Soil & Tillage Research 110 (2010) 167–174

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Tillage and traffic effects (planters and tractors) on soil compaction and soybean (*Glycine max* L.) yields in Argentinean pampas

G.F. Botta [a,b,*], A. Tolon-Becerra [c], X. Lastra-Bravo [c], M. Tourn [b]

[a] University of Buenos Aires, Agronomy Faculty, Av. San Martín 4453, Buenos Aires, Argentina
[b] National University of Luján, Technology Department, 6700 Luján, Argentina
[c] University of Almería, Ctra Sacramento s/n, La Cañada de San Urbano, 04120 Almería, Spain

ARTICLE INFO

Article history:
Received 22 March 2010
Received in revised form 16 May 2010
Accepted 4 July 2010

Keywords:
Deep tillage
Direct sowing
Soil cover
Implantation conditions

ABSTRACT

Direct drilling systems usually have lower traffic intensities than those using conventional tillage, but despite this, after several years of continuous direct drilling yields tend to decrease. This could be the result of increased weed control problems and root diseases as well as a gradual increase in soil compaction due to agricultural traffic. The draft required, soil cone index, root growth, soybean (*Glycine max* L.) yield and traffic (planters and tractors) compaction over the subsequent three growing seasons were measured. This initially high level of soil compaction in some direct sowing systems might suggest that the impact of subsequent traffic would be minimal, but data have not been consistent. Soil compaction is caused by the high traffic intensity and weight of tractor and seeding machines and combines in harvest operations, especially when these operations are carried out on wet soil or with high ground pressure. The techniques commonly used for control and management of topsoil and subsoil compaction are: subsoiling and chiseling and axle load reduction. Outlined hypothesis was: Traffic with high axle load equipment increases soil compaction and decreases soybean yield. This article quantifies: (a) the effects of subsoiling and chisel plowing were carried out at 350 and 280 mm depth, respectively, on soil compacted under 12 years of direct drill systems and (b) traffic effect on this soil conditions of two equipment for direct sowing (planters and tractors) on soybean yields (*G. max* L.) with two different loads: light equip (LE) and heavy equip (HE). The study showed that: In topsoil for three growing season, traffic with HE (185 kN) caused mean values of CI of 2178, 1506 and 1406 kPa for direct sowing, chiseled and subsoiled soil, respectively, while for the LE (127 kN) the values were of 1855, 1210 and 1206 kPa, respectively. Also in the subsoil traffic with HE caused higher CI values than the LE in all treatments. The CI mean values of the HE traffic were: 2465, 1920 and 1854 kPa for direct sowing, chiseled and subsoiled soil, respectively, while the LE traffic produced 2298, 1639 and 1637 kPa, respectively. For three growing seasons the HE traffic in soil under direct sowing reduces soybean grain yields close to 460 kg ha^{-1}, while for the LE was 250 kg ha^{-1}. When the traffic was made with LE on subsoiled soil there is an effective increase in soybean grain yields of about 330 kg ha^{-1}.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction and literature review

Conservation tillage includes any tillage or sowing system that maintains at least 30% soil cover with crop residue after planting (EP291.2, ASAE Standard, 1993). This includes non-inversion tillage systems, such as chisel plowing, and sowing without previously plowing, also called direct sowing or no-till. Direct sowing has been in use in Argentina since the 1980s due to the increased availability and lower price of agrochemicals, and also due to the reduction in number of operations and the machinery required (Botta et al., 2006).

In Argentina, of the total area cropped, 16 million hectares are planted by continuous direct sowing (DS), and the rest, approximately 22 million hectares, are cultivated using conventional tillage (CT). Direct drilling systems usually have lower traffic intensities than those using conventional tillage, however, after several years of continuous direct drilling, yields tend to decrease (Botta et al., 2008). This could be from a combination of increased weed control problems, root diseases, soil compaction, high axle load of the direct sowing machines and agricultural traffic. In this regard Botta et al. (2009) found that: the tracked area when sowing 1 ha with the conventional equipment is 4073 m^2 compared with 2461 m^2 for the direct sowing equipment; this is because the tyres of the tractor and planter, in direct sowing, track in the same place.

* Corresponding author at: National University of Luján, Technology Department, 6700 Luján, Argentina. Tel.: +54 2323 422350; fax: +54 2323 422350.
E-mail address: sad@s6.coopenet.com.ar (G.F. Botta).

0167-1987/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2010.07.001

Soil compaction has long been known to cause root growth and yield reductions in many crops, but both soybeans (*Glycine max* L. Merr.) and perennial crops are particularly susceptible in the west Argentine pampas region (Botta et al., 2004; Jorajuria et al., 1997). In this context Canarache et al. (1984), in Romanian soils, found that for each 1 kg/m^3 increase in bulk density, a decrease in maize grain yields was 18% relative to the yield on a non-compacted plot.

When agricultural soils are compacted the volume of pore is reduced, the aggregates crumble and smaller inter-aggregates pores are formed with non-accommodating faces (Pagliai and Vignozzi, 2002). The major loss of the largest pores, caused by soil compaction, has the effect of changing the pore size distribution and hence the water retention characteristic (Dexter, 2004).

These results illustrate the potential for compaction to depress crop yields. Extremely dense soil impedes root growth and thereby limits plants water consumption.

Root responses to compaction may be complex due to the numerous ways in which compaction can modify the physical properties of soil. There have been many attempts to find critical values of cone index, soil strength or permeability that are related to root growth limiting factors.

Taylor et al. (1966) measured the number of taproots of the cotton plant which penetrated compacted layers of different soils (soil types: Quinlan, Columbia, Naron and Miles), and characterized the degrees of compaction by means of measurements with a cone penetrometer. They found that: number of roots penetrating soil was reduced drastically as the penetration resistance approached 2 MPa pressure. In fact, at soils compacted to more than 2 MPa resistance, virtually no roots at all were able to grow.

The techniques commonly utilized for control and management of topsoil and subsoil compaction are: subsoiling and chiseling, controlled traffic farming and axle load reduction. Subsoiling and chiseling (depth of 280–450 mm) are utilized for controlling subsoil compaction and to increase crop yields (Balbuena et al., 1998; Cisneros et al., 1998).

Subsoiling and chiseling are carried out on an annual basis in some sandy and lime-rich soils in the west Pampas region because of these soils's susceptibility to aeolian erosion and soil compaction. The extent to which this compaction occurs naturally and the amount that is caused by wheel traffic has not been well quantified.

Reeder et al. (1993) studied the effects of deep tillage on physical properties in silty clay loam and on crop yields. They found that two passes of a tractor re-compacted the soil by the time the first crop was planted. They advised that controlled traffic is essential to obtain long term benefits from subsoiling. Deep tillage increased soybean and corn yields (3.0–6.9% in 1991 and 1.5–3.0% in 1992) in areas not trafficked.

Raper et al. (1994) compared various cotton tillage systems on a sandy loam complex soil (Typic Hapludults), including annual subsoiling at 0.4 and 0.5 m depth. They found that the positive effects of controlling traffic were significant only when in-row subsoiling was not used as an annual tillage treatment. In addition to the environmental benefit of maintaining surface residues, they found that strip tillage involving only in-row subsoiling to 0.4 m depth decreased cone index directly beneath the row, decreased topsoil bulk density, increased soil water content, decreased energy usage and increased yields.

The power and draft required by deep tillage implements vary according to depth, soil type and forward speed. A conventional straight shank subsoiler operating at 520 mm depth in clay soil required about 29 kN of draft. Drawbar power ranged from 24 kW at 1 ms^{-1} to 36 kW at 1.4 ms^{-1}. In same soil conditions Shinners (1989) found that a paraplow operating at 1.1 ms^{-1} required 28 kW at 220 mm depth and 32 kW at 300 mm depth. Increasing the operating depth to 380 and 460 mm meant that the forward speed had to be decreased to 0.94 and 0.89 ms^{-1}, respectively, to keep required power at about 32 kW.

Botta et al. (2004) working in different soils (sand and clay) at 350 mm depth, found that engine power increased by an average of 18% from about 28 kW per shank for a curved leg to about 36 kW per shank for a straight leg. The author concluded that a major factor in power requirement is the horizontal pressure of the leg against the soil, which significantly increased the shear force.

The main objectives of this work were: (a) to determine the main and interactive effects of various high load traffic (tractor and planter) and tillage systems on soil cone index and soybean productivity; (b) to quantify the change in cone index of a Typical Argiudol soil due to deep tillage operations (subsoiler and chisel plow) in three growing seasons; (c) to quantify power and draft required by deep tillage.

2. Hypothesis

Outlined hypothesis was: Traffic with high axle load equipment increases soil compaction and decrease soybean yield.

3. Materials and methods

3.1. The site

The experiment was conducted in the east of the Rolling Pampa region, Buenos Aires State, Argentina at 34°27′S, 58°40′ W; altitude 22 m above sea level; slope type 1 with gradient 0.5%; well drained, drainage class 4; no stone class 0. The soil was a fine clayey, illitic, thermic Typical Argiudol (Soil Conservation Service, 1994), with an organic matter content ranging from 3.6% (w/w) in the surface to 1.4% at 0.6 m depth. Soil physical and mechanical properties are given in Table 1.

3.2. Experimental treatments and layout

The soil management history includes 12 years of crop rotation following a very common regional pattern, winter wheat (*Triticum aestivum*) followed by soybean (*G. max* L.) in summer. For the duration of this trial only soybean was as summer crop, because in the Argentina the farmers (generally) does not own of the big sowing machine (the contractors are the owners of the machinery and work all over the productive zone). The contractors work against the time. It is very difficult to request them to delay their labors.

The experimental design consisted of a completely randomized blocks with six replications. The main plots were:

(T1) Soil under direct sowing for 12 successive years (unloosened).
(T2) Chisel plow (deep loosening to 280 mm depth) in the spring followed by secondary tillage in the sowing date.
(T3) A V-frame 7 shank subsoiler (deep loosening to 350 mm depth) in the spring followed by secondary tillage in the sowing date. The control plot was soil under direct sowing system per 12 years.

Power and draft (PD) required for subsoiler and chisel plow: drawbar load cells were provided by the Agricultural Machinery class (Agronomy Faculty Buenos Aires University Argentina). A cab-mounted unit collected draft force data with a sampling frequency of 200 Hz. Data were stored in a data logger and downloaded to Excel files for analysis.

Secondary tillage was similar for two deep tillage treatments and consisted of: two passes of a tandem disk harrow (490 N/disk,

Table 1
Soil physical and mechanical properties.

Depth (mm)	0–150	150–300	300–450	450–600
Proctor				
Optimum water content (%, w/w)	22.3 ± 0.18	23.0 ± 0.15	24.4 ± 0.11	25.2 ± 0.11
Maximum dry bulk density (Mg m^{-3})	1.49 ± 0.05	1.53 ± 0.04	1.68 ± 0.03	1.71 ± 0.03
Soil organic carbon (kg^{-1})	16.5 ± 4.6	7.00 ± 2.1	5.10 ± 1.1	4.3 ± 1.0
Total nitrogen (g kg^{-1})	1.80 ± 0.08	0.90 ± 0.02	0.70 ± 0.00	0.8 ± 0.00
C/N ratio	9.10	7.70	7.20	5.4
Clay (<2 m) (g kg^{-1})	230 ± 3.37	263 ± 2.30	330 ± 2.88	372 ± 2.63
Silt (2–20 m) (g kg^{-1})	308 ± 4.81	299 ± 4.01	309 ± 2.31	239 ± 1.89
Silt (20–50 m) (g kg^{-1})	454 ± 4.51	433 ± 3.46	357 ± 4.01	385 ± 3.86
Fine sand (100–250 mm)	8 ± 1.38	5 ± 1.10	4 ± 0.96	4 ± 1.12
pH in H_2O (1:2.5)	6 ± 0.02	5.6 ± 0.01	6.3 ± 0.03	6.2 ± 0.02

40 disks) to a depth of 150 mm, followed immediately by a shaped spring tooth harrow and one pass of a basket roller.

Deep loosening (treatments 2 and 3) was conducted with a 106.7 kW, FWA SAME Laser 150 tractor in fall of 2004 using: (a) A V-frame 7 shank subsoiler (S) with 35 mm wide and 550 mm long. Shanks spaced 500 mm (center to center) apart operating at 350 mm depth and pulled at 5 km h^{-1}. (b) A chisel plow with 11 rigidly mounted curved shanks measuring 25 mm × 20 mm spaced 285 mm apart operating at 280 mm depth and pulled at 6.2 km h^{-1}.

The treatments were applied to the plots 100 m long × 100 m (10,000 m^2) wide laid out in completely randomized blocks having six replications. Statistical analyses were performed utilizing the Statgraf program 7.1. An analysis of variance (ANOVA) was carried out on the data and means were analyzed by Duncan's multiple range test.

There were two traffic subtreatments for each plot (sowing operations): (1) heavy equip (HE) (Tractor 1 and Planter 1) and (2) light equip (LE) (Tractor 2 and Planter 2). These different traffic subtreatments were applied for three growing seasons. The effects in the crop yield were measured at harvest moment, in March 2005, 2006 and 2007. The first application of traffic subtreatments was at sowing moment, in November 2004, the second on 2005 and the third on 2006. Tractors and planters characteristics are shown in Table 2. For each subtreatments effective field capacity (EFC) and fuel consumption (FC) were measured during the sowing of soybeans. Travel speed of both equipments was 5 km h^{-1}.

3.3. The surveyed parameters

The soybean variety used was "Don Mario RR 4800", the drilling date in the first year was 5 November 2004, second year was 7 November 2005 and third year was 9 November 2006. Sowing rate was 65 kg ha^{-1}, depth sowing was 3 cm and emergence rate was 80% for all treatments. The fertilization rate was slightly

Table 2
Tractors and planters characteristics.

Heavy equip			
Tractor 1		Planter 1	
Characteristics	FWA SAME Laser 150	Characteristics	Schiarre 950 Plus
Engine power (CV/kW)	145/106.7	Type of seeding machine	Planter
Front tyres	16.9 R 30	Total weight loaded (kN)	105
Rear tyres	24.5 R 32	Width (mm)	4550
Inflation pressure, front tyre (kPa)[a]	80	Number of units	26
Inflation pressure, rear tyre (kPa)[a]	50	Distance between row spacing (mm)	175
Total weight (kN)	80	Seed metering system	Double-Run feed
Front weight (kN)	30.33	Tyres	400/60–15.5
Rear weight (kN)	50	Contact area (m^2)	0.21
Front tyre–soil contact area (m^2)	0.24	Ground pressure (kPa)	116.5
Rear tyre–soil contact area (m^2)	0.43	Furrower	Single disk with limiting wheel
Ground pressure front tyre (kPa)	141	Coverer and/or compacter	Covering–compacting wheels (variable angle)
Ground pressure rear tyre (kPa)	114		
Forward speed when sowing (km h^{-1})	5.5		
LIGHT EQUIP			
Tractor 2		Planter 2	
Characteristics	2WD John Deere 4050	Characteristics	Crucianelli Pionera III
Engine power (CV/kW)	123/90	Type of seeding machine	Planter
Front tyres	1100–16	Total weight loaded (kN)	69.6
Rear tyres	23.1–30	Width (mm)	4725
Inflation pressure, front tyre (kPa)[a]	200	Number of units	27
Inflation pressure, rear tyre (kPa)[a]	80	Distance between row spacing (mm)	175
Total weight (kN)	57.4	Seed metering system	Double-Run feed
Front weight (kN)	17.2	Tyres	400/60–15.5
Rear weight (kN)	40.2	Contact area (m^2)	0.19
Front tyre–soil contact area (m^2)	0.18	Ground pressure (kPa)	91.5
Rear tyre–soil contact area (m^2)	0.262	Cutting and soil penetration	Turbo cutler
Ground pressure front tyre (kPa)	47.7	Furrower	Double disk with double depth limiting wheel
Ground pressure rear tyre (kPa)	76.7	Coverer and/or compacter	Covering–compacting wheels (variable angle)
Forward speed when sowing (km h^{-1})	5.5		

[a] The tyre inflation pressure was within the range advised by the web page of Firestone Agricultural Tyre Division.

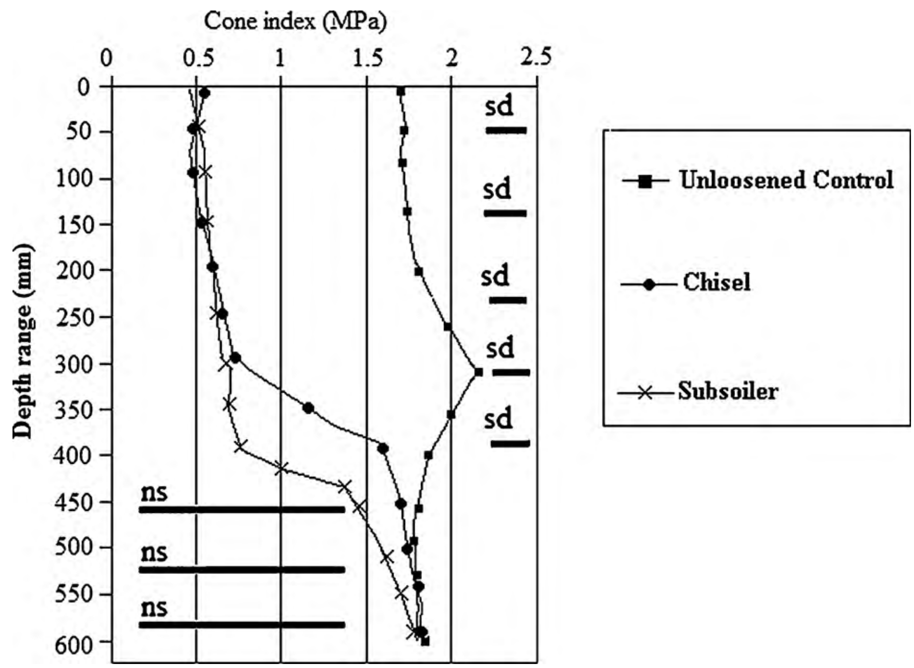

Fig. 1. Cone index for the three tillage treatments measured 6 weeks after subsoiling and chiseling before traffic (initial soil condition). sd, significant difference; ns, not significant ($P < 0.01$), Duncan's multiple range test.

(50 kg ha^{-1} diammonia phosphate) localized in seed line. Weeds were controlled using postemergence herbicides. The crops were harvested in the last 10 days of March for all treatments. The harvest operations were the same ones for all the treatments. Harvest traffic, which consisted solely of the combine harvester, was controlled along predefined tracks as above and the harvester filled the grain chaser on the headlands (Fig. 1). The tractor and the grain chaser were stopped in the headland.

Soybean yields: Soybean yields (SY) were measured in harvest 2005, 2006 and 2007. The soybean yields were measured using small quadrants. The soybean basis yield (control plot 2004) was 2.90 t ha^{-1}.

Root dry mater (RDM) and dry matter per plant (DMP) were measured 68 days after planting (R4 approximately). Roots were sampled from three depth levels: 0–150, 150–300 and 300–450 mm. Root dry matter was measured until 450 mm only because mostly of the roots are concentrated in the first 250 mm (Williams and Weil, 2004). Although the measurement was carried out up to 450 mm to avoid missing any root. A total of 70 samples were taken per treatment. The roots were washed from the soil samples and used conventional oven at 104 °C until constant weight, for root dry weight determination. For dry mater per plant (DMP) determination, the plants were cut just above soil level, rinsed in distilled water, oven dried until constant weight.

Soil water content (w/w) and cone index (CI) were measured, on the same day, after sowing in 5 November 2004, 7 November 2005 and 9 November 2006. The average over 3 years for water content (w/w) during traffic was 18.0% dry basis in the surface (0–150 mm), 19.0% at 150–300 mm, 20.1% at 300–450 mm and 20.4% at 450–600 mm (Table 3). The condition (soil water content) where the soybean was seeding is normal for the study area.

Cone index was determined with a Rimick CP20 recording penetrometer S 313 (ASAE Standards S 313.2, 1993). Each datum is the average of 20 samples for each plot in the depth range 0–600 mm taken at intervals of 25 mm. Cone index data collected 4 weeks after subsoiling and chiseling gave the clear indication of the initial soil condition in each tillage treatment. The effects of traffic treatment on soil were measured at sowing moment.

Table 3
Soil water content (w/w) at initiation of traffic treatments (sowing date) in each year.

Depth range	Average 3 years	Date of traffic		
		5/11/04	7/11/05	9/11/06
0–50		17 a	18 a	17.9 a
50–100		16.9 a	17 a	19 a
100–150		18 a	19 a	19.2 a
	18	17.3 a	18 a	18.7 a
150–200		18 a	19 a	19.4 a
250–300		18 a	19 a	19.6 a
300–350		19 a	19.2 a	19.5 a
	19	18.3 a	19.1 a	19.5 a
350–400		20 a	21 a	21 a
400–450		20.7 a	19 a	19.2 a
450–500		20 a	20.5 a	19.4 a
	20.1	20.2	20.2	19.9
500–550		20 a	20 a	20.4 a
550–600		21 a	20.2 a	20.5 a
	20.4	20.5 a	20.1 a	20.5 a

Different letters within each year (horizontally) indicate a significant difference for the different traffic treatments ($P < 0.01$, Duncan's multiple range test).

4. Results and discussion

4.1. Weather conditions

Total rainfall and average maximum temperature measured for 10 days intervals between 1 November and 31 March for each year are shown in Table 4. For three seasons the average maximum air temperature was moderate in December, February and March, but exceeded 31.8 °C in January, the rainfall received in December was adequate for soybean emergence. Significant rainfall was received before the harvest operations (last 10 days of March in the third year) causing a high soil water content. Because during soybean

Table 4
Average maximum air temperature and total rainfall received for 10-day intervals during soybean production seasons in Luján, Buenos Aires (C.I.D.E.P.A. Meteorology Station, Luján University).

Period		Rainfall (mm)			Avg. Max. Temp. (°C)		
		Nov/04–March/05	Nov/05–March 06	Nov/06–March/07	Nov/04–March/05	Nov/05–March/06	Nov/06–March/07
Nov	1–10	32	24	30	23.7	26	25
	11–20	40	31	26	24.5	25	23
	21–30	34	30	28	23.1	22	26
Dec	1–10	55.2	50	41	27	25	25
	11–20	80	15	75	27.6	26	27
	21–31	23.3	14.7	22	28	25	27
Jan	1–10	–	3	2	33.4	32	33
	11–20	25	40	21	31	32	32
	21–31	95	80	78	32.3	32.5	32.1
Feb	1–10	82	19	75	27.3	28	27.2
	11–20	26	22	20	28.5	27	27.5
	21–28	23	21	19	28	26.7	29
Mar	1–10	30	9	32	27.1	27.8	27
	11–20	6	6	4	26.2	25.6	26
	21–31	35	31	30	25.6	24	26

Table 5
Draft and total drawbar power required to pull a subsoiler and chisel plow through the soil.

Implement and depth of operation (mm)	Draft (kN/shank)	Total draft (kN)	Area cut (m^2)	Specific draft (kPa)	Total drawbar power (kW)
Chisel plow (280)	3.1 a	34.1a	0.8778 a	38.80 a	58.7 a
Subsoiler (350)	5.8 b	40.6 b	1.225 b	33.14 b	56.4 a

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

productions seasons the weather conditions were similarly enough, the variations in soybean yields could be due to soil compaction produced by traffic alternatives.

4.2. Chisel and subsoiler draft

The shape, width, rake angle and spacing of an individual soil cutting tool strongly influence the transport and mixing of soil particles and in this experiment were also found to influence implement draft. The chisel plow had a lower draft per shank than the subsoiler, but there were no significant differences ($P < 0.01$) in total drawbar power (Table 5) between these implements. Although the total cross-sectional area loosened by the chisel was 16% more than the subsoiler, the chisel efficiency was 87% less than the subsoiler. The speed was 6.2 and 5 km h^{-1} for the chisel and subsoiler, respectively. It should be noted that moisture averaged (at moment of tillage) 16.4% in the 0–300 depth range and 20% in the subsoil (300–600). The average soil water content of this profile was 18.2%, which is 31% lower than the soil water content for maximum compaction of this soil using the standard Proctor compaction test ASTM.D.698.T (Proctor, 1933).

4.3. Soil cone index

Differences in soil water content between treatments at the time of penetrometer measurements were generally not significant ($P < 0.01$) and no adjustments to the penetrometer data were therefore considered necessary (Table 3). Hence, CI can be regarded as a good representative parameter for assessing the degree of soil compaction.

Cone index data collected 6 weeks after subsoiling and chiseling (sowing operations) gave a clear indication of the initial soil condition in each treatment. Fig. 2 (statistical analysis between treatments) shows that CI in the unloosened control plots was greater than the 1500 kPa critical cone index quoted by Botta et al. (2004) for normal seed emergence of soybean for fine textured soils. At 300 mm depth, cone index was again higher than the 1800 kPa limit mentioned by Jorajuria et al. (1997) to avoid restricted root growth. The maximum CI was 2300 kPa recorded at 300 mm depth. It is important to note that typical tillage depth in Argentina is approximately 150 mm, and this constitutes Ap horizon based on the criterion proposed by Botta et al. (2002). In

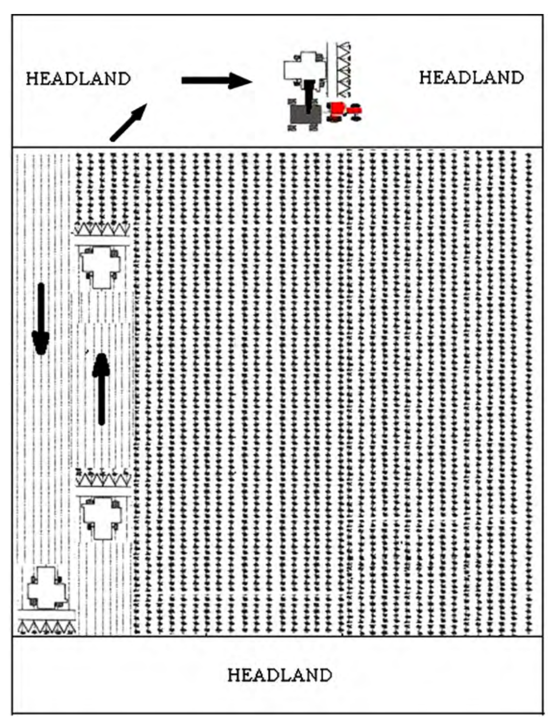

Fig. 2. Harvest traffic, which consisted solely of the combine harvester, was controlled along predefined tracks as above and the harvester filled the grain chaser on the headlands.

Table 6
Means of cone index (kPa) for three growing seasons and effect of heavy equip traffic on three tillage treatments: (T1) soil under direct sowing (unloosened), (T2) chiseled and (T3) subsoiled.

Depth range (mm)	Heavy equip (total load 185 kN)								
	Sowing 2004			Sowing 2005			Sowing 2006		
	T1[a]	T2[a]	T3[a]	T1[a]	T2[a]	T3[a]	T1[a]	T2[a]	T3[a]
0–150	2010 b	1330 d	1220 d	2224 a	1390 d	1320 d	2300 a	1800 c	1678 c
150–300	2340 ab	1430 d	1540 d	2530 a	1501 d	1601 d	2421 a	1789 c	1702 c
300–450	2380 b	1865 e	1690 f	2670 a	1940	2000 d	2689 a	2200 c	2078 cd
450–600	2200 c	2000 d	1989 d	2381 b	2190 c	1980 d	2578 a	2371 b	2106 c

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

Fig. 2 the effects of chiseling and subsoiling are seen most obviously compared with the unloosened tillage treatment. CI on the two deep tillage treatments was statistically different ($P < 0.01$) from that on the unloosened soil, but as it would be expected, to different soil depths: 300 mm for chisel plowing and 400 mm for subsoiling. The subsoiler greatly reduced soil compaction, especially in the immediately adjacent area to the subsoiler. Results of the analysis of variance on cone index values, averaged over depths from 300 to 400 mm, showed a significant difference between subsoiled and chiseled plots.

4.4. Traffic effects on soil treatments

Tables 6 and 7 show the CI values after traffic, for all treatments over the 3 years. Data showed that compaction by heavy equip (HE) caused considerable changes to the topsoil and subsoil properties than the light equip (LE). These results are in accord with those of Håkansson (1987), who indicated that compaction effects at high axle load are related to soil type, the number of passes and the number of years since compaction. In the first growing season Tables 6 and 7, the increase in CI as a result of traffic was particularly marked in the 0–300 mm depth layer, although the chiselled and subsoiled treatments gained less resistance than the area under direct sowing. Examination of the soil response to traffic in deeper layers revealed that soil compaction, as indicated by CI, had increased in the depth range 300–600 mm for two traffic treatments.

Although subsoiling and chiseling loosened the soil and CI, measurements taken in the trafficked area subsequently revealed that the benefit in terms of CI was almost completely eliminated during the first growing season (Fig. 2), canceling out any gains made by subsoiling and chiseling.

All the CI values measured in soil under direct sowing (T1) after traffic were higher than the ones measured on tillage treatments (T2 and T3). An important reason for greater CI in tillage treatments is the high compressibility of this weak soil, as shown by its low cone index values compared to direct sowing. At the 0–150, 150–300, 300–450 and 450–600 mm levels the CI in treatment 1 were on average, about 1800 kPa. This and the soil water content at traffic moment that was considerably high could cause a decrease on the air filled porosity, destroying macropores and affecting the crop response.

Table 7 (HE 185 kN) shows that CI for all treatments in the topsoil, was greater than the 1200 kPa quoted by Botta et al. (2004) as critical for normal emergence of soybean in fine textured soils. For heavy and light equips, CI between 300 and 600 mm depth in all 3 years was higher than the 1500 kPa limit mentioned by Jorajuria et al. (1997) to avoid restricted root growth. The highest values of CI for heavy equip between soil treatments were measured in the depth range 300–600 mm in all years (Table 7). Also, peak values of CI occurred at progressively greater depths year by year. All values exceeded those quoted as critical for root growth retardation (Botta et al., 2004; Ressia et al., 1998; Jorajuria et al., 1997). These values of CI indicate over-compaction in subsoil, these overcome 1000 and 1200 kPa quoted by Narro Farias (1994) and Terminiello et al. (2000) recommended to avoid yield decreases. Probably due to a combination of high axle load, trafficking with high soil water contents values and several years under direct drilling.

Finally, in this trial was demonstrated that when the axle load increases on soils with high bearing capacity (soils under long term direct sowing system) the crop yields decrease and the soil compaction problems increase (Tables 9, 7, and 6, respectively). Hence, the data support the work hypotheses.

4.5. Work rate and fuel consumption

The work rate of seeding equipments is a function of the rated width, the speed of travel and the amount of field time lost during the operations, the work rate is not similar because the different widths of seeding machines produce different loss of time. It is supposed that covering a greater area of the field efficiencies (effective work rate/theoretical work rate) would decrease because there would be more loss of time but there would be an improvement of the soil conservation and crop yields.

Table 8 shows that LE required significantly less fuel per hectare than HE ($P < 0.01$). Effective work rate was higher in the LE than the HE as a result of decreased width and load.

Table 7
Means of cone index (kPa) for three growing seasons and effect of light equip traffic on three tillage treatments: (T1) soil under direct sowing (unloosened), (T2) chiseled and (T3) subsoiled.

Depth range (mm)	Light equip (total load 127 kN)								
	Sowing 2004			Sowing 2005			Sowing 2006		
	T1[a]	T2[a]	T3[a]	T1[a]	T2[a]	T3[a]	T1[a]	T2[a]	T3[a]
0–150	1810 a	1050 b	980 b	1825 a	1250 c	1230 c	1930 a	1330 d	1410 d
150–300	2165 a	1201 b	1110 b	2300 d	1480 c	1490 c	2350 d	1570 c	1520 c
300–450	2220 a	1559 c	1280 b	2380 f	1820 d	1910 d	2500 g	1900 d	2008 e
450–600	2000 a	1530 b	1590 b	2289 d	1790 c	1850 c	2480 f	1902 a	1990 a

Values with different letters (horizontally) are significantly different at each depth ($P < 0.01$), Duncan's multiple range test.
[a] Soil tillage treatments.

Table 8
Work rate and fuel consumption for two equipments and the three treatments.

Traffic treatments	Work rate ($ha\,h^{-1}$)	Fuel consumption ($l\,ha^{-1}$)
Heavy equip (185 kN)	2.27 a	9.7 a
Light equip (127 kN)	2.36 a	6.5 b

Different letters within each treatment (vertically) indicate a significant difference for the different traffic treatments ($P < 0.01$, Duncan's multiple range test).

4.6. Root dry mater and soybean yields

Interestingly, root dry matter (RDM) was affected by soil compaction, as soil cone index was increased; the root dry mater was decreased in total soil profile. For three treatments in three growing seasons 65 days after planting (R4 approximately) and trafficking with two equipments, large differences (average) in dry mater production of soybean were observed in different tillage plots. The highest root dry mater (RDM) values were on the subsoiler plots (0.77 and 0.48 g pl^{-1} for LE and HE, respectively) followed by the chisel plow (0.66 and 0.35 pl^{-1} for LE and HE, respectively) and the direct sowing (0.45 and 0.29 g pl^{-1} for LE and HE, respectively). Dry mater per plant (DMP) in average for three growing seasons was 2.83 g pl^{-1} on susbsoiled treatment followed by that on the chisel plow (1.78 g pl^{-1}) and on direct sowing treatment (1.64 g pl^{-1}).

Finally, Figs. 3–5 show that after traffic for three treatments in three growing seasons the relationship between root dry mater and soybean yields was strongly positive. In all treatments root dry mater was directly proportional to soybean yields with a high correlation coefficient.

After traffic with LE soybean yields revealed a downward trend (Table 9) but in all 3 years only the difference between treatment 1 and treatments 2 and 3 were significant ($P < 0.01$). Traffic with HE caused severe significant reduction ($P < 0.01$) in soybean yields for three treatments. In the first year of this trial the peaks values of CI were found in the topsoil (0–150 mm), so, according to Riley et al. (1994), most of this yield reduction (for all treatments) was probably caused by damage to topsoil structure due to higher ground pressure of this equip (>110 kPa, see Table 2).

This conclusion is supported by the fact that the saleable percentage of soybean yield, which is governed largely by topsoil structure, was significantly lowered by the traffic intensity of

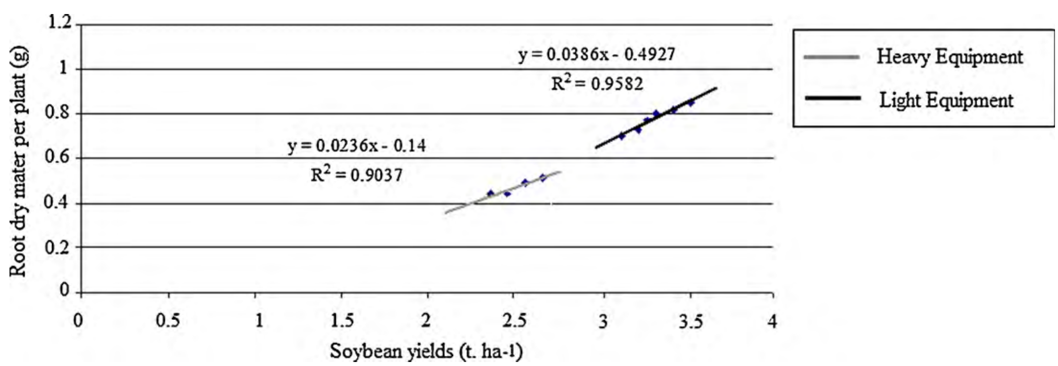

Fig. 3. Relationship between root dry mater per plant and soybean yields for heavy and light equipments on subsoiled soil.

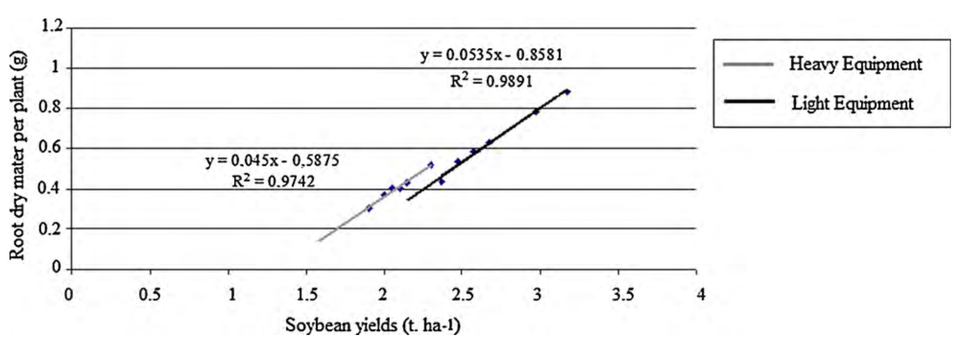

Fig. 4. Relationship between root dry mater per plant and soybean yields for heavy and light equipments on chiseled soil.

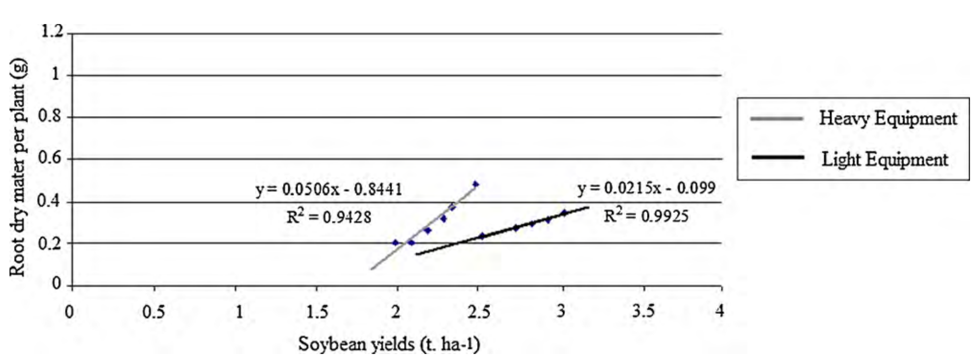

Fig. 5. Relationship between root dry mater per plant and soybean yields for heavy and light equipments on soil under direct sowing.

Table 9
Soybean yields for the different soil tillage treatments and traffic (light equip (LE) and heavy equip (HE)) in three growing seasons (2005, 2006 and 2007).

	Treatments compared					
	(T1) Direct sowing		(T2) Chiseled soil		(T3) Subsoiled soil	
	LE[a]	HE[a]	LE[a]	HE[a]	LE[a]	HE[a]
Crop yield (t ha^{-1}) (2005)	2.70 b	2.50 a	3.30 c	2.65 b	3.50 c	2.80 b
Crop yield (t ha^{-1}) (2006)	2.65 b	2.42 a	3.00 c	2.56 b	3.20 c	2.80 b
Crop yield (t ha^{-1}) (2007)	2.60 b	2.40 a	2.92 c	2.50 a	3.00 c	2.76 b

Different letters within each year (horizontally) indicate a significant difference for the different traffic treatments ($P < 0.01$, Duncan's multiple range test).
[a] Equipments.

treatment 1. In the second and third year the peaks values of CI were found in the subsoil (limit or below 150 mm) and the high values of this parameters, probably caused by the high axle load, would have also affected the crop response.

Taking 2004 as the base year for soybean yield (2.90 t ha^{-1}), treatment 3 (subsoiled soil) when trafficked with LE exceeded this by approximately: 20.7, 10.3 and 3.4%, respectively, for year 2005, 2006 and 2007 and these agree, approximately, with those presented by Botta et al. (2004) and Jorajuria et al. (1997). For the same treatment in the three growing seasons (2005, 2006 and 2007), when trafficked with HE resulted in 3.4, 3.4 and 4.82% less soybean grain yields than the base year (2004).

In treatment 1 (soil under direct sowing) when trafficked with HE soybean yields reduction were: 13.8, 16.5 and 17.2% for 2005, 2006 and 2007, respectively.

Finally, for treatment 2 (chiseled soil) when trafficked with LE, there was an increment above base yield, for the first year (2005) in approximately 13.7, for 2006 and 2007 soybean yields were increased in 3.4 and 0.69%, respectively (Table 9).

The economics of soybean production based on yield increases for seeding with light equip (127 kN) respect to the heavy equip (185 kN), were improved by US$ 129.6 ha^{-1} in the first year, US$ 64.8 ha^{-1} in the second year and by US$ 21.6 ha^{-1} in the third year (based on an average soybean price of US$ 216 t^{-1}).

5. Conclusions

- Even though the soil under direct drilling is initially more compacted, compared with the tillage treatments (subsoiled and chiseled), the results shows that it can still be compacted with heavy (185 kN) and light (127 kN) equip traffic, decreasing soybean yields year by year.
- Soybean final yield was directly related with root dry matter weight in R4, which is affected by soil compaction caused by traffic. It was clear that the 58 kN of difference between the equipments caused a decrease in yields, even though deep tillage was used.
- Finally, subsoiling lasted 2 years only when trafficked with the 127 kN equip while chiseled lasted only 1 year when trafficked with the same equip.

References

ASAE Standards, 1993. Soil Cone Penetrometer S 313.2. Am. Soc. Agric. Eng, p. 611.

ASAE Standard, 1993. Terminology and Definitions for Soils Tillage and Soil Tool Relationships Engineering Practice, EP291.2. American Society of Agricultural Engineering.

Balbuena, H.R., Aragón, A., Mc Donagh, P., Claverie, J., Terminiello, A., 1998. Effect of three different tillage systems on penetration resistance and bulk density. In: Proceedings of IV CADIR (Argentine Congress on Agricultural Engineering), vol. 1. pp. 197–202.

Botta, G., Tolón-Becerra, A., Bellora Tourn, F., 2009. Effect of the number of tractor passes on soil rut depth and compaction in two tillage regimes. Soil Till. Res. 103, 381–386.

Botta, G., Rivero, D., Pozzolo, O., Tourn, M., Bellora-Melcon, F., Nardon, G., Balbuena, R., Tolón–Becerra, A., Rosatto, H., Stadler, S., 2008. Soil compaction produced by tractor with radial and bias—ply tyres in two soil conditions: conventional tillage and direct sowing. Soil Till. Res. 101, 44–51.

Botta, G., Jorajuria, D., Rosatto, H., 2006. Light tractor frequency on soil compaction in the rolling Pampa region of Argentina. Soil Till. Res. 86, 9–14.

Botta, G., Jorajuria, D., Balbuena, R., Rosatto, H., 2004. Mechanical and cropping behaviour of direct drilled soil under different traffic intensities: Effect an soybean (*Glycine max* L.) yields. Soil Till. Res. 78, 53–58.

Botta, G., Jorajuria, D., Draghi, L., 2002. Influence of the axle load, tyre size and configuration, on the compaction of a freshly tilled clayey soil. J. Terramech. 39 (1), 47–54.

Canarache, A., Colibas, I., Colibas, M., Horobeanu, I., Patru, V., Simota, H., Trandafirescu, T., 1984. Effect of induced compaction by wheel traffic on soil physical properties and yield of maize in Romania. Soil Till. Res. 4 (2), 199–213.

Cisneros, J., Cantero, G., Marcos, J., Degioanni, A., Bricchi, E., Giayetto, O., Cholaky, C., Bonadeo, E., Cerioni, G., Uberto, M., 1998. Performance of a wing subsoiler adaptable to common use machinery. In: Proceedings of the IV CADIR (Argentine Congress on Agricultural Engineering), vol. 1. pp. 128–136.

Dexter, A.R., 2004. Soil physical quality. Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120, 201–214.

Håkansson, I., 1987. Long term effects of modern technology on productivity of arable land. K. Skogs-o. Lantbr. Akad. Tidskr. 126, 35–40.

Jorajuria, D., Draghi, L., Aragon, A., 1997. The effect of vehicle weight on the distribution of compaction with depth and the yield of Lolium/Trifolium grassland. Soil Till. Res. 41, 1–12.

Narro Farias, E., 1994. Physical of Soils. Ed. Trillas, México, 287 pp.

Pagliai, M., Vignozzi, N., 2002. Soil pore system as an indicator of soil quality. In: Pagliai, M., Jones, R. (Eds.), Sustainable Land Management Environmental Protection: A Soil Physical Approach. Advances in Geoecology, vol. 35. Catena Verlag, Reiskirchen, pp. 71–82.

Proctor, R., 1933. Fundamental principles of soil compaction. Eng. News Rec. 111, 245–248 286–289, 348–351.

Raper, L., Reeves, D., Burt, E., Torbert, H., 1994. Conservation tillage and traffic effects on soil condition. Trans. ASAE 37 (III), 763–768.

Reeder, R., Wood, R., Finck, H., 1993. Five subsoiler designs and their effects on soil properties and crop yields. Trans. ASAE 36 (VI), 1525–1531.

Ressia, J.M., Mendivil, G., Balbuena, R.H., Chidichimo, O., 1998. Root growth and grain yield of corn in relation to tillage systems. In: Proceedings of the IV CADIR (Argentine Congress on Agricultural Engineering), vol. 1. pp. 98–104.

Riley, H., Børresen, T., Ekeberg, E., Rydberg, T., 1994. Trends in reduced tillage research 340 and practice in Scandinavia. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agro 341 ecosystems. Lewis publishers, Boca Raton, Florida, USA, pp. 23–45.

Shinners, J., 1989. Costs and benefits of subsoil tillage in a Wisconsin soil. ASAE Paper No. 89-1507, ASAE, St. Joseph, MI.

Soil Conservation Service, 1994. Keys to Soil Taxonomy, 6th edition. Soil Survey Staff, USDA, Washington DC, USA.

Taylor, H.M., Roberson, G.M., Parker, J.J., 1966. Soil strength root penetration relations for medium coarse-textured soil materials. Soil Sci. 102, 18–22.

Terminiello, A.M., Clverie, J., Casado, J., Balbuena, R., 2000. Cone index evolution through the growth season of cabbage crop (*Brassica oleracea* L.). In: Proceedings of the IV CADIR (Argentine Congress on Agricultural Engineering), vol. 1. pp. 68–73.

Williams, S.M., Weil, R., 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68, 1403–1409.