollikofen, Hughes et al. (1992) concluded that NT might be unsuitable for such soils because it restricts the development of the roots. In addition, Zollikofen is a slightly cooler site than Schafisheim; thus, further reduction of the soil temperature in a system without tillage is more critical for the early growth of maize at this site. Despite this, the growth of maize shoots at Zollikofen was affected by the lack of tillage only in 1997. In 1998, a 3 week period without rain after the maize was planted led to a dry seedbed in the plowed treatment, whereas the water content in the topsoil under NT remained higher. This counterbalanced partly the benefits of moldboard

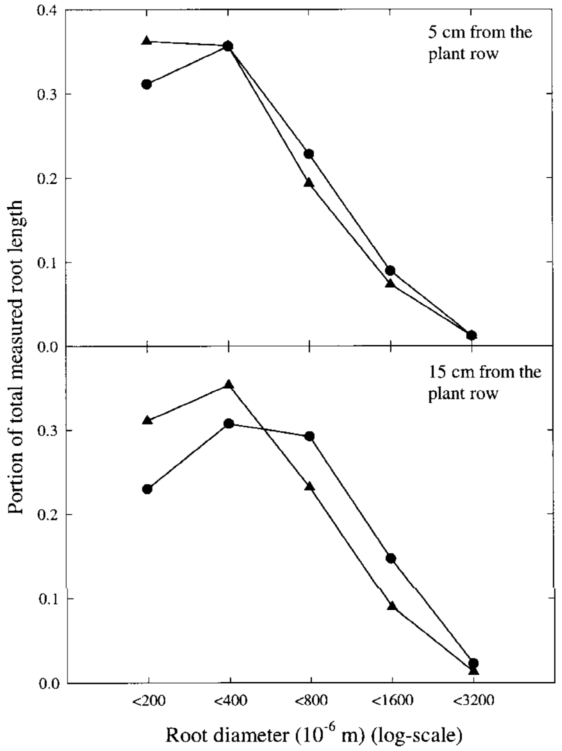

Figure 5. Distribution of root length by diameter classes at the V6 stage of maize from 0 cm to the depth of 50 cm as a function of tillage and distance from the plant row, averaged over two years and two sites. ▲ CT; ● NT.

Table 8. Means and analysis of variance for N concentration of shoot dry matter (Nc), P concentration of shoot dry matter (Pc) of maize at the V6 stage as a function of tillage at two sites in the Swiss midlands

Year	Site	Tillage	Nutrient concentration	
			N_c	P_c
			g kg^{-1}	
1997	Schafisheim	CT	35.6 a[a]	4.6 a
		NT	37.3 a	3.9 b
	Zollikofen	CT	35.4 a	4.1 a
		NT	37.7 a	4.0 a
1998	Schafisheim	CT	44.1 a	5.5 a
		NT	45.5 a	6.2 b
	Zollikofen	CT	42.8 a	4.4 a
		NT	39.1 a	4.7 b
Source of variation		df		
Year (Y)		1	***	***
Site (S)		1	NS	***
Y × S		1	NS	**
Reps within Y × S		8		
Tillage (T)		1	NS	NS
T × Y		1	NS	***
T × S		1	NS	NS
T × Y × S		1	NS	*
Error		8		
Total		23		
R^2			0.88	0.95
CV (%)			3.1	2.8

*, **, *** Significant at the α = 0.05, 0.01, and 0.001 levels, respectively; NS is not significant.

[a] Means followed by the same letter within a year x site combination do not differ significantly at α = 0.05.

tillage. A similar observation has been made by Azooz et al. (1995).

The relative distribution of roots with depth and distance from the row did not seem to be affected by tillage, contrary to several reports that roots accumulated in the topsoil of untilled soils (Ball-Coelho et al., 1998; Barber, 1971). The lack of differences in the relative distribution of the roots in both tillage systems indicates (i) that mechanical impedance was not great enough to alter the principal patterns of root distribution and (ii) that soil water patterns must have been similar in the two tillage treatments, as soil water was identified as a major factor in the early distribution of maize roots (Dwyer et al., 1996; Kovar et al., 1992). Under NT, 41.8% more biopores were counted below the plow layer than under CT at Zollikofen in the second experimental year (Nakamoto, pers. comm.), thus, counterbalancing adverse effects of the higher soil strength on maize root growth. The greater number of biopores could be associated to the significantly higher abundance of vertically burrowing (anecic) earthworms under NT compared with CT (Maurer, personal communication). The difference in moisture content mentioned above was too brief to have an effect on root distribution.

Root distribution was drastically modified by the presence of an NP-fertilizer band. RLD increased severalfold in the immediate vicinity of the enriched zone, similar to previous studies (Duncan and Ohlrogge, 1958; Kaspar et al., 1991). The root response was as strong in the NT treatment as in the CT treatment, indicating the lack of restriction to root growth by increased penetration resistance under NT. The placement of starter fertilizer has been considered to be effective in improving the early growth of maize when the soil temperature and/or the nutrient status of the soil is low (Marschner, 1995). Contrary to previous results (Anderson, 1987; Kaspar et al., 1991), no effect of localized nutrient supply on LDD was observed in our study.

The relatively stronger reduction of root length compared with shoot dry weight under NT suggests that the shoot might require more nutrients per unit root length (Engels et al., 1992; Krannitz et al., 1991). Mackay and Barber (1984) found that low soil temperature inhibited root growth more than the uptake kinetics per unit root length, particularly in combination with soil compaction (Al-Ani and Hay, 1983). The reduced extension of the root system under NT at Zollikofen must have been partially compensated for by a greater uptake of nutrients per unit root length. Thus, despite reduced root growth, shoot growth was probably not limited by the negative effect of low temperature on P supply in the root zone. Furthermore, reductions in shoot dry matter occurred in the NT treatment in both years at Schafisheim, although root growth was hardly affected by the lack of tillage at this site. Based on these findings and because the content of P in the shoot was always in the sufficiency range of 4.0 to 8.0 g kg^{-1} (Jones and Eck, 1973), it is concluded that reductions in shoot growth under NT were not due to a limited supply of P but to the low temperature in environment of the shoot apex. As mentioned above, the placement of fertilizer at planting contributed greatly to this result because there was an ample supply of N and P to the roots. A slow rate of growth of the shoots, due to a limited nutrient supply, is more likely to occur in nutrient-poor soils (Engels and Marschner, 1990). Gavito and Miller (1998) and Miller et al. (1995) associated the lack of P deficiency in NT treatments to the contribution of the mycorrhizae. Both studies referred to an ‘unknown factor’ that causes a reduced rate of shoot growth in NT systems.

Conclusions

The increased bulk density of the topsoil in the NT treatment probably restricted root growth only to a limited extent, more pronounced in the soil with the finer texture. This confirms that such soils must be tilled more intensively. The lower temperature of the topsoil under NT was probably the main cause of the reduction of the growth of roots and shoots of maize seedlings, mainly because of a direct effect of temperature on the meristems. An indirect temperature effect, caused by an insufficient supply of nutrients to the shoot due to a smaller root system, did not occur owing to the increased root growth in the zone enriched by the placement of a starter fertilizer. This emphasizes the importance of placing fertilizer in the root zone at planting under NT.

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