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ROOT ABUNDANCE OF MAIZE IN CONVENTIONALLY-TILLED AND ZERO-TILLED SOILS OF ARGENTINA[1]

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SUMMARY

Maize root growth is negatively affected by compacted layers in the surface (e.g. agricultural traffic) and subsoil layers (e.g. claypans). Both kinds of soil mechanical impedances often coexist in maize fields, but the combined effects on root growth have seldom been studied. Soil physical properties and maize root abundance were determined in three different soils of the Rolling Pampa of Argentina, in conventionally-tilled (CT) and zero-tilled (ZT) fields cultivated with maize. In the soil with a light Bt horizon (loamy Typic Argiudoll, Chivilcoy site), induced plough pans were detected in CT plots at a depth of 0–0.12 m through significant increases in bulk density (1.15 to 1.27 Mg m^{-3}) and cone (tip angle of 60 º) penetrometer resistance (7.18 to 9.37 MPa in summer from ZT to CT, respectively). This caused a reduction in maize root abundance of 40–80 % in CT compared to ZT plots below the induced pans. Two of the studied soils had hard-structured Bt horizons (clay pans), but in only one of them (silty clay loam Abruptic Argiudoll, Villa Lía site) the expected penetrometer resistance increases (up to 9 MPa) were observed with depth. In the other clay pan soil (silty clay loam Vertic Argiudoll, Pérez Millán site), penetrometer resistance did not increase with depth but reached 14.5 MPa at 0.075 and 0.2 m depth in CT and ZT plots, respectively. However, maize root abundance was stratified in the first 0.2 m at the Villa Lía and Pérez Millán sites. There, the hard Bt horizons did not represent an absolute but a relative mechanical impedance to maize roots, by the observed root clumping through desiccation cracks.

Index terms: zero tillage, conventional tillage, soil compaction, root growth.

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RESUMO: *ABUNDÂNCIA DE RAÍZES DE MILHO (ZEA MAYS L.) EM SOLOS DE ARGENTINA SOB PREPARO CONVENCIONAL E PLANTIO DIRETO*

O crescimento das raízes do milho é alterado negativamente quando o solo apresenta camadas compactadas superficiais (trânsito de maquinário) ou subsuperficiais (camada argilosa). Os dois tipos de impedimentos mecânicos muitas vezes coexistem nos campos sob cultura de milho, porém seus efeitos combinados no crescimento das raízes do milho foram raramente estudados. As propriedades físicas do solo e a abundância de raízes de milho foram estudadas em três diferentes solos da região do Pampa Ondulado, na Argentina, que foram cultivados em parcelas próximas com milho em preparo convencional e em plantio direto. No solo com um horizonte Bt incipiente (Argiudol típico franco, local Chivilcoy), as compactações induzidas pelo preparo foram identificadas nas parcelas sob preparo convencional na profundidade de 0–12 cm por meio de significativos incrementos na densidade aparente (1,15 e 1,27 Mg m^{-3}) e na resistência à penetração com penetrômetro de cone (ponta com ângulo de 60°), com valores de 9,37 e 7,18 MPa, no verão, nas parcelas sob preparo convencional e plantio direto, respectivamente. Isso ocasionou diminuição da abundância nas raízes do milho entre 40 e 80 % sob preparo convencional, se comparado com plantio direto, abaixo das compactações induzidas. Dois dos solos estudados tinham horizontes Bt fortemente estruturados, porém somente um deles (o Argiudol abrúptico franco-argilo-siltoso, localizado em Villa Lia) apresentou os incrementos na resistência à penetração esperados (até 9 MPa) em profundidade. No outro solo com camada argilosa compactada (Argiudol vértico franco-argilo-siltoso, de Pérez Millán), a resistência à penetração não aumentou com a profundidade, mas atingiu 14,5 MPa a 0,075 e 0,2 m de profundidade para o plantio convencional e o plantio direto, respectivamente. Todavia, a abundância das raízes de milho foi estratificada dentro dos primeiros 0,2 m nos locais Villa Lia e Pérez Millán. Assim, os horizontes Bt bem desenvolvidos não representaram um impedimento mecânico absoluto para a penetração das raízes do milho, e sim um impedimento relativo, já que foram localizadas raízes que penetraram pelas fendas ocasionadas por ciclos de umedecimento e secagem.

Termos de indexação: plantio direto, raízes, plantio convencional, camadas compactadas.

INTRODUCTION

Deep reaching compaction in many fertile soils of the world, often managed under modern, industrial-agricultural management, is an issue of great concern (Hamza & Anderson, 2005). In such soils it is often the frequent and repeated use of conventional tillage (CT: e.g. mouldboard- and disc- ploughs, disk harrows) that results in the formation of induced plough pans in subsoil (Canarache, 1991). This compacted layer can impede crop root growth when soil resistance measured with a cone (tip angle of 30 °) penetrometer exceeds the threshold of 2–3 MPa (Gupta & Allmaras, 1987; Glinski & Lipiec, 1990; Passioura, 2002). The magnitude of restriction is closely related to the soil water content, because of the resulting increases in soil resistance (Gupta & Allmaras, 1987; Raper, 2005).

For different reasons, many of these fertile agricultural soils were converted to conservation tillage systems in the last decade. Zero tillage (ZT), the paradigm of conservation agriculture, was implemented in about 95 million hectares worldwide (Lal et al., 2007). In the Pampas region of Argentina, half of the cultivated area passed to this system in the last 15 years (Díaz Zorita et al., 2002; Steinbach & Alvarez, 2006). Conventional tillage (ploughing, disking, harrowing, and so on) induces the development of so-called "plough pans" near the surface in many soils (Canarache, 1991; Taboada et al., 1998; Micucci & Taboada, 2006). These plough pans are expected to disappear under continuous ZT. In exchange, surface compaction problems have often reported in fine-textured, zero-tilled topsoils (Díaz Zorita et al., 2002; Sasal et al., 2006; Taboada et al., 1998). Although conservation tillage minimizes agricultural traffic (Hamza & Anderson, 2005; Raper, 2005), wheel tracks are not erased in ZT topsoils (Botta et al., 2006). This can contribute to increase surface compaction problems.

Among the crops used in industrial agriculture, maize (*Zea mays* L.) is one of the most susceptible to soil compaction (Maddonni et al., 1999; Amato & Ritchie, 2002). Maize root growth is negatively affected by subsoil compacted layers, but the consequences on maize yields are not always direct (Erbach et al., 1986; Díaz Zorita et al., 2002). Soil hardness may also have a genetic origin, as in the case of many argillic Bt horizons that behave as "clay pans" (Canarache, 1991). These hard togh B horizons may restrict the amount of available water stored in the soil profile in areas with high intra-seasonal rainfall variability (Dardanelli et al., 2003). However, clay pans are not found in all Bt horizons since the occurrence does not only depend on the clay percentage but also on the characteristics of soil prisms and the occurrence of desiccation cracks between them (Amato & Ritchie, 2002; Dardanelli et al., 2003). In Mollisols of the Pampas region of Argentina, farms converted to ZT systems coexist with farms where the CT system is still being used. Within a distance of few kilometres (Figure 1), both the topsoil and subsoil horizons consist of soils with different textural and structural properties. This situation represents an interesting opportunity to study the combined effects of man-made compaction and genetic compaction on maize root growth in the field. In this study we report field results obtained in three different soils, under CT and ZT management regimes. At each site we investigated the occurrence of man-made and genetic soil compaction and the effects on maize root abundance and root distribution.

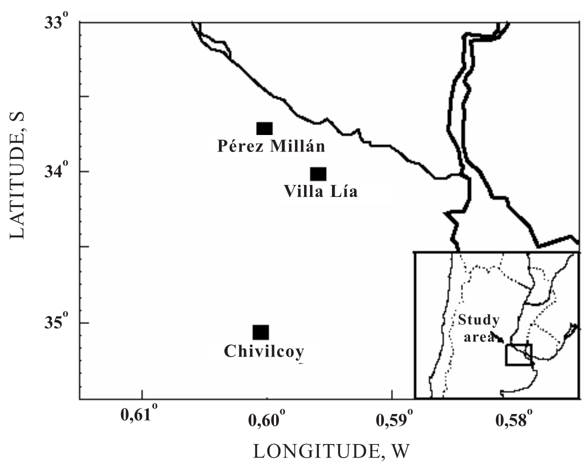

Figure 1. Geographical location of studied sites in the province of Buenos Aires, Argentina.

MATERIALS AND METHODS

Description of the region

The Rolling Pampa of Argentina is one of the most important temperate crop areas of the Southern Hemisphere and covers around 5 Mha. The climate is temperate and humid, with an average annual rainfall of 940 mm, concentrated in the spring - summer seasons (Hall et al., 1992), and a mean annual temperature of 17 °C (Soriano, 1991). The entire area is covered by Mollisolls, which developed from aeolian sediments (loess) under grassland vegetation (Soriano, 1991). In the West soils are mainly Typic Argiudolls with loamy texture and light Bt horizon, while in the East soils are Abruptic and Vertic Argiudolls with silty loam or silty clay loam topsoil texture and strong Bt horizon (Salazar Lea Plaza & Moscatelli, 1989).

Soils and tillage systems

This work was carried out in three agricultural soils, in the North of the province of Buenos Aires, Argentina (Figure 1). At each site a different type of Mollisol is found: (a) in Chivilcoy: a loamy, thermic, Typic Argiudoll (US Soil Taxonomy) from the O'Higgins Series (Luvic Phaeozem in the FAO Soil Classification) (INTA, 1980a); (b) in Villa Lía: a fine, illitic, thermic, Abruptic Argiudoll from the Portela Series (Luvic Phaeozem) (INTA, 1980a); and (c) in Pérez Millán: a fine, illitic, thermic. Vertic Argiudoll from the Ramallo Series (vertic Phaeozem) (INTA, 1980b) (Table 1).

Two agricultural fields under different managements were selected per site. Each field was divided in three adjacent plots. Soil studied managements were: (a) Long-term conventional tillage (CT): two or three passes of tandem disk harrow at 0.10 m depth and spike-tooth harrow were continuously applied over the last years. After maize sowing, weeds were mechanically controlled; (b) Zero tillage (ZT): zero till planting after long-term CT, with herbicide weed control. The number of years under continuous ZT was 9, 6, and 7 for the Chivilcoy, Villa Lía, and Pérez Millán sites, respectively. The selected agricultural fields did not differ in the technological level or crop rotation. The crop sequence over three years consisted basically of maize - wheat (*Triticum aestivum* L.) / soybean double cropping and full season soybean.

Determinations

In winter (June 2004), composite soil samples were taken from the 0–0.05, 0.05–0.15 and 0.15–0.30 m layers to determine the pH in soil suspensions (1:5 distilled water), and organic C content by the Walkley and Black method (Nelson & Sommers, 1982).

Three soil cores of 6 cm diameter from each plot were taken from the layers 0–0.05, 0.10–0.15 and 0.25–0.30 m to determine bulk density (BD) by the core method (Burke et al., 1986). Cores were collected between rows, unaffected by recent traffic compaction. At the sites of Chivilcoy and Villa Lía, three replicated measurements of soil penetrometer resistance (PR) were regularly made at each plot. A cone-shaped probe (tip angle of 60 °; basal diameter 1.4 cm) was driven into the soil (0.45 m deep) through consecutive falls of a 2 kg load falling from a height of 0.515 m (Burke et al., 1986). Soil PR was recorded as the number of falls required to penetrate each 5 cm of soil to a depth of 0.54 m. Apart from each penetrometer measurement, soil samples were taken from the 0–0.05, 0.1–0.15 and 0.25–0.3 m layers, to determine the gravimetric water content (SWC) by oven-drying at 105 °C in the laboratory. Magnitude of soil

Table 1. Soil properties of the studied sites

Horizon	Depth	Clay	Silt	Textural classification	Structure (class, type and grade)
a) Chivilcoy: O'Higgins Series (Typic Argiudoll)					
	m	g kg^{-1}			
Ap	0-0.15	185	440	Sandy loam	fine, moderate, granules
A	0.15 - 0.28	215	400	Sandy loam	medium, coarse, subg. blocks
Bt	0.28 - 0.50	245	357	Clay loam	Weak, medium, prisms (breaking down to blocks and granules)
BC	0.50 - 0.70	168	380	Sandy loam	Medium, moderate, subg. blocks (breaking down to granules and single grain)
C	0.70 - +	67	348	Loamy sand	Massive
b) Villa Lía: Portela Series (Abruptic Argiudoll)					
Ap	0-0.15	260	599	Silty loam	Medium, coarse, subg. blocks
A	0.15-0.30	283	564		
Bt_1	0.30-0.62	584	364	Clayey	Coarse, strong, prisms, with slickensides
Bt_2	0.62-0.86	533	416	Silty clay	Coarse, strong, prisms, with slickensides
BC_1	0.86-1.27	402	491	Silty clay	Coarse, moderate, prisms, with slickensides
BC_{2k}	1.27-1.42	292	559	Clay silty loam	Medium, moderate, ang. blocks
Ck	1.42-1.90	280	583	Clay silty loam	Massive
c) Pérez Millán: Ramallo Series (Vertic Argiudoll)					
A1	0.13-0.27	317	642		
BA	0.27-0.40	341	614	Silty clay loam	Medium, moderate, sub. blocks
Bt_1	0.40-0.76	565	396	Clayey	Coarse, strong, prisms, with slickensides
Bt_2	0.76-1.31	403	553	Clay loam	Coarse, moderate, prisms, with slickensides
BC	1.31-1.98	385	567	Silty clay loam	Medium, moderate, ang. blocks
C	1.98-2.20	262	664	Silty loam	Massive

Data were abtained from published soil maps (INTA, 1980a, b) and checked in situ.

desiccation was inferred by SWC/FC quotient (FC = field capacity). FC (g g^{-1} soil) was calculated using a pedo-transfer function (Campbell, 1985) validated for Pampean soils (Damiano & Taboada, 2000):

$$FC = 0.258 – 0.002 \text{ x Sand (\%)} + 0.0036 \text{ x Clay (\%)} + 0.03 \text{ x SOM (\%)}$$

being FC = soil water retentional -33.3 kPa matric potential; SOM = soil organic matter.

Soils were cultivated with maize from September 2004 to March 2005. Sowing dates, seed density and maize hybrids were similar at each site, for both tillage treatments. In summer (December 2004–January 2005), at maize flowering, 1 m deep soil pits were dug in each plot to determine the horizontal and vertical distribution of maize roots by a semi-quantitative method (Manichon, 1987). Each pit was 0.6 m wide with a maize plant in the centre. The abundance and vertical distribution of maize roots was determined using a 0.5 x 0.3 m rectangle subdivided in 0.05 x 0.05 m squares. In each square, root abundance was determined using a semi-quantitative scale (0 to 5). The root abundance of each 0.05 m soil layer was the average of 12 squares. Beside each pit the soil PR was evaluated in two measurements, by the same method as in the winter. On the opposite side of the pits, soil samples were taken at different depths for SWC determination in the laboratory. Magnitude of desiccation was inferred by SWC/FC quotients.

Statistical inference

At each site a factorial arrangement was applied. Factors were tillage treatment (CT and ZT) and soil depth. Differences were inferred from the analysis of variances, and in the case of significant treatment effects ($p < 0.05$), means were compared using contrasts (Student's test).

RESULTS AND DISCUSSION

Soil profiles

Soils differed in the horizon sequences, topsoil texture and texture degree of Bt horizons. In Chivilcoy, the sandy loam Ap and A horizons and light textured Bt horizon do not indicate *a priori* the occurrence of genetic mechanical impedances in soil profile (Table 1). On the other hand, Villa Lía and Pérez Millán soils do not only have silty topsoils but also clayey and well-developed prismatic Bt horizons (Table 1). In Villa Lía the Bt horizon has no vertic features, unlike in Pérez Millán where it has slickensides and desiccation cracks.

Soil organic C content was higher in the sandy loam Chivilcoy topsoil than in silty loam and silty clay loam Villa Lía and Pérez Millán topsoils (Table 2). This is likely due to different historical agricultural intensities at the study sites. In addition, organic C content was higher in ZT than in CT plots (0 to 0.15 m), at the Chivilcoy and Villa Lía sites, with modest C sequestration under zero tillage (Lal et al., 2007; Steinbach & Alvarez, 2006). Soil pHs were slightly acid in Chivilcoy and Pérez Millán, and acid in Villa Lía (Table 2), evidencing once more intense agricultural intensity in this soil. Soil pH was essentially the same in CT and ZT soils. Soil organic C losses and, to a lesser extent, soil acidification were reported as expected consequences of long-term cropping in pampas soils (Senigagliesi & Ferrari, 1993; Steinbach & Alvarez, 2006).

Table 2. Soil organic carbon and pH in conventionally-tilled (CT) and zero-tilled (ZT) soils of each studied site. Data were obtained by composite sample analysis

Soil depth	Chivilcoy		Villa Lía		Pérez Millán	
	CT	ZT	CT	ZT	CT	ZT
	Organic carbon					
m	g kg^{-1}					
0-0.05	25.1	31.0	19.8	21.6	22.6	24.9
0.05-0.15	21.9	25.8	16.0	17.1	17.7	16.2
0.15-0.30	15.1	16.2	12.2	14.0	17.0	15.5
	pH					
0-0.05	5.96	5.84	5.44	5.34	5.85	5.96
0.05-0.15	5.77	5.82	5.32	5.30	5.76	5.76
0.15-0.30	5.91	5.91	5.59	5.56	5.97	5.97

Soil bulk density

Soil BD was significantly affected by both soil depth and tillage, without respective interaction (Table 3). Soil depth effects were mainly caused by the lower BD determined in all cases by C enrichment in the 0–0.05 m layer. Tillage effects differed from site to site. In Chivilcoy BD was significantly lower in ZT than in CT plots, in all evaluated layers. A higher BD value was noted in the CT soil compared with ZT determined in the 0.05–0.15 m layer. This BD increase may be caused by an induced plough pan at this depth (Canarache, 1991). Contrastingly, in Villa Lía and Pérez Millán soil BD was significantly higher in ZT than in CT plots, although in different soil layers (Table 3). Such increases in BD can be the result of surface compaction under zero tillage (Thomas et al., 1996).

Table 3. Soil bulk density in conventionally-tilled (CT) and zero-tilled (ZT) soils of each studied site. ANOVA P-values for tillage, depth and respective interaction

Soil depth	Chivilcoy		Villa Lía		Pérez Millán	
	CT	ZT	CT	ZT	CT	ZT
	Soil bulk density					
m	Mg m^{-3}					
0-0.05	1.05	0.91	0.96	1.03	0.93	0.95
0.05-0.15	1.27	1.15	1.17	1.24	1.12	1.25
0.15-0.30	1.20	1.14	1.15	1.16	1.18	1.26
	ANOVA P values					
Tillage	< 0.001		0.011		0.012	
Depth	< 0.001		< 0.001		< 0.001	
Tillage x Depth	0.189		0.243		0.327	

Soil water content

In the winter, SWC was determined in the top 0.3 m at the sites Chivilcoy and Villa Lía (Table 4a,b). The SWC/FC quotient indicated the magnitude of soil desiccation on each sampling date. In the winter, soils reached a field capacity of 0.73–0.95, with significantly higher SWC in ZT than in CT plots in topsoil in Chivilcoy. In Villa Lia, SWC/FC quotients were lower and only differed between management in the top 5 cm (CT > ZT). In the summer, only the Villa Lía soil showed significant differences between tillage treatments. Even in summer and under maize crop flowering, the magnitude of soil desiccation was not high (i.e. high SWC/FC quotients) in the deep profile of Chivilcoy (0.95–1 m layer) and in the intermediate profile (0.45–0.5 m layer) of Villa Lía and Pérez Millán sites (Table 4). In the latter, high SWC were due to water storage in the clayey Bt horizons at

Table 4. Soil water retention at - 33.3 kPa matric potential (field capacity = FC), gravimetric soil water contents (SWC) in winter and in summer, and the FC/SWC quotients

Soil layer	CT			ZT			CT vs ZT
	FC	SWC	SWC/FC	FC	SWC	SWC/FC	P
			WINTER				
			a) Chivilcoy				
m	g kg^{-1}			g kg^{-1}			
0-0.05	390	326	0.84	421	369	0.95	< 0.05
0.1-0.15	373	272	0.73	394	293	0.79	< 0.05
0.25-0.3	316	283	0.90	316	295	0.93	ns
			b) Villa Lía				
0-0.05	451	314	0.65	461	249	0.63	< 0.05
0.1-0.15	431	272	0.63	437	251	0.58	ns
0.25-0.3	427	294	0.74	436	282	0.58	ns
			SUMMER				
			a) Chivilcoy				
0-0.05	390	182	0.47	421	169	0.40	ns
0.2-0.25	337	171	0.51	343	143	0.42	ns
0.45-0.5	316	187	0.59	316	164	0.52	ns
0.75-0.8	350	171	0.49	350	189	0.54	ns
0.95-1	176	237	1.35	176	235	1.34	ns
			b) Villa Lía				
0-0.05	451	244	0.54	461	232	0.50	ns
0.2-0.25	427	202	0.47	436	164	0.38	< 0.001
0.45-0.5	516	475	0.92	516	495	0.96	ns
0.75-0.8	489	310	0.63	489	270	0.55	< 0.001
0.95-1	399	279	0.70	399	260	0.65	ns
			c) Pérez Millán				
0-0.05	475	98	0.21	487	119	0.24	ns
0.2-0.25	459	178	0.39	452	176	0.39	ns
0.45-0.5	512	425	0.83	512	428	0.84	ns
0.75-0.8	512	228	0.45	512	237	0.46	ns
0.95-1	426	222	0.52	426	231	0.54	ns

these depths; in spite of the high water extraction by maize crops at flowering, high amounts of available water still remain unused in the studied clayey subsoils (Amato and Ritchie, 2000).

Soil penetrometer resistance

Soil resistance is highly dependent on soil water condition (Gupta & Allmaras, 1987); lower PR values were thus observed in winter than in summer (Figure 2). Soil PR was significantly affected by a tillage-by-depth interaction in the winter. PR values increased from 1–3 MPa in topsoil to 5–7 MPa in subsoil (0.45 m) in the Chivilcoy and Villa Lía soils. Taking into account the wet soil conditions in these periods (Table 4), the higher PR values were the result of profile anisotropy in deep Bt horizons. Statistical differences observed between treatments at two soil depths were little relevant in magnitude.

In summer, soil PR was affected by significant and independent effects of depth and tillage in Villa Lía only (Figure 2). Depth effects differed from site to site. In Chivilcoy, soil PR was significantly lower in topsoil than in the rest of the profile. Despite a higher water content under CT than ZT, PR was higher at 0.15 m. Taking into account the higher BD determined in CT soil at the same depth (Table 3), this PR increase can be ascribed to an induced plough pan by long-term conventional tillage (Canarache, 1991). It is likely that after nine years ZT this induced compaction is recovered at the Chivilcoy site. Similar recoveries were also found in other medium-textured soils of the region (Taboada et al., 1998; Micucci & Taboada, 2006). Soil PR was as high as 15 MPa in the 0.1–0.2 m layer of the fine textured Pérez Millán soil. This PR increase occurred both in CT and ZT soils, so that it is questionable to ascribe it to an induced plough pan. No clear explanation was found for the persistence in ZT plots either, since the high number of years (seven) would have allowed the recovery of porosity in the untilled soil (Rhoton, 2000). Therefore, the PR data recorded here could be ascribed to a genetic cause. At the same

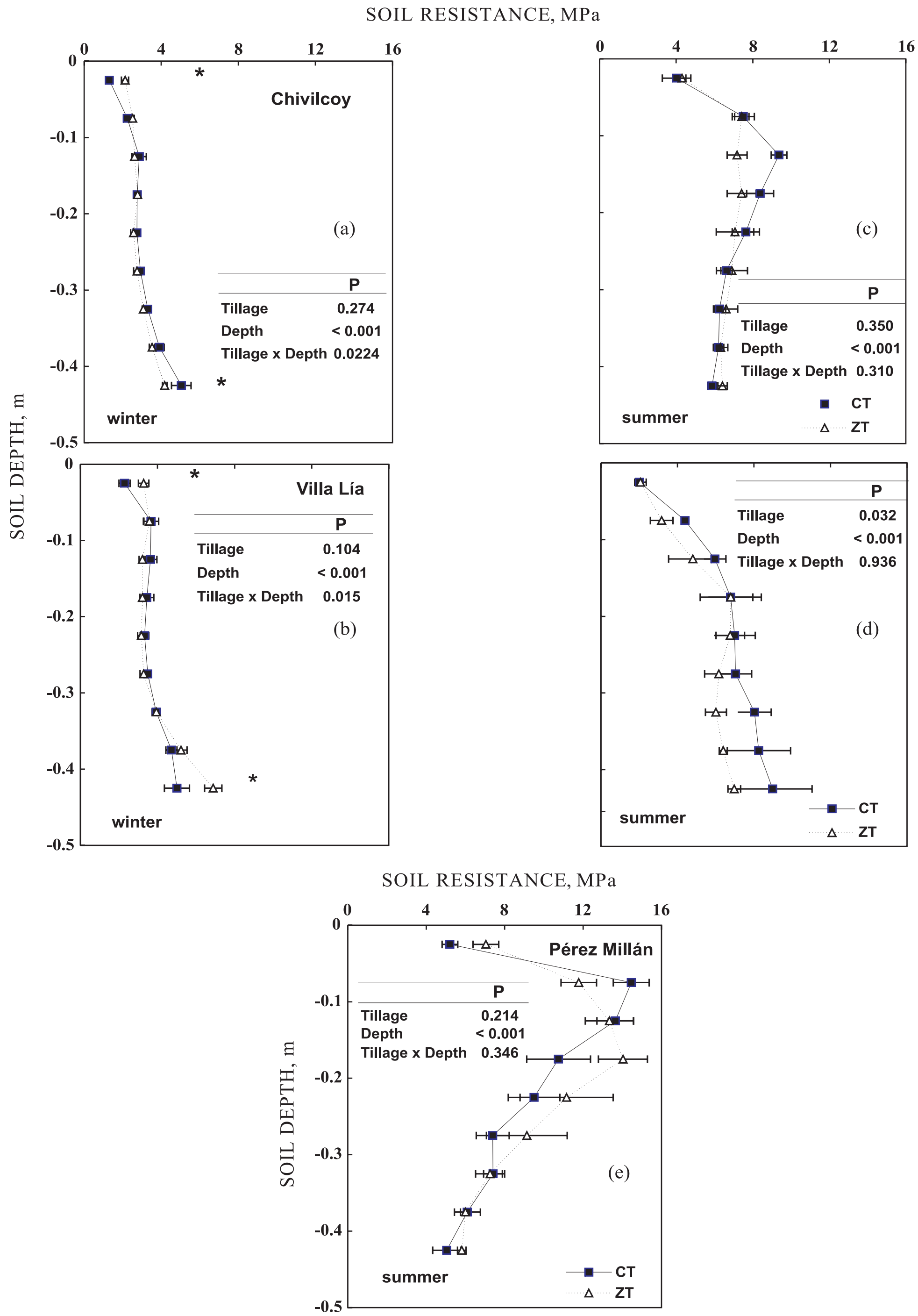

Figure 2. Soil penetrometer resistances in different layers of conventionally-tilled (CT) and zero-tilled (ZT) soils in winter and summer. Standard errors of means are indicated by bars. ANOVA tables are also included. (*) indicates statistical differences between management at a specific soil depth.

depth, there is a thin BA horizon with a lower organic C content than in the higher A horizon and with a lower clay content than in the deeper Bt horizon (Tables 1 and 2). Considering the very low GWC found in summer at 0.2-0.25 m depth in both CT and ZT plots of Pérez Millán soil (Table 4), it can then concluded that this BA horizon behaved as a natural compacted layer in the summer. Soil PR decreased sharply below 0.2 m, despite the strong Bt horizon existing at this depth (Table 1). Unlike the desiccated upper horizons, higher GWC was determined at this depth (Table 4). The combined action of water and clay plasticity may have allowed an easy penetration of the probe in this clayey subsoil (Pilatti & Orellana, 2000).

Although the Villa Lía soil also has a silty clay loam topsoil and clayey subsoil, soil PR behaved completely different here (Figure 2d). Soil PR was not only significantly higher in CT than in ZT plots, but also increased significantly with depth. This PR increase was not related to the higher GWC found in this Bt horizon (Table 4), and can be ascribed to the low cracking potential of this subsoil. In contrast, soil cracking is very high in the vertic Pérez Millán subsoil, which could help to decrease soil hardness. Both Bt horizons of Villa Lía and Pérez Millán soils differed substantially from each other in clay content (Table 1) and have different clay mineralogy. The expansible clay mineralogy of Pérez Millán soil determined lower mechanical impedance, incompatible with a clay pan. This different behaviour can be ascribed to the characteristics of soil prisms and the occurrence of desiccation cracks among them (Amato & Ritchie, 2002; Dardanelli et al., 2003).

A threshold of 2 MPa, measured with probes (tip angle of 30 °), has often been mentioned to detect mechanical impedances for crop root growth (Gupta and Allmaras, 1987; Glinski & Lipiec, 1990; Passioura, 2002). However, soil resistance can increase by 68 % when 60 ° probes are used instead of 30 ° probes (Voorhees et al., 1975). Soil PR values determined here exceeded both threshold limits by far. In Argentina, Pilatti & Orellana (2000) observed that a threshold of 6 MPa is more suitable for Pampean soils similar to those studied here, using a 60 ° probe.

Maize root abundance

The abundance of maize roots was affected by independent and highly significant effects of tillage and depth (Figure 3a,b,c). Tillage effects were most evident in Chivilcoy, where maize root abundance was significantly higher in ZT than in CT plots below 0.1 m. This can be explained by the higher BDs (Table 3) and PRs (Figure 2c) observed in the CT plot, due to the occurrence of induced plough pans. This situation represents an effect known as "shadow effect", as shown by Tardieu (1988) for surface-compacted soil layers. Even when there is no mechanical impedance in the rest of the profile, the occurrence of surface compaction affects root exploration in the zone of the profile below this compacted layer. Map distributions of maize roots showed that a major soil volume of the CT plot has little or no roots below 0.75 m (Figure 4a). In the ZT plot of Chivilcoy Maize root exploration occurs throughout the profile (Figure 4b). A differentiated water and nutrient absorption by maize can therefore be expected in each tillage treatment (Tardieu, 1988; Passioura, 2002).

Although soil profiles differed greatly in summer in Villa Lía and Pérez Millán sites (Figure 2d,e), the root abundance profiles did not (Figure 3b,c). Tillage affected

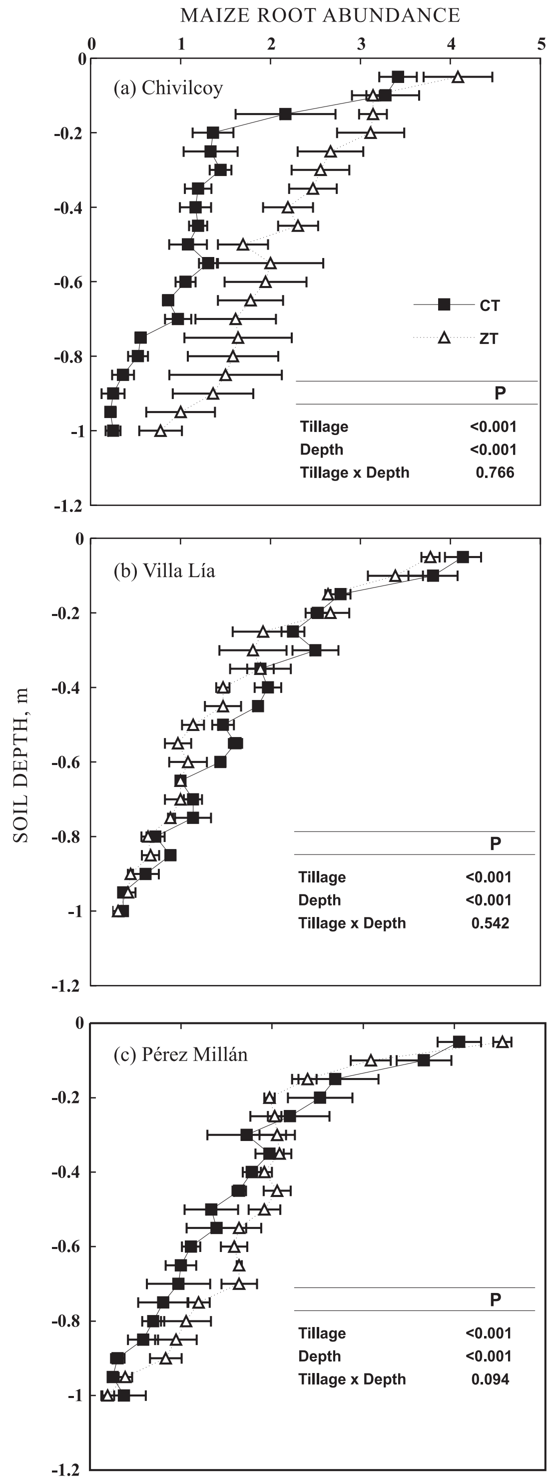

Figure 3. Relative abundance of maize roots in 1 m deep soil profiles in conventionally-tilled (CT) and zero-tilled (ZT) soil profiles of study sites. Standard errors of the means are indicated by bars. ANOVA tables are also included.

maize root abundance in both soils significantly, while the magnitude of this effect was generally little relevant.

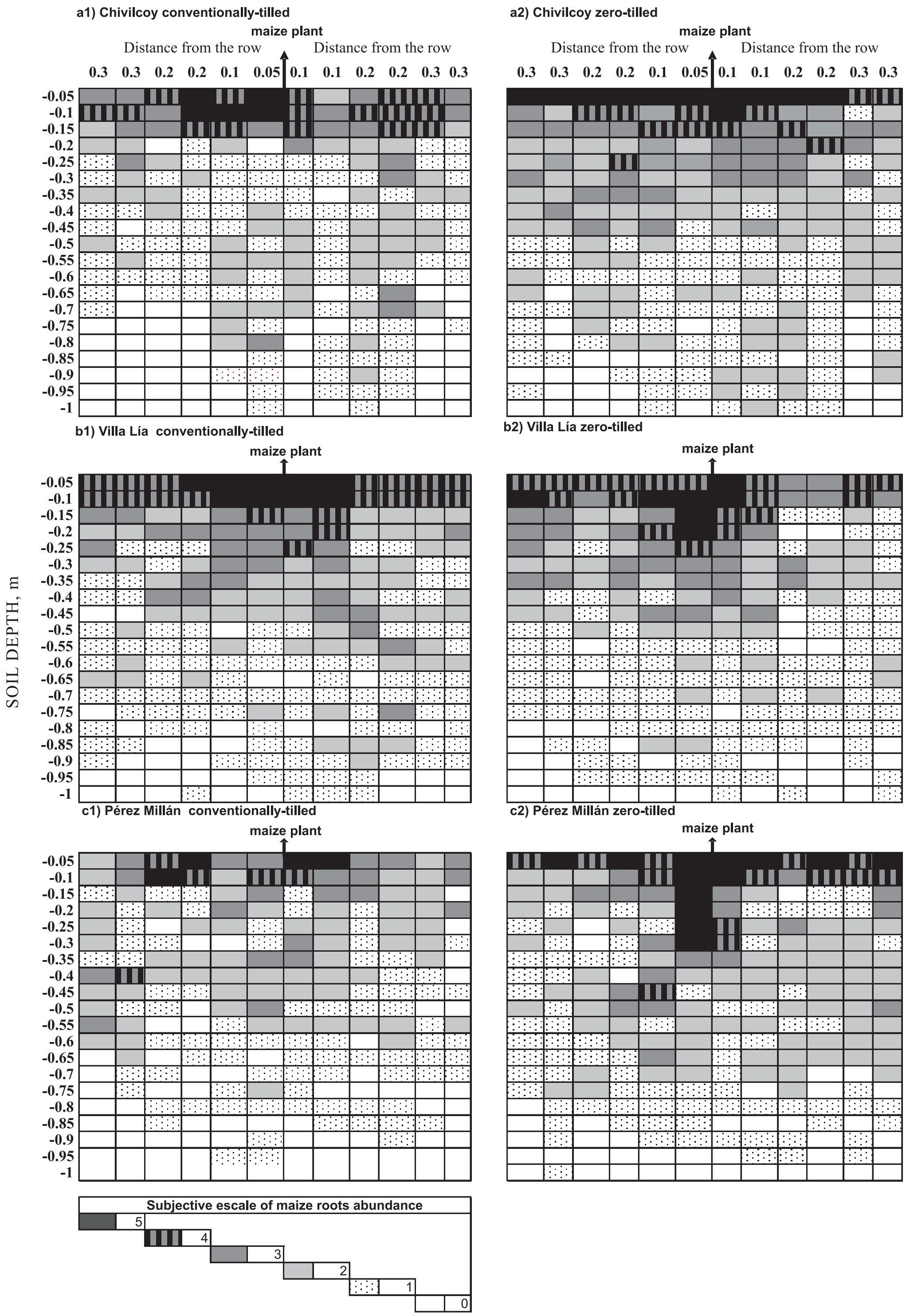

Figure 4. Spatial distribution of maize roots in 0.6 wide and 1 m deep soil profiles under conventional tillage (CT) and b) zero tillage (ZT) at the studied sites.

An exception was the higher maize root abundance under ZT in Pérez Millán profile below 0.4 m (Figure 3c). Because of this root abatement only 10 % relative maize abundance was observed below 0.8–0.9 m. However, taking the sharp PR drop with depth in Pérez Millán into account, maize root abundance decreases with depth were due to the sharp PR increase detected in the deeper BA horizon under both CT and ZT.

Results obtained here give rise to a highly controversial issue: Do structured subsoils, like these tough Bt horizons, represent an absolute mechanical impedance to crop root growth or not, and to which extent? In a recent work carried out in Pampean soils, Micucci & Taboada (2006) observed that soybean root abundance decreases sharply when subsoil clay content reaches 35 %. In another study Dardanelli et al. (2003) found that rather than forming absolute impedance, structured Bt horizons change root distribution pattern of soybean by clumping. This seems to be the case in Villa Lía and Pérez Millán subsoils, as shown by the respective maps of maize root distribution (Figure 4b,c). In these figures, root clumping through desiccation cracks can be detected in dark coloured zones connected downward? As a result, the distribution of maize roots in the Villa Lía and Pérez Millán subsoils is uneven. This irregular distribution strongly limits water absorption in Bt horizons, as shown by Amato & Ritchie (2002). In our soils, the evidence is given by the high GWC (close to field capacity) in both Bt horizons in the summer, unlike the drier condition of soil horizons above and below (Table 4). Although a huge amount of available soil water can be stored in the clayey Bt horizons, most of it can not be absorbed by maize roots because of the uneven distribution in subsoil.

CONCLUSIONS

The only man-made compaction was an induced pan observed in the CT loamy Chivilcoy soil. Compared to the ZT plots, this induced pan caused a reduction in maize root abundance of 40–80 % below 0.1 m. ZT caused no surface compaction in the three studied soils. Both fine-textured soils were affected by genetic compaction in the subsoil, although the causes were different. Penetrometer measurements helped to detect a clay pan in an Abruptic Argiudoll (Villa Lía), but not in a Vertic Argiudoll (Pérez Millán). The profiles of maize root abundance and root distribution were however similar in both soils and little affected by tillage. Maize roots grew through desiccation cracks through the clayey Bt horizons of Villa Lía and Pérez Millán soils (root clumping). Despite the strong Bt horizon in Pérez Millán, maize root growth was impeded by a strong compacted layer detected at the bottom of the BA horizon.

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