

Effects of different tillage regimes on soil compaction, maize (*Zea mays* L.) seedling emergence and yields in the eastern Argentinean Pampas region

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ARTICLE INFO

Article history:

Received 15 March 2011

Received in revised form 11 October 2011

Accepted 12 October 2011

Available online 9 November 2011

Keywords:

Planter

Direct sowing

Soil cover

Cone index

Mouldboard plough

Chisel plough

ABSTRACT

Crop establishment depends primarily on the methods used for seedbed preparation and sowing. Our main objective was to evaluate the soil compaction and crop residue effects on maize (*Zea mays* L.) seedling emergence and yields in three tillage regimes: direct sowing (DS), chisel plough (ChP) and mouldboard plough (MP). The current study was performed in the eastern section of the humid subtropical Rolling Pampa region, Buenos Aires State (Argentina) between October 2004 and March 2007. The soil of the study site is a typical Argiudoll. We hypothesised that maize yields are affected by different tillage regimes used for seedbed preparation and that the traffic for the three tillage regimes caused subsoil compaction. The variables measured were: (1) cone index (CI) in the 0–450 mm depth profile; (2) root dry matter per plant (RDM); (3) dry matter per plant (DMP); (4) seedling emergence (SE); and (5) maize yields (MY). The results showed that in DS, the high soil compaction level causes smaller yields (decrease between 10.7 and 15.2%) compared with the other two tillage systems. SE was slower under ChP and MP compared with DS, but similar results were achieved 18 days after sowing. The highest RDM average values for three growing seasons were observed in ChP and MP (42.3 and 46.1 g plant⁻¹, respectively) compared to DS (37.1 g plant⁻¹). The study produced the following conclusions. Maize yield was directly related to root dry matter per plant, which was affected by soil compaction. The soil Ap horizon needs to be tilled to improve yields. Despite the greater number of tractor passes in ChP and MP, all systems caused subsoil compaction. SE was not affected by plant residue.

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1. Introduction

In Argentina, 20 million hectares of crops are planted by continuous direct sowing (DS). The remaining crop area, approximately 18 million hectares, is cultivated using conventional tillage. The area's climate is characterised by very intense rainfall periods, particularly when summer crops have not completely covered the land or are not yet sown (Pecorari, 1988). The predominant soils have high clay content (heavy soils). The use of conservation tillage in such soils reduces erosion at least 50% compared with bare, fallow soils (Botta et al., 2009a).

Conservation tillage includes any tillage or sowing system that allows at least 30% of the soil to remain covered with crop residue after planting (EP291.2, ASAE Standard, 1993). This definition includes non-inversion tillage systems, such as chisel ploughing, and sowing without previous ploughing, also called DS or no-till. One obstacle preventing the wide use of conservation tillage is the

difficulty of planting in such soils. DS has been in use in Argentina since 1980s owing to the increased availability and lower price of agrochemicals and owing to the reduction in the number of operations and the machinery required (Botta et al., 2006). DS systems usually have lower traffic intensities than those used in conventional tillage systems. However, yields tend to decrease after several years of continuous DS (Botta et al., 2008). This decrease could result from a combination of increased weed control problems, root diseases, soil compaction and abundant crop residues on the soil surface.

If agricultural soils are compacted, the pore volume is reduced, the aggregates crumble and smaller inter-aggregate pores are formed with non-accommodating faces (Pagliai and Vignozzi, 2002).

Botta (2000) found that on a soil with high clay content (Vertisol soil) in the northeast Pampas region, the loosening of the soil by conventional tillage forms more macropores at the beginning of the season. However, the persistence of this alteration depends primarily on the structural stability of the soil, the rainfall patterns that may occur after tillage, and the occurrence and timing of field traffic. In this context, Canarache et al. (1984) found

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that for each 1 kg m^{-3} increase in bulk density, the decrease in maize grain yields in Romanian soils (Continental climate) was 18% of the yield on a non-compacted plot.

Botta et al. (2004) and Jorajuria et al. (1997) state that soil compaction has long been known to cause root growth and yield reductions in many crops. Both soybeans (*Glycine max* L. Merr.) and perennial crops are particularly susceptible in the humid subtropical climate of the west Argentine Pampas region.

Taylor et al. (1966) measured the number of cotton plant taproots that penetrated compacted layers of different soils in semiarid environments in the USA. They found that the number of roots penetrating the soil decreased markedly as the penetration resistance approached 2 MPa.

However, the spatial distribution of residues in the soil under DS is not uniform over the soil surface, and areas of different temperature are formed. The ground tools used by the planter normally displace surface residues from the row zone. Optimising the placement of surface residues requires knowledge of the influence of residues on the conditions in the bare-row zone. In this type of system, the planter seeding assembly plays an essential role because it works soil that has not been tilled previously.

Maize (*Zea mays* L.) shows poor leaf plasticity, poor tillering capacity and low prolificacy. These characteristics reduce its ability to compensate for low plant densities (Tourn et al., 2003). Moreover, if the plants do not reach the growth threshold for fixing the ear during the period between the fortnight before flowering and the fortnight after flowering, they will be sterile (Andrade et al., 1996). This observation demonstrates the importance of a uniform stand.

The need for sowing maize directly at an early planting date when crop residue volumes are large to improve the plant population has prompted the use of row cleaners in seeding assemblies. This addition also reflects the need to reduce the amount of plant debris along the seeding line to enhance seedling emergence and the resulting yield (Tourn et al., 2003).

Surface residue delays drying, lowers the soil temperature and delays the development of strong surface seals by limiting the energy input to the soil. Such effects result primarily from the interception and reflection of incident radiation (Abrecht and Bristow, 1990). Seedling emergence is impaired by the presence of crop residues and soil compaction, which lowers soil temperature. Increased seeding density is therefore required to achieve the same plant population obtained with conventional systems (Botta et al., 2009b).

This study hypothesised that: (a) maize yields are affected by the tillage regime used for seedbed preparation and (b) the traffic for the three tillage regimes examined caused subsoil compaction.

The objectives of the study were to quantify the soil compaction and crop residue effect on maize seedling emergence in three

tillage regimes using two planters currently in use by Argentinean farmers and to assess maize grain yields during three growing seasons in response to different tillage regimes.

2. Materials and methods

2.1. The site

The experiment was conducted in the eastern Rolling Pampa region, Buenos Aires State, Argentina at $34^{\circ} 82' 50\text{S}$, $59^{\circ} 81' 50\text{W}$. The altitude of the site is 22 m above sea level. The slope is type 1, with a gradient of 0.5%. The soil is a fine clayey, illitic, thermic typical Argiudoll (Soil Conservation Service, 1994), with an organic matter content ranging from 3.6% (w/w) at the surface to 1.4% at a depth of 0.6 m. The physical and mechanical properties of the soil are given in Table 1. Soil management history includes 10 years of crop rotation following a very common regional pattern, winter wheat (*Triticum aestivum* L.) followed by maize (*Zea mays* L.) in the summer.

2.2. Tillage treatments

The following three tillage regimes (treatments) were used (Table 2).

- Direct sowing (DS) for 11 successive years. This system is a common regional alternative in a crop rotation of winter wheat (*Triticum aestivum* L.) and soybean (*Glycine max* L.) or maize (*Zea mays* L.).
- Primary tillage with a chisel plough (ChP) with 11 rigidly mounted curved shanks measuring $25 \text{ mm} \times 20 \text{ mm}$ spaced 285 mm apart operating at a 280-mm depth and pulled at 6.12 km h^{-1} , followed by a disk harrow (600 N/disk, 30 disks) to a depth of 150 mm, followed immediately by an eight-section spike-tooth harrow and two passes of a basket roller.
- Conventional primary tillage with a mouldboard plough (MP) to a depth of 200 mm, followed immediately by two passes with a tandem disk harrow (490 N/disk, 40 disks) and one pass of a shaped spring tooth harrow. This treatment represents a tillage system commonly used in the region. This treatment has been used in conventional tillage for over 30 years.

2.3. Machinery used

A Valmet (160 CV/117 kW engine) front wheel assist (FWA) tractor weighing 98 kN (39.2 and 58.8 kN on the front and rear axles, respectively) was used at a travel speed of 5.5 km h^{-1} . New 16.9 R 28 front tyres and 20.1 R 30 single rear tyres were inflated to 100 kPa and 80 kPa, respectively, both within the range advised by

Table 1
Characteristics of the soil profile.

Horizons	Ap	A12	B1	B21t	B22t	B23t	B3	Cca
Depth range (cm)	0–15	16–22	23–35	35–60	65–80	90–110	120–150	160–220
Organic carbon (g kg^{-1})	17.4	13.5	9.3	6.3	5.0	3.1	2.2	1.4
Total nitrogen (g kg^{-1})	2.4	1.4	1.0	0.85	0.75	0.58	0.42	–
Clay (<2 μm) (g kg^{-1})	212	255	249	332	475	330	230	158
Silt (2–20 μm) (g kg^{-1})	32.3	34.7	29.8	29.3	20.8	31.2	32.9	287
Silt (2–50 μm) (g kg^{-1})	756	708	672	613	500	630	727	799
Fine sand (100–250 μm) (g kg^{-1})	3.0	2.0	3.0	4.0	4.0	4.0	5.0	4.0
Coarse sand (500–1000 μm) (g kg^{-1})	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pH in H_2O (1:2.5)	5.8	5.8	6.0	6.2	6.5	6.4	6.4	7.9
Cation of change (m.e. 100 g^{-1})								
Ca^{2+}	11.4	12.7	12.0	13.8	18.3	17.2	16.5	–
Mg^{2+}	2.9	2.5	3.1	4.5	6.5	6.4	3.8	–
Na^+	0.2	0.1	0.2	0.1	0.2	0.2	0.3	0.5
K^+	1.4	1.0	0.9	1.3	2.3	2.4	2.3	2.4

Table 2
Description and characteristics of the treatments.

Tillage treatments	Description	Number of tillage/passes per hectare	Total load ^a (kN)	Total displacement ^a (km ha ⁻¹)
DS	Sprayer (pre seeding) and direct planter	2	187	3.11
ChP	11 rigidly mounted curved shanks – disk harrow (600 N/disk, 30 disk) – eight section spike tooth harrow – two passes of a basket roller	5	60.4	7.1
MP	Mouldboard plough – twice tandem disk harrow – one pass of a shaped spring tooth harrowing	4	94.4	10.98

^a Load and displacement: complete equipment and weights are loaded.

Firestone Agricultural Tyres (2011). The tyre/soil contact area was 0.400 and 0.873 m² in the front and the rear, respectively, and the ground pressure was 49 and 33.7 kPa in the front and the rear, respectively. These measurements were conducted on the experimental field by reversing or driving the tractor onto the field and spraying the area around the tyre with paint. A hydraulic lift was then used to raise the tractor so that the tyre impression could be transferred to a sheet of glass and then to paper and measured with a planimeter. The average ground pressure was estimated as the total axle load divided by the tyre/soil contact area for both tyres on the axle. This tractor was used on all the tillage treatments.

Two different planters were used: Planter 1 (Super Walter) and Planter 2 (John Deere 1750 Max Emerge). DS was trafficked with one pass of a FWA Valmet tractor (160 CV/117 kW engine) and a Super Walter planter, whereas the ChP and MP treatments were trafficked with one pass of the same tractor and a John Deere 1750 Max Emerge. Both of these tractor and planter models are commonly used on commercial farms in the area of the experiment. Notably, this experiment involves two planters in three treatments. This approach was used because a specific planter was required for DS and can only be used under this condition. In the other two treatments (ChP and MP), a specific planter was used for this condition. This planter cannot be used for DS. The specifications for the planters are shown in Table 3.

2.4. Treatments and survey parameters

Twelve 100 m by 7 m plots (for 10 rows 0.70 m apart) were randomly assigned to four replicates for each tillage treatment with 20 m wide buffer zones between plots to avoid interactions.

DK4F37 hybrid maize (*Zea mays* L.) was sown on October 5, 2004; October 8, 2005 and October 6, 2006.

The previous grain crop was wheat. Maize was harvested on March 28, 2005; March 10, 2006; and March 9, 2007, for all treatments. The yield was measured using small quadrants.

The number of emerged plants per linear metre was observed for all the rows and tractor tracks. The sample consisted of 320 observations in each case (track and row) (40 observations/

row × 8 rows/replicate). Counts were taken 11, 14 and 18 days after seeding. Before planting (pre-seeding), residue cover was determined by the transect method (Gargicevich, 1995).

The trial was designed to determine the density of dynamic sowing at a tractor speed of 5 km h⁻¹. After sowing, the seeds distributed along each linear metre in uncovered furrows were counted. The resulting value was 5.8 seeds per metre. The seeding depth was maintained at 5 cm.

The soil water content (w/w) and cone index (CI) were measured on the same day after sowing. These measurements were made on 5 October, 2004; 8 October, 2005; and 6 October, 2006.

The soil water content was measured with a Troxler 3440 gamma-ray and neutron probe over depth ranges of 0–150 mm and 150–300 mm and in a trench of 300–450 mm depth. In soils with high organic matter, as was the case here, the neutron probe can overestimate soil water content substantially. Accordingly, this parameter was verified by cylinder method.

The cone index was determined with a Scout 900 S 313 recording penetrometer (ASAE Standard S313.2, 1992). Each datum represented the average of 25 samples taken from each plot in the 0- to 450-mm depth range at depth intervals of 25 mm. The soil water content and CI were measured at randomised locations on all plots. The CI data collected before sowing (control plot) furnished a clear indication of the initial soil condition in each tillage treatment. The effects of the traffic treatments on the soil were measured at the moment of sowing in the centre lines of the tyre tracks because the compressive effects tend to be concentrated at this point (Söhne, 1958).

Root dry matter (RDM) and dry matter per plant (DMP) were measured 8 weeks after seedling emergence (in tasseling). Roots were sampled in the 0- to 300-mm depth range. Root dry matter was measured to 300 mm only because most of the roots were concentrated in the first 250 mm. A total of 70 samples were taken per treatment. To determine the dry weight, the roots were dried at 104 °C in a conventional oven to constant weight after the soil particles were washed from the roots. For DMP determination, the plants were cut just above the soil level, rinsed in distilled water and oven dried to constant weight.

Table 3
Planter specifications.

Specifications	Super Walter PLANTER 1	John Deere 1700 Max Emerge PLANTER 2
Total weight loaded (kN)	69.6	14.9
Width (mm)	7000	5600
Number of units	10	8
Distance between row spacing (mm)	700	700
Seed metering system	Seed plate	Pneumatic vacuum distribution
Tyres	400/60–15.5	7.60–15
Ground pressure (kPa)	122	91.6
Seed units	Turbo coulter blade + double disc opener	Double disc with double depth limiting wheel (without coulters)

Table 4

Ten-day average maximum air temperature and total rainfall during maize production in Luján, Buenos Aires (C.I.D.E.P.A. Meteorology Station, Luján University).

Period		Rainfall (mm)			Avg. max. temp. (°C)		
		Oct/04-March/2005	Oct/05-March 2006	Oct/06-March/2007	Oct/04-March/2005	Oct/05-March/2006	Oct/06-March/2007
October	1–10	28.5	26.0	22.0	25.4	23.0	25.0
	11–20	15.0	12.0	18.0	26.1	20.0	24.0
	21–31	14.0	15.0	19.0	24.0	21.0	22.0
November	1–10	32.0	24.0	30.0	23.7	26.0	25.0
	11–20	40.0	31.0	26.0	24.5	25.0	23.0
	21–30	34.0	30.0	28.0	23.1	22.0	26.0
December	1–10	55.2	50.0	41.0	27.0	25.0	25.0
	11–20	80.0	15.0	75.0	27.6	26.0	27.0
	21–31	23.3	14.7	22.0	28.0	25.0	27.0
January	1–10	0.0	3.0	2.0	33.4	32.0	33.0
	11–20	25.0	40.0	21.0	31.0	32.0	32.0
	21–31	95.0	80.0	78.0	32.3	32.5	32.1
February	1–10	82.0	19.0	75.0	27.3	28.0	27.2
	11–20	26.0	22.0	20.0	28.5	27.0	27.5
	21–28	23.0	21.0	19.0	28.0	26.7	29.0
March	1–10	30.0	9.0	32.0	27.1	27.8	27.0
	11–20	6.0	6.0	4.0	26.2	25.6	26.0
	21–31	35.0	31.0	30.0	25.6	24.0	26.0

The data were subjected to analysis of variance (ANOVA), and the means were separated by Duncan's multiple range test using the Statgraf 7.1 program (Botta et al., 2006). To analyze the effects of soil compaction and residue cover (factors) and their interaction on maize seedling emergence, we used a two-way ANOVA procedure.

3. Results and discussion

3.1. Soil water content, weather conditions and initial soil conditions

The soil water content (w/w) on the sowing day, averaged over all three years, was 18% dry weight from 0 to 150 mm deep, 19% from 150 to 300 mm deep and 20.1% from 300 to 450 mm. In general, the soil water content did not differ significantly between treatments at the time of measurement of seedling emergence. Therefore, the differences found in seedling emergence could be the result of the treatments. The cone index may also be regarded as an effective indicator of the degree of soil compaction during treatment.

The ten-day total rainfall and average maximum temperatures from October 1 to March 31 for each year are shown in Table 4. The average maximum air temperature was moderate in October, November, December, February and March, but it exceeded 32 °C in January. The rainfall in October was suitable for seedling emergence. Because the rainfall was heavy before harvesting (during the last 10 days of March), the soil water content was high. According to our

study of the complete cycle of maize cultivation, the temperature was normal for the summer. According to Tourn et al. (2003), the temperature affects the length of the crop cycle from seeding until physical maturity is reached, whereas the photoperiod can affect the time between sprouting and flowering. During the maize production season, the weather conditions were quite similar over the three study years. Therefore, any variations in the maize yields would be the result of the different soil tillage treatments.

Fig. 1 shows the cone index before planting (pre-seeding) for the three tillage treatments and offers a clear indication of the initial soil condition in each treatment. This figure shows that the CI in the DS was greater than 2 MPa in the 0- to 450-mm depth range. The effects of MP and ChP are evident compared with the DS tillage treatment. The CI in the two primary tillage treatments was statistically different ($P < 0.01$) from that on the DS soil, but at different soil depths (as expected), 280 mm for ChP and 200 mm for MP. The analysis of variance of the cone index values averaged over depths from 200 to 350 mm showed a significant difference between the ChP and MP plots. The CI was higher for MP than for ChP.

3.2. Plant residue and soil compaction

Effects of soil compaction and plant residue cover and their interaction on maize seedling emergence were analyzed. The mean percentage residue retained after tillage showed that MP soil

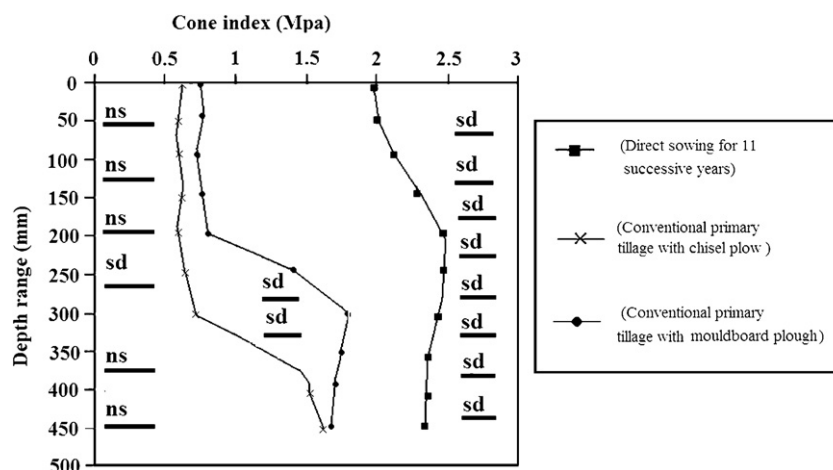


Fig. 1. Cone index (MPa) on sowing day in 2004. References: ns, non-significant; sd, significant difference ($P < 0.01$) Duncan's multiple range test.

Table 5
Effect of soil compaction (as cone index 0–150 mm) and plant residue cover on maize seedling emergence for three growing seasons.

Tillage treatments	Cone index (kPa)	Plant residue cover (%)	Maize seedling emergence								
			1st Growing season 2004–2005			2nd Growing season 2005–2006			3rd Growing season 2006–2007		
			Days after planting			Days after planting			Days after planting		
			11	14	18	11	14	18	11	14	18
MP	1.13 a	12.1 a	0.35 a	2.80 a	4.50 a	0.30 a	2.60 a	5.00 a	0.35 a	2.20 a	5.50 a
ChP	1.17 a	40.1 b	0.25 a	2.71 a	5.00 a	0.35 a	2.30 a	4.80 a	0.31 a	2.80 a	5.00 a
DS (in furrow)	2.62 b	11.4 a	1.50 b	4.50 b	5.70 a	1.60 b	5.10 b	5.80 a	1.61 b	5.20 b	5.70 a

Different letters within columns indicate a significant difference ($P < 0.01$).

cleared the plant residue significantly more effectively than ChP and DS. Botta et al. (2009a) found that the continued use of DS (each year for several years) resulted in an accumulation of crop residue and soil compaction (Table 5).

A survey of planting practices in the study area revealed that plant residue is a significant impediment to the planting of row crops by direct sowing, especially if heavy planters with runner-type furrow openers are used. In maize cultivation, clearing surface crop residues helps to planting and also accelerates soil warming (Andrade et al., 1996).

On soil managed under the DS system, the plant residue cover in the furrow depends on the use of a cleaner system in the planter. The cleaner system consisted of a turbo coulter blade and a double-disc opener. The smaller amount of residue left in the furrow by planter 1 was primarily the result of the large amount of soil removed by the turbo coulter blade even though the blade was correctly attached.

According to Tourn et al. (2003) residue clearance owing to the action of the turbo blade significantly improved seedling emergence over the conventional treatments (ChP and MP). However, no differences in seedling emergence were observed in this study. Seedling emergence did not differ between treatments 18 days after seeding (Table 5).

Table 6 shows the CI values after sowing for all treatments over the 3 years studied. The study found that compaction by the heavy equipment (planter 1 and tractor) caused greater changes in the topsoil and subsoil properties than did the light equipment (planter 2 and tractor). These results are consistent with those of Botta et al. (2006), who showed that compaction effects at a high axle load are related to the soil type, the number of passes and the number of years since compaction. In the first growing season, the increase in CI resulting from sowing traffic was particularly marked in the 0–300 mm depth layer, although the increase in resistance in the ChP and MP treatments was smaller than that in the area under DS. Examination of the soil response to traffic in

deeper layers revealed that soil compaction, as indicated by CI, increased in the depth range of 300–450 mm (peak values for three years). All the CI values measured in soil under DS after sowing traffic were higher than the values measured for the tillage treatments (ChP and MP). An important reason for the greater CI in DS soil is the low compressibility of this firm soil, as shown by its high cone index values compared with tillage treatments. At the 300- to 450-mm depth range, the average CI values in treatment 1 (DS) for the three study years were 2.80, 2.94 and 3.05 MPa for 2004, 2005 and 2006, respectively.

For all treatments, the CI between a depth of 300 and 450 mm in all 3 years was greater than the 1.5 MPa limit cited by Jorajuria et al. (1997) as necessary for avoiding restricted root growth. Moreover, the peak values of CI occurred at progressively greater depths in later years. All values exceeded those cited as critical for root-growth retardation (Botta et al., 2004, 2008; Jorajuria et al., 1997). These values of CI indicate over-compaction in subsoil. They exceed the 1 and 1.2 Mpa limits recommended by Narro Farias (1994) and Terminiello et al. (2000), respectively, to avoid decreases in yield. Hence, these data support the second hypothesis. Reminding what the second hypothesis was: the traffic for the three tillage regimes examined caused subsoil compaction.

3.3. Root dry matter, dry matter per plant and maize yields

Root dry matter (RDM) was affected negatively by soil compaction. As the soil cone index increased, RDM decreased within the soil profile (Fig. 2). For the three soil tillage regimes in the three growing seasons 8 weeks after seedling emergence (at tasseling), significant differences in the average RDM were observed in different tillage plots. The highest average RDM values during the three growing seasons were found in the MP and ChP treatments (46.1 and 42.3 g plant⁻¹, respectively), whereas the highest value in DS was 37.1 g plant⁻¹.

Table 6
Means of cone index (MPa) for three growing seasons and traffic effect on three tillage regimes: (DS) soil under direct sowing, (ChP) chiseled and (MP) ploughed with mouldboard plough.

Depth level (mm)	Sowing 2004			Sowing 2005			Sowing 2006		
	Treatments			Treatments			Treatments		
	DS	ChP	MP	DS	ChP	MP	DS	ChP	MP
0	2.50 b	1.10 a	0.97 a	2.61 b	0.9 a	1.12 a	2.68 bc	1.13 a	1.1 a
50	2.58 b	1.15 a	1.12 a	2.69 bc	1.10 a	1.15 a	2.76 c	1.15 a	1.16 a
100	2.63 b	1.19 a	1.18 a	2.72 bc	1.16 a	1.20 a	2.80 c	1.21 a	1.20 a
150	2.77 b	1.23 a	1.27 a	2.85 bc	1.20 a	1.24 a	2.89 c	1.28 a	1.26 a
200	2.81 c	1.35 a	1.39 a	2.88 c	1.42 a	1.37 a	2.93 cd	1.54 b	1.49 b
250	2.87 d	1.51 b	1.52 a	2.94 de	1.63 bc	1.60 a	2.99 e	1.69 c	1.72 c
300	2.93 c	1.61 a	1.67 a	2.97 c	1.75 ab	1.72 ab	3.02 c	1.82 b	1.83 b
350	2.80 c	1.72 a	1.74 a	3.00 d	1.84 a	1.80 a	3.08 d	1.89 ab	1.86 ab
400	2.75 d	1.63 a	1.61 a	2.95 d	1.78 b	1.73 b	3.10 e	1.95 c	1.91 c
450	2.72 c	1.57 a	1.58 a	2.86 d	1.59 a	1.64 a	2.98 d	1.99 b	2.0 b

Values with different letters (horizontally) are significantly different at each depth ($P < 0.01$) Duncan's multiple range test.

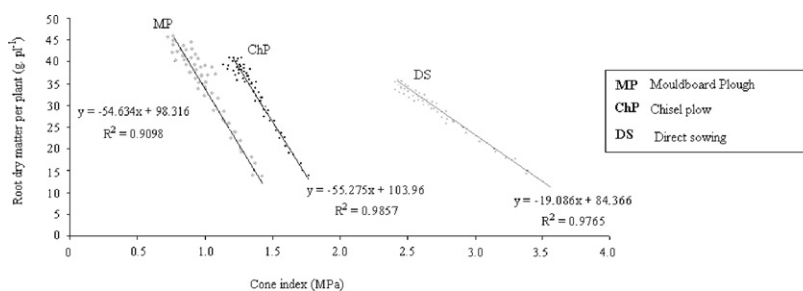


Fig. 2. Relationship between root dry matter per plant and cone index for the three tillage regimes.

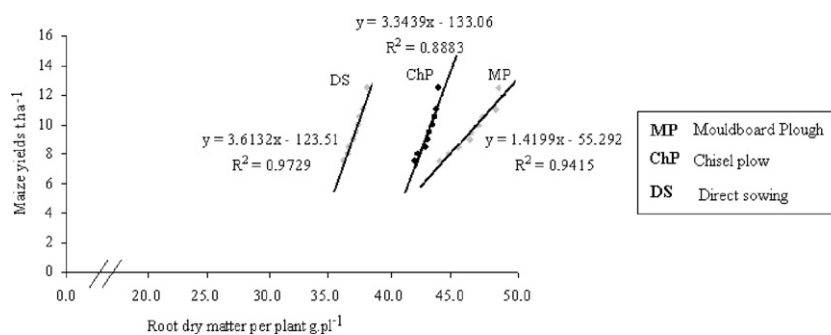


Fig. 3. Relationship between maize yields and root dry matter per plant for three tillage regimes.

Table 7

Root dry matter and dry matter per plant (g plant^{-1}) for three growing seasons in three tillage regimes.

Tillage regimes	1st Growing season	2nd Growing season	3rd Growing season	Average three growing seasons
Root dry matter per plant (g plant^{-1})				
Direct sowing	37.0 a	37.3 a	37.1 a	37.1 a
Chisel plough	43.0 b	42.3 b	41.6 b	42.3 b
Mouldboard plough	47.2 c	46.1 c	45.0 c	46.1 c
Dry matter per plant (g plant^{-1})				
Direct sowing	142.4 a	143.2 a	141.0 a	142.2 a
Chisel plough	152.0 b	153.6 b	150.2 b	152.0 b
Mouldboard plough	158.4 c	160.0 c	159.0 c	159.0 c

Values with different letters between tillage regimes are significantly different at each depth ($P < 0.01$) Duncan's multiple range test.

Fig. 3 shows that after sowing traffic for all treatments during the three growing seasons, the relationship between root dry matter and maize yields was strongly positive. In all treatments, root dry matter was directly proportional to maize yields, with a high regression coefficient. Furthermore, the maize yields were greater in the treatments with weaker soil (ChP and MP). Lower values of soil compaction were associated with greater maize yields. This result confirms the first hypothesis, this was: maize yields are affected by the tillage regime used for seedbed preparation.

For the three growing seasons, the dry matter per plant (DMP) differed significantly among treatments (Table 7). The average DMP for the three growing seasons was 159 g plant^{-1} in the MP treatment, followed by 152 g plant^{-1} in ChP and 142 g plant^{-1} in DS.

Table 8

Maize yields for three treatments in three growing seasons.

Treatments	Direct sowing (DS)	Chisel plough (ChP)	Mouldboard plough (MP)
Crop yield (t ha^{-1}) Harvested 2005	9.9 b	10.8 a	11.1 a
Crop yield (t ha^{-1}) Harvested 2006	10.1 b	11.6 a	11.9 a
Crop yield (t ha^{-1}) Harvested 2007	10 b	11.2 a	12.5 a
Average (t ha^{-1})	10 b	11.2 a	11.8 a

Values with different letters between tillage regimes show significant differences among treatments ($P < 0.01$) Duncan's multiple range test.

Data from the three growing seasons (Table 6) showed that the best results for seedling emergence were produced on soil under DS. However, the average maize yields (Table 8) over the three growing seasons were between 10.8 and 11.6 t ha^{-1} for ChP and between 11.1 and 12.5 t ha^{-1} for MP, respectively.

The DS treatment resulted in a significantly lower maize yield than the ChP and MP. The percentage decreases ranged between 10.7 and 15.2% , respectively. Although soil compaction was much greater in the first 200 mm in DS than in ChP and MP, these differences were small. An overriding factor may have been that for the three growing seasons, the rainfall patterns were particularly favourable for maize growth. This favourable rainfall may have overridden the higher compaction level in the DS treatment. Another contributing factor (Botta et al., 2010) is topsoil damage. It is probable that most of the yield reduction for DS was caused by

damage to the topsoil structure resulting from the higher ground pressure produced by the planter used (>122 kPa; see Table 3). This conclusion is supported by the observation that the saleable percentage of maize yield, which is governed primarily by topsoil structure, was significantly lowered by the sowing traffic intensity in DS. In the second and third years, the peak values of CI found in the subsoil (at or below 200 mm) and the high values of this parameter, probably produced by the high axle load, would have also affected the crop response.

This study also demonstrated that if the axle load increases in soils with a high bearing capacity (soils under a long-term direct sowing system), the crop yields decrease and the subsoil compaction increases. In this situation, furrow openers could be unable to cut the soil after several years of direct sowing owing to strong soil compaction. As a result, the seed placement depth would be incorrect and would contribute to reduced maize yields.

4. Conclusions

- Maize yield was directly related to root dry matter per plant, which was affected by soil compaction caused by equipment traffic in the different tillage regimes.
- The maize yield results obtained for the ChP and MP treatments indicate that the soil Ap horizon needs to be tilled and that the continuous direct sowing used on most farms in the Argentinean Pampas region should be avoided.
- Despite the differences in the number of passes between the DS treatment and the ChP and MP treatments, the subsoil compaction was higher for DS.
- Although many differences in plant residue cover were found among tillage treatments, seedling emergence was not affected.
- Despite the use of a low-load planter, the subsoil compaction in the MP and ChP treatments was high. This outcome is the result of the large number of machinery passes during the crop growing season.

Acknowledgements

This work was carried out under the project of the Iberoamerican Agricultural Sustainability Group. Project Code: A/030047/10.

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