

Continuous application of direct sowing: Traffic effect on subsoil compaction and maize (*Zea mays* L.) yields in Argentinean Pampas



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ARTICLE INFO

Article history:

Received 1 November 2012

Received in revised form 19 July 2013

Accepted 27 July 2013

Keywords:

Cone index

Heavy axle load

Tractor traffic

Planter machine

Bearing capacity

ABSTRACT

Our main objective was to evaluate the effect of subsoil compaction on maize (*Zea mays* L.) yields. This work was performed on clayey soil and on loamy Entic Haplustoll soil. Three types of direct sowing (DS) equipment (heavy load (HL), medium load (ML) and light load (LL)) were utilised. We hypothesised that the application of DS over five continuous years would cause subsoil compaction and that maize yields would be affected. The cone index (CI), root dry matter per plant (RDM), dry matter per plant (DMP) and maize yields (MY) were measured. The results show that after five years, the CI values produced by the HL treatment were higher in clayey soil than in loamy soil, which decreased maize yields. At site 1, the highest average RDM values were found in 2005; the measurements for the LL and ML treatments were 45.9 and 43.1 g plant⁻¹, respectively, whereas the highest value in the HL treatment was 35.6 g plant⁻¹. For site 2, the highest RDM values were found in 2006; the measurements for the LL and ML treatments were 42.6 and 38.2 g plant⁻¹, respectively, whereas the highest value in the HL treatment was 30.2 g plant⁻¹. The average DMP measurement (site 1) was 150 g plant⁻¹ in the LL treatment, followed by 147 g plant⁻¹ in ML and 137 g plant⁻¹ in HL. Site 2 values were 143, 137 and 130 g plant⁻¹ in LL, ML and HL, respectively. At both sites, the HL treatment resulted in a significantly lower maize yield (14.3% and 11% for sites 1 and 2, respectively) compared to the ML and LL treatments. The main conclusions were as follows: when clayey and loamy soil was trafficked with between loads of 144 and 177.9 kN for five years, the cone index was increased in the subsoil. These high CI values caused by the combination of a high axle load and ground pressure would have affected the maize yields.

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1. Introduction

From the point of view of soil conservation, there is evidence that direct sowing (DS) is a more sustainable system, even though information concerning the rheology of non-tilled soil under traffic is still lacking. Despite lower traffic intensity during seeding with this technique, soil compaction assessment is necessary to identify the compaction caused by DS and further changes over time.

DS became popular in Argentina in the 1980s with the increased availability and lower price of agrochemicals, as well as a reduction in the amount of equipment required. At present, >25 Mha are sown by this system in Argentina, generally on the typical

Argiudoll (east) and Entic Haplustoll soils (west Pampas region). After several years of continuous DS, the yields tend to decrease. This decrease could be a result of increased weed control problems, root diseases and soil compaction due to heavy tractor traffic in crop protection treatments and harvesting, especially when these operations are performed on wet soil or with high-pressure tyres (Botta et al., 2004).

In Argentina, maize is grown mainly on clayey and loamy soils (3.1 million ha⁻¹ in DS) which are very susceptible to compaction by heavy traffic. In this country, soil compaction due to the use of heavy equipment for DS, such as maize (*Zea mays* L.) seeding machines (50–110 kN) and tractors (50–100 kN), is the main agricultural problem (Botta et al., 2008). The problem is worsened by the typical tillage depths (plough layer), which in Argentina are around 200 mm (varies by region).

On a clay loam soil in Argentina, Botta et al. (2004) applied traffic by a 4 Mg tractor at intensities of 60–180 Mg km ha⁻¹ in a field where DS had been practised for seven years in a wheat-soybean

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double cropping rotation. This caused compaction all the way to 600 mm depth and a yield decrease in next soybean crop that increased with traffic intensity from 10 to 39%.

In addition to the trials mentioned above, other trials showing the effects of traffic by heavy vehicles have also been carried out, some of them on the same soil type. Eg: On a clay soil in Ohio, USA, a total of three passes under wet conditions by vehicles with axle loads of 10 and 20 Mg caused residual effects during four subsequent years on maize and soybean yields (Lal, 1996).

Extremely dense soil impedes root growth and thereby limits plants water consumption affecting the crops yields. 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 and plant growth limiting factors.

In west Pampas region (loamy Entic Haplustoll soil), Botta et al. (2006) reported that the root dry weight of sunflower (*Helianthus annuus* L.) was reduced drastically as penetration resistance approached 1750 kPa. At >1.8 MPa, root growth became virtually impossible.

Soza et al. (2003) found that on a soil with high clay content (under DS) in the east Pampas region, soil compacted to a cone index of >1200 kPa reduced wheat (*Triticum aestivum* L.) emergence by 26%.

According with Tolón-Becerra et al. (2011) cone index values >1.7 MPa, particularly in the surfaces layers, generates physical soil conditions inadequate for emergence of maize seedlings. Therefore, the challenge is to attain a suitable seedbed whilst minimising traffic-induced soil compaction so that the physical properties of the soil do not diminish normal root growth.

Finally, soil compaction is of concern in DS systems because it is not alleviated by tilling. Negative effects of soil compaction on plant growth and soil physical properties in DS systems have been reported (Sidhu and Duiker, 2006; Botta et al., 2007, 2002; Terminiello et al., 2000). However, results vary depending on the climate and the time required by soils to adapt to a new management system. Moreover, little is known about the long-term effects of DS equipment traffic on soil properties and maize yields in the Argentinean Pampas.

The main objectives of this work were (a) to determine the effects of different high load traffic on the soil cone index and maize productivity and (b) to quantify the change in the subsoil cone index of two soils, typical Argiudoll and Entic Haplustoll, after five years of the continuous application of DS systems.

This study hypothesised that (a) maize yields are affected by subsoil compaction and (b) the application of DS systems over five continuous years causes subsoil compaction.

2. Materials and methods

2.1. The sites

The work was performed over five years (2004–2009) on fine clayey soil (typical Argiudoll; Soil Conservation Service, 1994) in the state of Buenos Aires, Luján county (site 1), Argentina at 34°82'50 S, 59°81'50 W and on loamy Entic Haplustoll soil (Soil Conservation Service, 1994) in the state of La Pampa, Quemu Quemu Department (site 2), Argentina at 36°49' S, 69°32' W. The typical Argiudoll site was approximately 22 m above sea level. The soil is fine clayey 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 loamy Entic Haplustoll, at an altitude of 26 m above sea level was well drained and had moderate permeability. Surface runoff was negligible on 0–1% slopes, low on 1–5% slopes and moderate on 5–8% slopes. The distance between the two sites was 600 km. The physical and mechanical properties of the two soils are provided in Tables 1 and 2.

In both locations, three types of equipment (heavy (HL), medium (ML) and light (LL) load) were utilised for DS over five years. The equipment and treatments used are provided in Table 3.

2.2. Machinery used

A Valmet (160 CV/117 kW engine) front wheel assist (FWA) tractor weighing 98 kN (39.2 kN 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 Firestone Agricultural Tyres. Each piece of equipment was

Table 1
Typical Argiudoll soil profile (site 1).

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 ± 0.27	13.5 ± 0.2	9.3 ± 0.11	6.3 ± 0.71	5.0 ± 0.61	3.1 ± 0.6	2.2 ± 0.54	1.4 ± 0.50
Total nitrogen (g kg ⁻¹)	2.4 ± 0.05	1.4 ± 0.02	1.0 ± 0.21	0.85 ± 0.02	0.75 ± 0.01	0.58 ± 0.01	0.42 ± 0.03	–
Clay (<2 μ) (g kg ⁻¹)	212 ± 2.51	255 ± 2.49	249 ± 2.66	332 ± 2.09	475 ± 2.61	330 ± 2.52	230 ± 2.71	158 ± 2.61
Silt (2–20 μ) (g kg ⁻¹)	32.3 ± 4.20	34.7 ± 3.01	29.8 ± 3.11	29.3 ± 3.21	20.8 ± 2.88	31.2 ± 1.92	32.9 ± 1.81	287 ± 1.62
Silt (2–50 μ) (g kg ⁻¹)	756 ± 1.52	708 ± 1.82	672 ± 1.94	613 ± 1.08	500 ± 0.91	630 ± 0.85	727 ± 1.01	799 ± 0.99
Fine sand (100–250 μ) (g kg ⁻¹)	3.0 ± 0.02	2.0 ± 0.01	3.0 ± 0.03	4.0 ± 0.02	4.0 ± 0.04	4.0 ± 0.02	5.0 ± 0.03	4.0 ± 0.05
pH in H ₂ O (1:2.5)	5.8 ± 0.08	5.8 ± 0.05	6.0 ± 0.03	6.2 ± 0.04	6.5 ± 0.03	6.4 ± 0.01	6.41 ± 0.02	7.91 ± 0.03

Table 2
Entic Haplustoll soil profile (site 2).

Horizons	Ap	A12	AC	C
Depth range (cm)	0–12	15–30	35–65	70–120
Organic carbon (g kg ⁻¹)	12.3 ± 0.22	6.7 ± 0.18	5 ± 0.25	–
Total Nnitrogen (g kg ⁻¹)	1.5 ± 0.03	0.8 ± 0.02	0.7 ± 0.01	–
Clay (<2 μ) (g kg ⁻¹)	161 ± 2.25	284 ± 2.37	184 ± 2.01	63 ± 1.90
Silt (2–20 μ) (g kg ⁻¹)	98 ± 1.34	63 ± 1.43	76 ± 1.25	99 ± 1.10
Silt (2–50 μ) (g kg ⁻¹)	176 ± 2.02	144 ± 2.12	131 ± 1.99	206 ± 2.01
Very fine sand (74–100 μ) (g kg ⁻¹)	402 ± 4.01	302 ± 3.80	398 ± 3.99	367 ± 3.10
Fine sand (100–250 μ) (g kg ⁻¹)	159 ± 1.80	201 ± 1.92	207 ± 2.01	261 ± 2.24
Medium sand (250–500 μ) (g kg ⁻¹)	4 ± 0.03	6 ± 0.05	4 ± 0.04	4 ± 0.04
pH in H ₂ O (1:2.5)	6.4 ± 0.02	6.6 ± 0.05	6.9 ± 0.04	6.9 ± 0.06

Table 3

Equipment specifications (tractor and planters).

Treatments	Tractor Valmet FWA (160 CV/117 kW) Total weight 98 kN + Planter 1 Light load (144 kN) (LL)	Tractor Valmet FWA (160 CV/117 kW) Total weight 98 kN + Planter 2 Medium load (167.6 kN) (ML)	Tractor Valmet FWA (160 CV/117 kW) Total weight 98 kN + Planter 3 Heavy load (177.9 kN) (HL)
Planter specifications	Planter 1	Planter 2	Planter 3
Type of seeding machine	Planter	Planter	Planter
Total weight loaded (kN)	46.0	69.6	79.9
Width (mm)	4375	7000	8400
Number of rows	7	10	12
Seeding rows load (kN)	2.92	3.72	4.9
Distance between row spacing (mm)	700	700	700
Seed metering system	Seed plate	Seed plate	Seed plate
Tyres	14.9–24	400/60–15.5	6.50–16
Inflation pressure (kPa)	220	185	200
Ground pressure (kPa)	95.1	122	155
Seed units	Double disc with double depth limiting wheels	Turbo coulter blade + double disc opener	Double disc 16" with two level wheels

configured with a different planter: Planter 1 (D750), Planter 2 (SWI) or Planter 3 (CGIII). Both sites were trafficked each year with one pass of a FWA Valmet tractor with a D750, SWI and CGIII planter. These tractor and planter models are commonly used on commercial farms in these areas.

The control treatment consisted of normal field operations with equipment consisting of a Tractor Valmet and CGIII planter (HL). This treatment represents a tillage system commonly used in both regions.

2.3. Treatments and survey parameters

Twelve 100-by-70 m plots were randomly assigned traffic treatments with four replicates for each treatment and 20 m wide buffer zones between plots were used to prevent interactions (Fig. 1).

DK4F37 hybrid maize (*Zea mays* L.) was sown in all plots at both sites with a row spacing of 0.70 m. In both sites, the soil management history includes an alfalfa (*Medicago sativa* L.) crop for 10 successive years. Maize was sown on October 7, 2004, October 5, 2005, October 6, 2006, October 8, 2007 and October 6, 2008.

At site 1, maize was harvested on March 28, 2005, March 10, 2006, March 9, 2007, March 11, 2008 and March 9, 2009 for all treatments. At site 2, maize was harvested on March 21, 2005, March 20, 2006, March 24, 2007, March 28, 2008 and March 27 2009 for all treatments.

The harvest operations were the same for all treatments (in both sites). 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 headland. The tractor and the grain chaser were stopped in the headland. The yield was measured using small quadrants (Tolón-Becerra et al., 2011).

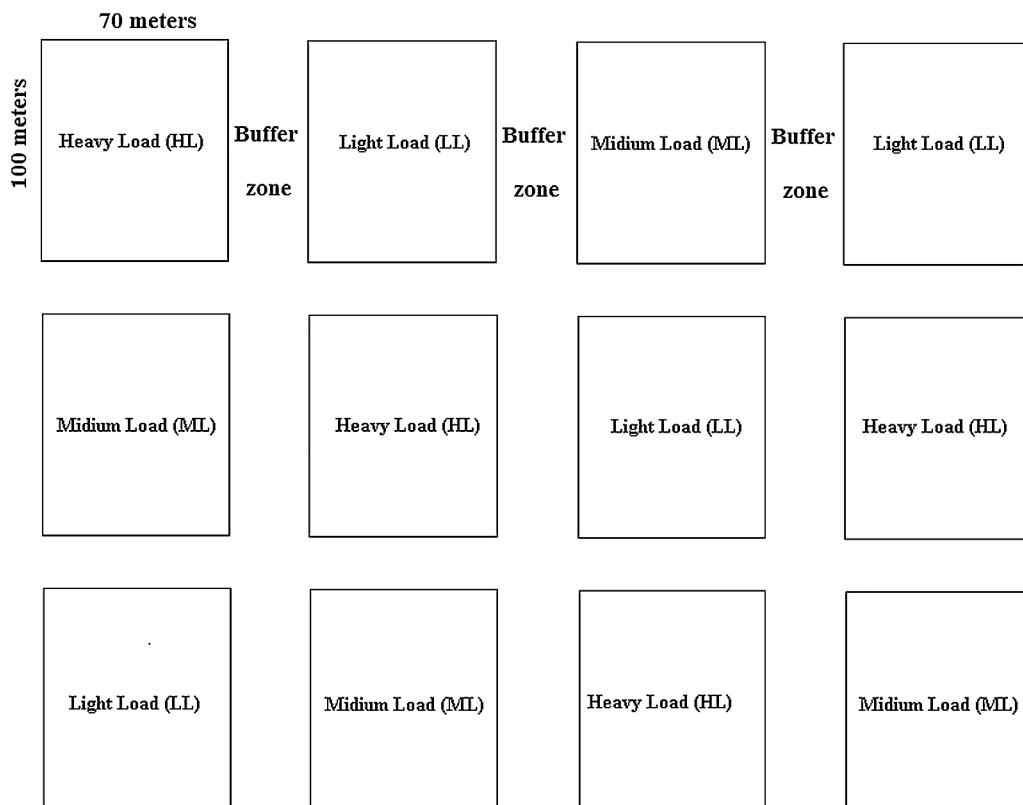
**Fig. 1.** Plots for the traffic treatments (site 1 and site 2).

Table 4
Soil water content (w/w) at initiation of three traffic treatments (sowing date) in each year and each site.

Depth range	Average five years	Date of traffic (sowing day)				
		7 October 2004	2 October 2005	6 October 2006	8 October 2007	9 October 2008
Site 1						
0–50		17.3 a	19.2 a	21.1 a	20 a	18.1 a
50–100		18.1 a	18 a	20 a	19 a	20.2 a
100–150		19.2 a	18.6 a	21 a	21 a	22 a
	19.5	18.2 a	18.6 a	20.7 a	20 a	20.1 a
150–200		20 a	21 a	21 a	20 a	20.1 a
250–300		19.8 a	19.7 a	20.2 a	19.8 a	19 a
350–350		19 a	19.9 a	21 a	20.9 a	21 a
	20.1	19.6 a	20.2 a	20.7 a	20.2 a	20 a
350–400		21 a	21 a	21.8 a	22 a	21.9 a
400–450		21 a	21.5 a	21.5 a	21.9 a	22 a
	21.5	21 a	21.2 a	21.6 a	21.9 a	21.9 a
Site 2						
0–50		15.1 a	17.1 a	19 a	18.1 a	16.5 a
50–100		16.2 a	16.2 a	17.6 a	17.2 a	18.1 a
100–150		17.1 a	17.1 a	19.3 a	18.2 a	18.9 a
	17.4	16.1 a	16.8 a	18.6 a	17.8 a	17.8 a
150–200		18 a	18.2 a	17.6 a	18.1 a	17.5 a
250–300		17.2 a	17.3 a	18.1 a	17.5 a	17.2 a
350–350		18 a	18 a	19.2 a	18.3 a	18.3 a
	17.9	17.7 a	17.8 a	18.3 a	18 a	17.7 a
350–400		19.2 a	18.6 a	18.9 a	19.4 a	19.2 a
400–450		19 a	19.5 a	19.2 a	18.9 a	20.1 a
	19.1	19.1 a	19 a	19 a	19.1 a	19.6 a

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

At both sites, the trial was designed to determine the density of dynamic sowing at a tractor speed of 5.5 km h^{-1} . The seeds were distributed along each linear metre in uncovered furrows and counted after sowing. The resulting value was 5.8 seeds per metre. The seeding depth was maintained at 5 cm . The number of emerged plants per linear metre was observed for all rows and tractor tracks. The sample consisted of 320 observations in each case (track and row; 40 observations/row \times 8 rows/replicate). Counts were taken 10 , 15 and 20 days after seeding.

The soil water content (SWC) and penetrometer measurements were collected simultaneously at sowing. In each plot the SWC was measured with a Troxler 3440 gamma-ray and neutron probe over depths of 0 – 150 mm , 150 – 300 mm , and in a trench of 300 – 450 mm depth. In soils with high organic matter, as in this experiment, the neutron probe can substantially overestimate the soil water content. Accordingly, the SWC measurements were verified using cylinder methods.

The cone index (CI) was measured with a Scout 900 S 313 recording penetrometer (ASAE Standard S313.2, 1992). Twenty measurements were made within the centre row of each plot. Each CI measurement is the average of 20 samples from each plot between depths of 0 – 450 mm at intervals of 25 mm .

The root dry matter (RDM) and dry matter per plant (DMP) were measured 8 weeks after seedling emergence (in tasseling). The roots were sampled between depths of 0 – 300 mm . The root dry matter was measured only to 300 mm because most 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 a constant weight after the soil particles were washed from the roots. For the DMP determination, plants were cut just above the soil level, rinsed in distilled water and oven-dried to a constant weight.

The data were subjected to an analysis of variance (ANOVA) for each year and the means were separated by Duncan's multiple range tests using the Statgraf 7.1 program (Botta et al., 2007).

3. Results and discussion

3.1. Soil water content and weather conditions

Differences in the soil water content (SWC) at initiation of three traffic treatments (sowing date) in each year and each site were generally not significant (Table 4). Therefore, differences found in seedling emergence (SE) could be the result of different traffic

Table 5
Seedling emergence (seed m^{-1}) for three traffic treatments in five growing seasons and two sites.

Treatments	1st growing season			2nd growing season			3rd growing season			4th growing season			5th growing season		
	Days after planting			Days after planting			Days after planting			Days after planting			Days after planting		
	10	15	20	10	15	20	10	15	20	10	15	20	10	15	20
(Site 1)															
LL	1.3 b	4.4 b	5.7 a	1.5 b	5.0 b	5.8 a	1.5 b	5.1 b	5.7 a	1.3 b	5.0 b	5.7 a	1.5 b	4.8 b	5.8 a
ML	0.3 a	2.6 a	5.3 a	0.5 a	2.4 a	4.8 a	0.41a	2.5 a	5.2 a	0.3 a	2.8 a	5.0 a	0.50 a	2.8 a	4.8 a
HL	0.38 a	2.9 a	4.5 a	0.41a	2.5 a	5.2 a	0.36 a	2.8 a	5.5 a	0.6 a	2.81 a	5.1 a	0.32 a	2.8 a	5.3 a
(Site 2)															
LL	1.0 b	4.1 b	5.1 a	1.1 b	4 b	5 a	1.2 b	4.2 b	4.7 a	1.0 b	4 b	4.5 a	1.2 b	4.3 b	5 a
ML	0.4 a	2.3 a	5.0 a	0.4 a	2.1 a	4.2 a	0.38 a	2.2 a	5 a	0.31 a	2.1 a	4 a	0.43 a	2.2 a	5.1 a
HL	0.3 a	2.5 a	4.1 a	0.38 a	2.1 a	4.5 a	0.3 a	2.6 a	4.5 a	0.42 a	2 a	4.8 a	0.30 a	2.2 a	5 a

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

treatments. However, no significant difference in SE was observed over five years. SE did not differ between traffic treatments at 20 days after seeding (Table 5).

For all five growing seasons in both sites, the differences found in SWC between plots for the traffic treatments are shown in Figs. 2 (site 1) and 3 (site 2). In addition, differences in SWC between traffic plots at the time of penetrometer measurements were generally not significant ($P < 0.01$) and no adjustments to the penetrometer data were therefore considered necessary. Hence, CI can be regarded as a good representative parameter for assessing the degree of soil compaction.

According to our study of the complete maize cultivation cycle, the temperature and rainfall were normal over the summer at both sites. The average maximum air temperature was moderate in October, November, December, February and March, but it exceeded 30 °C in January at both sites. 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 five study years. Therefore, any variations in the maize yields would be the result of the different soil load of the treatments.

The rainfall in October was suitable for seedling emergence; at the two sites, the averages in this month were 21.3 and 25.8 mm and the averages for the complete cycle of maize for five years were 89.7 and 79 mm for sites 1 and 2, respectively.

3.2. Traffic effect soil compaction

This study found that compaction by heavy equipment (HL) caused greater changes in the topsoil and subsoil properties than did compaction by medium (ML) or light equipment (LL).

Figs. 4 and 5 show the CI measurements for sites 1 and site 2 from 2004 to 2009 for the three treatments and offer a clear indication of the effects of equipment traffic. These figures show

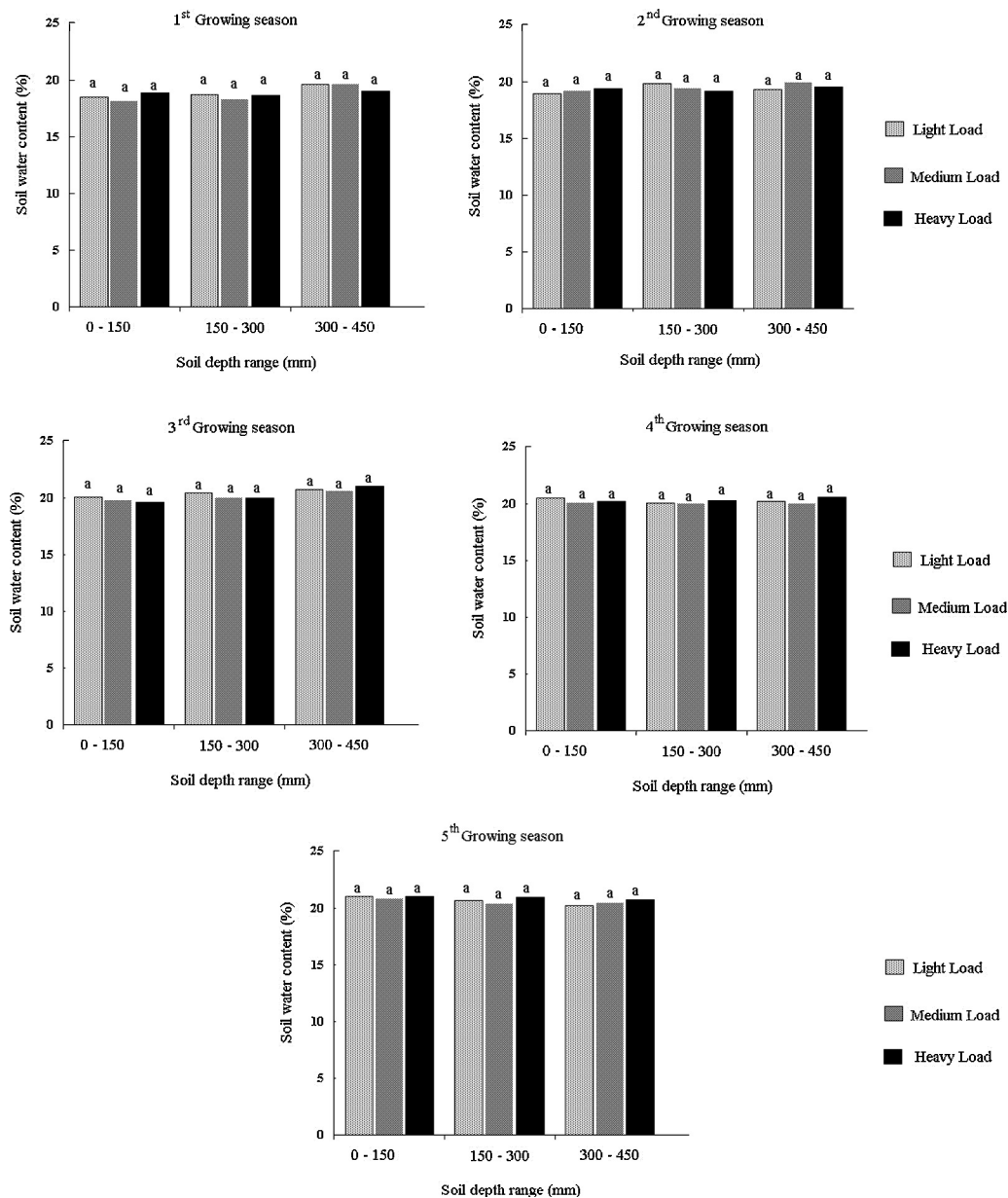


Fig. 2. Mean of soil water content (%) for five growing seasons in three traffic treatments (site 1). Means in the same soil depth followed by same letters are not significant ($P > 0.01$) Duncan's multiple range test.

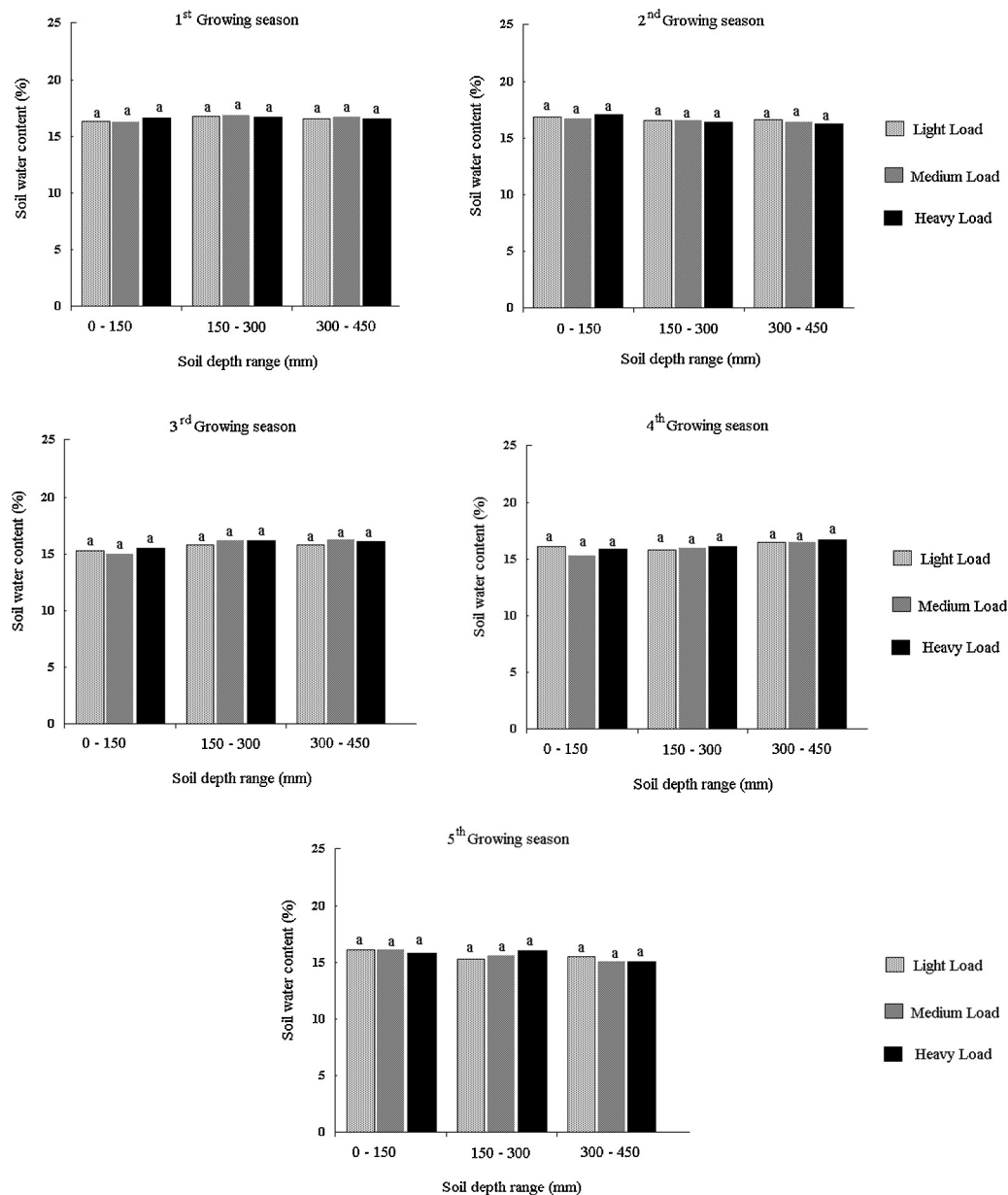


Fig. 3. Mean of soil water content (%) for five growing seasons in three traffic treatments (site 2). Means in the same soil depth followed by same letters are not significant ($P > 0.01$) Duncan's multiple range test.

that, after HL traffic, soil compaction extended to the subsoil starting in the first year and remained at both sites throughout the study period.

For the HL treatment in the two sites, the CI values were greater than 2 MPa between depths of 0 and 450 mm over five years. The analysis of variance of the CI values averaged over depths from 350 to 450 mm showed a significant difference between the HL and ML plots. The CI was higher for HL and ML compared to LL.

The CI values indicate that over-compaction occurred in the subsoil; these values must overcome 2.0 and 2.5 MPa to avoid yield decreases, as suggested by Terminiello et al. (2000) and Botta et al. (2008).

It is important to note that the typical tillage depths in Argentina are approximately 200 mm; therefore, the Ap horizon is considered the topsoil layer from 0 to 200 mm in this experiment and the subsoil can be defined as the soil below the tillage layer.

Figs. 4 and 5 show that the CI values for treatments LL and ML were very similar at 0 and 20 cm at both sites, despite weight (23.6 kN) and ground pressure (26.9 kPa) differences between LL and ML. This curious result could be consequence of higher tyre inflation pressure in treatment LL (220 kPa) compared to ML (185 kPa), masking the lower ground pressure of treatment LL. From the inflation pressure point of view, Arvidsson and Keller (2007) found similar results with tyre inflation pressures of 50, 70 and 150 kPa until 10 cm depth. In our study, higher pressures were used (220 and 185 kPa), producing effects until 20 cm depths for the LL and ML treatments.

At site 1, at depths between 350 and 450 mm, the average CI values in the HL treatment were 2.86, 3.03, 3.40, 4.20 and 4.50 MPa for 2004–2005, 2005–2006, 2006–2007, 2007–2008 and 2008–2009, respectively. At site 2, at depths between 350 and 450 mm, the average CI values in treatment HL were 2.30, 2.63, 3.06, 4.03 and 4.20 MPa for 2004–2005, 2005–2006, 2006–2007, 2007–2008 and 2008–2009, respectively.

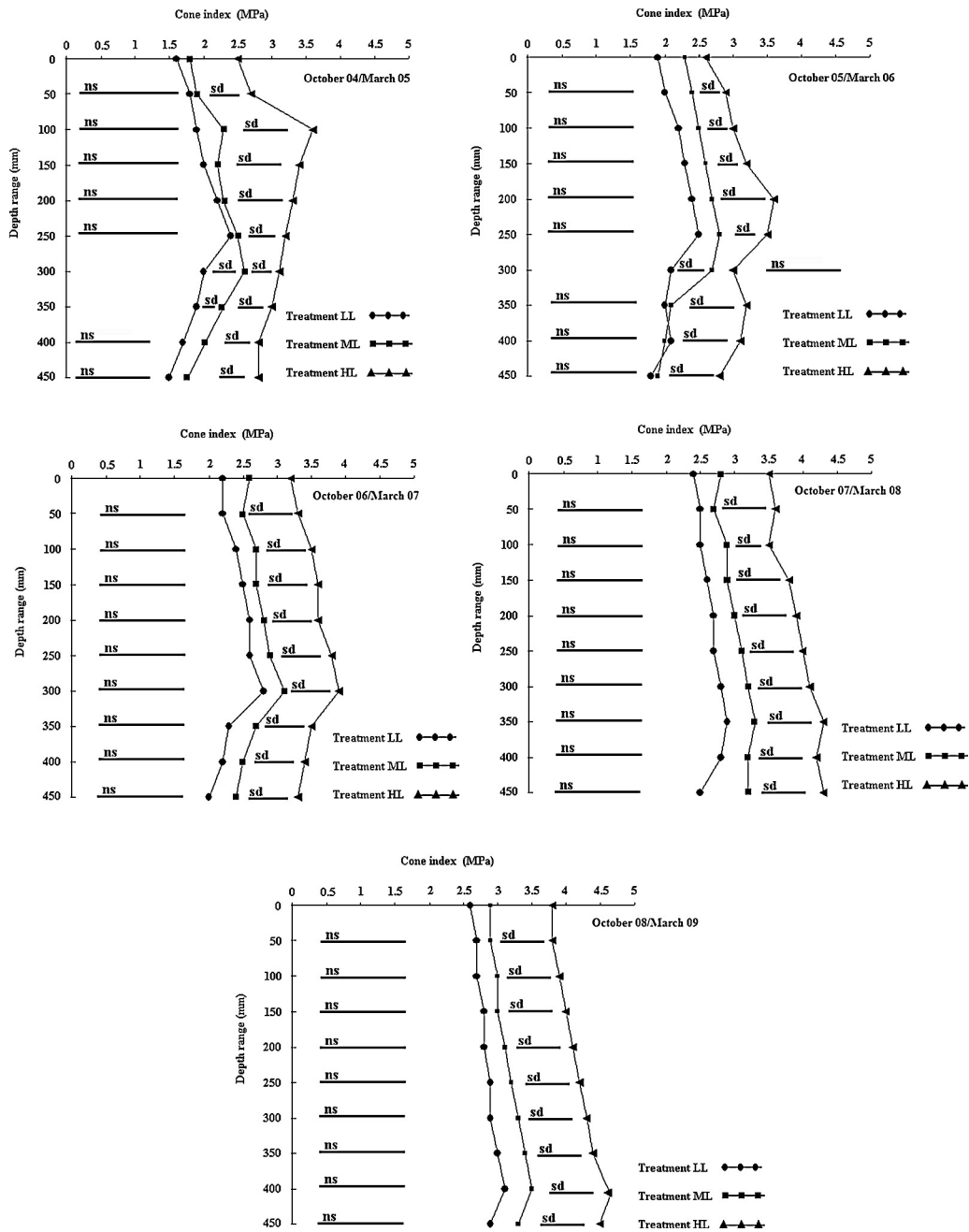


Fig. 4. Cone index values (MPa) measured after sowing for three treatments (tractor and planters) over soil under direct sowing. (sd): significant difference, (ns): not significant ($P < 0.01$) Duncan's multiple range test (site 1).

The highest CI measurements for the HL and ML treatments and the greatest contrast between these treatments and the LL treatment were measured between depths of 200–450 mm in all years studied.

For HL in the two sites, the peak CI values occurred at greater depths each year (Figs. 4 and 5). All values exceeded those known to be critical for root growth retardation (Botta et al., 2002; Jorajuria et al., 1997). In the first and second year of this trial, the peak CI values were found in the topsoil (0–200 mm). According to Riley et al. (1994), most of this yield reduction was most likely caused by damage to the topsoil structure as a result of higher ground pressure. After two years, the peak CI values were found in the subsoil (limited to below 200 mm). In the fifth year of this trial, the largest CI values were noted at approximately 400 mm for the two sites.

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

At both sites, the root dry matter (RDM) was negatively affected by soil compaction. As the soil cone index increased, the RDM decreased within the soil profile. At 8 weeks after seedling emergence (at tasseling), significant differences in the average RDM were observed for all three treatments over all five years. At site 1 (Fig. 6), the highest average RDM values during the five growing seasons were found between 2004 and 2005; the measurements for the LL and ML treatments were 49.1 and 44.1 g plant⁻¹, respectively, whereas the highest value in HL was 38.2 g plant⁻¹. For site 2 (Fig. 7), the highest RDM values during the five growing seasons were found in 2006; the measurements for the LL and ML treatments were 42.6 and 36.2 g plant⁻¹, respectively, whereas the highest value in HL was 30.2 g plant⁻¹.

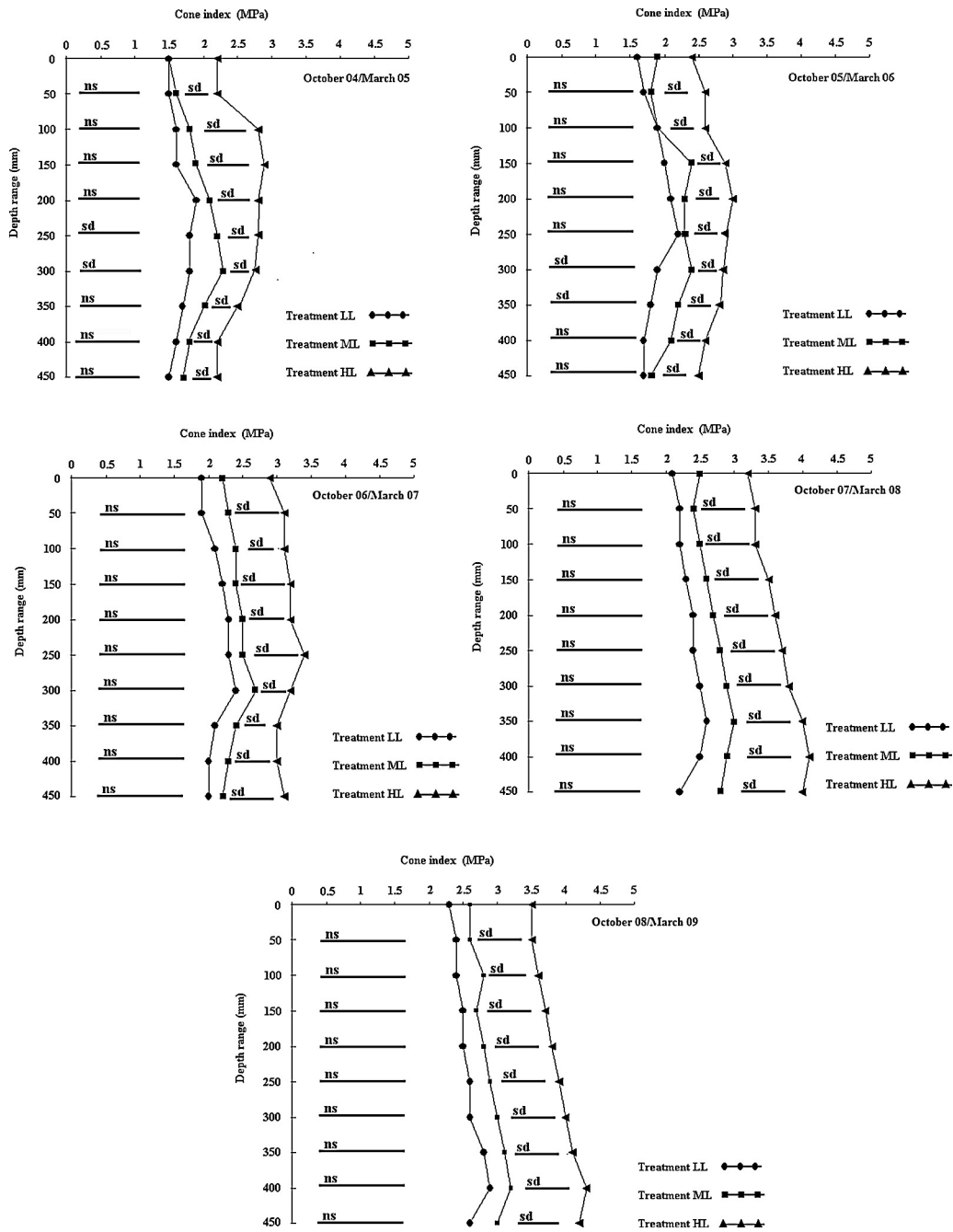


Fig. 5. Cone index values (MPa) measured after sowing for three treatments (tractor and planters) over soil under direct sowing. (sd): significant difference, (ns): not significant ($P < 0.01$) Duncan's multiple range test (site 2).

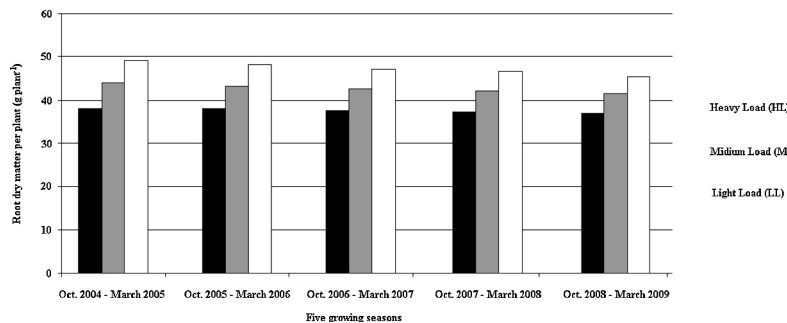


Fig. 6. Root dry matter and dry matter per plant (g plant^{-1}) for five growing seasons and three traffic treatments (site 1).

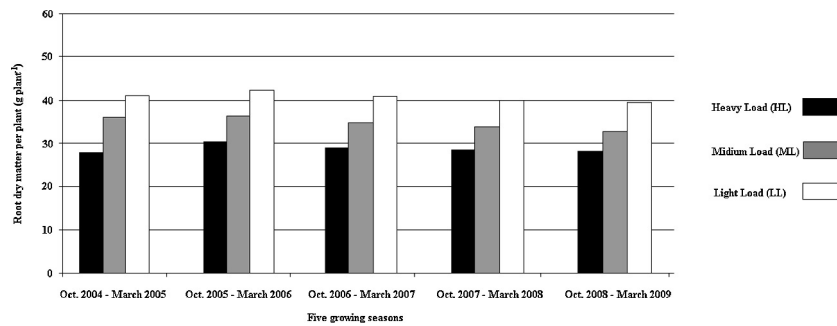


Fig. 7. Root dry matter per plant (g plant^{-1}) for five growing seasons and three traffic treatments (site 2).

For all five growing seasons at site 1, the dry matter per plant (DMP) differed significantly among treatments (Fig. 8). The average DMP measurement over five growing seasons was $154.5 \text{ g plant}^{-1}$ in the LL treatment, followed by $149.8 \text{ g plant}^{-1}$ in ML and $143.7 \text{ g plant}^{-1}$ in HL. The site 2 (Fig. 9) average values were 146.6, 137.9 and 130 g plant^{-1} in LL, ML and HL, respectively.

At two sites for the third, fourth and fifth year, the HL treatment resulted in a significantly ($P < 0.01$) lower maize yield compared to the ML and LL treatments.

The HL treatment resulted in a significantly lower maize yield than the ML and LL treatments. The percentage decreases ranged between 14.3 and 11% for sites 1 and 2, respectively (Table 6). Although soil compaction was much greater at 400 mm in HL compared to ML and LL, these differences were small. It is likely that most of the yield reduction for HL was caused by damage to the topsoil and subsoil structures from the subsoil structures from the higher ground pressure and higher load. Between the second and fifth years, the high peak CI values found in the subsoil (at or below 200 mm) were most likely produced by the high axle load and would have also affected the crop response. These data are in agreement with Sidhu and Duiker (2006), Botta et al. (2007), Lal (1996) and Håkansson, 1987. Moreover, Table 5 shows that there

are no significant differences between treatments 20 days after seeding. Taking into account these results, HL and ML have a slower seeding emergence than LL, but in the end the results we found are similar.

This study also demonstrated that if the axle load increases in soils with high clay and loamy contents, the crop yields decrease and the subsoil compaction increases. Then, from the analysis of the soil compaction pattern assessed, it is clear that the fine textured soils attain higher penetration resistance values, as stated by Vaz et al. (2011). Additionally, according to Söhne (1958) and Botta et al. (2002), soil compaction of the subsoil was higher for the heavier equipment, independent of ground pressure. Stress in the topsoil depends on the average ground pressure and inflation pressure, but the stress in the subsoil is determined mostly by the axle load.

Finally, it was demonstrated that when the axle load increases on soils with high bearing capacity (soils under a long-term DS system), the crop yields decrease and the subsoil compaction problems increase. Hence, the data support both hypotheses. These hypotheses include the following: (a) maize yields are affected by subsoil compaction and (b) the application of DS systems over five continuous years causes subsoil compaction.

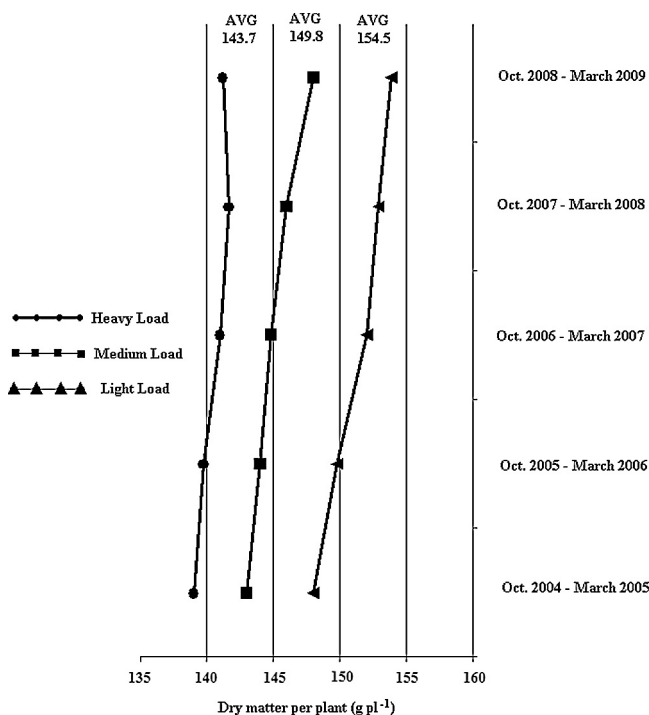


Fig. 8. Dry matter per plant (g plant^{-1}) for five growing seasons and three traffic treatments (site 1).

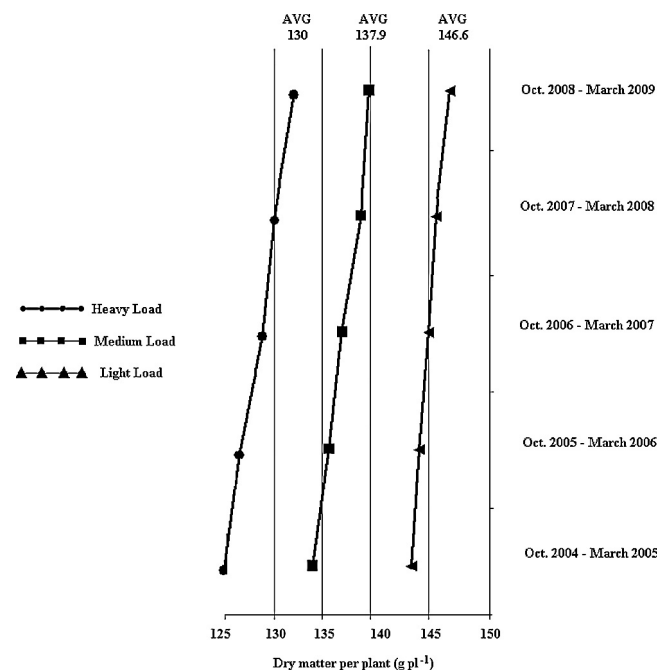


Fig. 9. Dry matter per plant (g plant^{-1}) for five growing seasons and three traffic treatments (site 2).

Table 6
Maize yields (t ha^{-1}) for three treatments in five growing seasons (two sites).

Treatments	Heavy load HL (177.9 kN)	Medium load ML (167.6 kN)	Light load LL (144 kN)
Site 1			
Crop yield (t ha^{-1}) harvested 2005	10.1 a	10.2 a	10.5 a
Crop yield (t ha^{-1}) harvested 2006	9.9 a	10.4 a	10.9 a
Crop yield (t ha^{-1}) harvested 2007	9.2 a	11.3 b	11.7 b
Crop yield (t ha^{-1}) harvested 2008	8.9 a	11.3 b	11.8 b
Crop yield (t ha^{-1}) harvested 2009	8.6 b	11.0 b	11.9 c
Average (t ha^{-1})	9.3 a	10.8 b	11.4 c
Site 2			
Crop yield (t ha^{-1}) harvested 2005	2.7 a	2.8 a	3.0 a
Crop yield (t ha^{-1}) harvested 2006	2.6 a	2.9 a	3.2 a
Crop yield (t ha^{-1}) harvested 2007	2.57 a	3.1 b	3.3 b
Crop yield (t ha^{-1}) harvested 2008	2.5 a	3.2 b	3.4 b
Crop yield (t ha^{-1}) harvested 2009	2.4 a	3.2 b	3.5 b
Average (t ha^{-1})	2.5 a	3.0 b	3.3 b

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

4. Conclusions

When clayey and loamy soil was trafficked with loads of 144, 167.6 and 177.9 kN for five years, the cone index was increased in the subsoil to depths of 40 cm. These increases persisted during this time and soil compaction resulting from these loads reduced the root growth and dry matter per plant. It was clear that the 33.9 kN difference between the LL and HL equipments caused a higher decrease in maize yields.

Taking into account that the subsoil compaction is very persistent, the sowing operations on soils under direct sowing system using equipment with a high axle load and high ground pressure (between 95 and 155 kPa) should be performed with as low of a traffic intensity as possible to avoid high soil compaction.

When the two soils were trafficked by HL equipment with 177.9 kN, the maize yields were reduced significantly for the last three growing seasons at both sites. Additionally, in both sites the cone index measurements showed that subsoil compaction persisted for more than 4 years.

During the fourth and fifth growing seasons of the experiment (October 2007–March 2008 and October 2008–March 2009), the peak CI values in the subsoil were higher than 4 MPa when heavy equipment (HL) was trafficked at both sites. The maize yields decreased year by year and the cone index increased; therefore, these high CI values caused by the combination of a high axle load and ground pressure would have affected the maize responses.

Acknowledgement

This work was carried out under project of the Iberoamerican Agricultural Sustainability Group. Project Reference Number AGR198.

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