Traffic of harvester combines: effect on maize yields (*Zea Mays* L.) and soil compaction under direct sowing system

Tráfico de cosechadoras: efecto sobre los rendimientos de maíz (*Zea Mays* L.) y compactación del suelo bajo el sistema de siembra directa

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Abstract

In this work, we quantified the effects of harvest traffic having different tyre ground pressures and axle loads on soil properties and maize *(Zea Mays* L.*)* yields. The treatments consisted of a control plot with no traffic (T1), a combine harvester with low tyre ground pressure (T2) and the same harvest traffic with high tyre ground pressure (T3). Cone index (CI), soil water content (SWC), rut depth (RD), root dry matter per plant (RDM) and maize yields (MY) were measured at seven places in relation to the tracks, namely: centre of the tracks (0), and at 70, 140 and 210 cm on either side of them. For three growing seasons, the results showed that in the topsoil (0 to 20 cm), CI values produced by treatment T3 were > 2.7 MPa and between 3.4 to 4.25 MPa in the subsoil (20 to 60 cm). Also, when the soil was trafficked by tyres with infaltion pressures of 120 to 240 kPa, the CI increased in the topsoil and subsoil, but differences in rut depth (RD) at the surface did not extend into the subsoil in terms of CI. The greatest differences in RDM were found in the third growing season. The minimum MY of 4.7 Mg ha^{-1} was observed in 2016 (third growing season) in the centre line of the tyre tracks after one pass of combine harvester with high tyre ground pressure. Yield increased with distance from the track centres reaching 5.10 Mg ha^{-1} at 210 cm on either side of them. The main conclusions were that one pass of the combine harvesters with total weight load between 16.67 and 21.10 Mg was sufficient to increase the CI in both the topsoil and subsoil layers while maize yields were significantly reduced by all compaction in the combine harvesters tracks, as well as all positions alongside them.

Keywords
soil bearing capacity • cone index • crop yield • root growth

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Resumen

En este trabajo se cuantificaron los efectos del tráfico de cosechadoras con diferentes presiones en el área de contacto rueda/suelo y cargas por eje sobre las propiedades del suelo y los rendimientos del maíz (*Zea Mays* L.). Los tratamientos consistieron en una parcela testigo sin tráfico (T1), una cosechadora con baja presión en el área de contacto rueda/suelo (T2) y una cosechadora con alta presión en el área de contacto rueda/suelo (T3). Se midieron el índice de cono (IC), el contenido de agua en el suelo (CAS), la profundidad de huella (PFH), la materia seca de raíz por planta (MSR) y los rendimientos de maíz (RM) en siete distancias a un lado y otro de las huellas: (0), 70, 140 y 210 cm. Durante las tres temporadas de cultivo, los resultados mostraron que en la capa superficial del suelo (0 a 20 cm), los valores de IC producidos por el tratamiento T3 fueron > 2,7 MPa y entre 3,4 y 4,25 MPa en el subsuelo (20 a 60 cm). Además, cuando el suelo fue transitado por neumático con presiones de inflado entre 120 y 240 kPa, el IC aumentó en la capa superficial y el subsuelo, sin embargo la PFH en la superficie no se extendió al subsuelo en términos de IC. Las mayores diferencias en MSR se encontraron en la tercera temporada de crecimiento. El mínimo RM fue de 4,7 Mg ha^{-1} y se observó en 2016 en el centro de la huella de los neumáticos después de un paso de la cosechadora con alta presión en el área de contacto rueda/suelo. El rendimiento aumentó con la distancia desde el centro de la huella alcanzando 5,10 Mg ha^{-1} a 210 cm en cada lado de la misma. Las principales conclusiones fueron que una pasada del equipo de cosecha con un peso total entre 16,67 y 21,10 Mg fue suficiente para incrementar la IC en las capas de suelo y subsuelo, mientras que los rendimientos de maíz fueron significativamente reducidos por compactación en las vías de recolección, así como todas las posiciones a su lado.

Palabras clave

capacidad portante del suelo • índice de cono • rendimiento del cultivo • crecimiento de la raíz

Introduction

Maize (*Zea mays* L.) is South America's second most important crop with 19.3 Mha devoted to it. The main producers are Brazil and Argentina, which in the 2015/2016 season produced 98 million metric tonnes (33).

Argentina is the second largest exporter of maize after the United States, 70% of its production being exported and Brazil is the third largest (13).

In Argentina, maize is produced in the Rolling Pampa region, mainly on clayey and loamy soils (4.2 Mha under direct sowing (DS)) (33), which are very susceptible to compaction by high traffic intensity with heavy machinery such as seeding machines (50-110 kN), tractors (50-100 kN), combine harvesters (90 to 150 kN) and grain chasers (100-200 kN)). In harvest operations, Botta *et al.* (2007), found that when the traffic intensity increases on clay soils with a high bearing capacity (soils under long term DS) crop yields decrease and soil compaction problems increase. According to (ASAE Standarts (1992)), compaction is caused by high wheel loads and tyre ground pressures from machinery used in DS crop operations, particularly when these operations are carried out on wet clay soil or with high inflation pressure tyres (between 140 to 218 kPa).

The roots of the majority of plants species are unable to penetrate deeper in the profile when there is compaction in the topsoil, and this is a frequently reported problem.

Nunes *et al.* (2015) also observed a higher concentration of maize (*Zea mays*) roots (63.8%) in the 0 to 7cm layer due to physical deterioration in the subsurface of an Oxisol (27) under no-tillage .

According to Lapiec (2012), the mean crop yield reduction was 2.5%, but varied considerably among sites, years and crops. For example, the maize yield reduction due to persistent subsoil compaction as a consequence of high axle load was 6% in Minnesota and 12% in Quebec. The negative impact of agricultural tyres, with high ground pressure, heavy equipment and traffic on soil physical properties, root elongation and crop yields are well known (8, 11, 15). The equipment weight and the resulting wheel load are directly related to the machine and affect subsoil compaction (1, 8).

However, the tyre ground pressure and the distribution of pressure throughout the topsoil are linked to the tyre's attributes (21, 25) and are major engineering tools that can be used to control soil compaction (23).

Acording to Schjønning *et al.* (2015) small values of stress in the transverse direction of the tyre at high inflation pressures reflect a stress peak at the center of the tyre, which was also observed in other studies (16, 18, 19). These statements argue that a single determination of bulk density made at the center of the tyre track at a single depth is probably not representative of the highest value at each horizontal or vertical location (32).

Studies by Hidalgo *et al.* (2014), in rice cultivation working in (Planosoil) with special treads for these conditions, reported that in a packed soil with no structure, the passage of the special tyres caused more horizontal compaction due to soil displacement. These data are of relevant importance to compaction (8, 21). In this respect, Cambie *et al.* (2015), concluded (on a Dystric Cambisol), that deep ruts occurred in moist soil with just a single pass.

The largest negative impact on soil occurred when using a wheeled tractor on moist soil. A general rule of thumb is to prohibit traffic when soils are wetter than field capacity, although this may not account for conditions in the subsoil (12).

Although DS systems have been developed and tested around the world, the results vary depending on the climate and the time required by soils to adapt to a new management regime. Also, there is very little information in the literature on differences in maize (*Zea mays* L.) yields under DS caused by the horizontal transfer of compaction from the centre of tracks.

Objectives

Quantify soil parameters that affect maize crop development in different positions relative to equipment tracks.

Compare the effect of two different pressures of harvest equipment (combine harvester, tractor and grain chaser) on compaction of a Hapludol entic soil and maize yields cultivated under DS.

Hypothesis

That maize yields are negatively affected by one pass of harvest equipment and that this traffic causes horizontal soil displacement as well as subsoil compaction.

Materials and methods

The site and crop operations

The work was carried out at the *La Ines* farm (36°04'33.18" S y 62°29'14.57" W), located in west of the Buenos Aires province on a soil classified as Loamy Entic Haplustol (29). Typical profile characteristics are shown in table 1. Soil management history includes 8 years of crop rotation following a very common regional pattern, winter wheat/soya (*Triticum aestivum* L.)/(*Glicine max* L.) followed by maize (*Zea mays* L.) in the summer. The hybrid maize used was "Dekalb vt 670 3p", and was direct drilled in the first growing season on 10 October 2014, in the second growing season on 8 October 2015, and in the third grawing season on 7 October 2016.

The sowing rate was 71500 pl ha^{-1}, and the sowing depth was 3 cm. The row spacing was 70 cm and the average emergence was 90% in all treatments. Maize was harvested on: April 26, 2015 (end of the first growing season), April 25, 2016 (end of the second growing season) and April 26, 2017 (end of the third growing season) for all treatments. Yields on the control plot (T1) averaged 8.2 Mg ha^{-1}.

Fertilizer (60 kg ha^{-1} of diammonium phosphate and 45 kg ha^{-1} of liquid nitrogen) was applied nominally along the seed line while weeds were controlled using post-emergence herbicides.

Treatments

Two main treatments and a control plot without traffic (T1) were applied in three consecutive growing seasons using the equipment outlined in table 2 (page 89).

Treatment 2 (T2) consisted of combine harvester, all with tyres applying a low axle load and low tyre ground pressure. Treatment 3 (T3) used the combine harvester but with applying high axle loads and high tyre ground pressures.

Each experimental plot was trafficked with one pass of the harvest machines, each with its own centre line.

Table 1. Soil profile characteristics of the Entic Haplustoll.

Tabla 1. Perfil tipico del suelo Haplustol Entico.

Horizons	Ap	A_{12}	AC	C
Depth range (mm)	0-120	150-300	350-650	710-1120
Organic carbon g kg^{-1}	10.2	6.1	5.2	-
C/N ratio	8	8	7	-
Clay (<2 μ) g kg^{-1}	161	284	184	63
Silt (2-20 μ) g kg^{-1}	98	63	76	99
Silt (2-50μ) g kg^{-1}	176	144	131	206
Very fine sand (74 - 100) g kg^{-1}	402	302	398	367
Fine sand (100 - 250 μ) g kg^{-1}	159	201	207	261
Medium sand (250 - 500) g kg^{-1}	4	6	4	4
pH	6.1	6.1	6.3	6.7
pH in H_20 (1: 2.5)	6.4	6.6	6.9	6.9

Table 2. Description and harvest characteristics.

Tabla 2. Descripción y características de las cosechadoras.

	Combine Harvester (T2)	**Combine Harvester (T3)**
Engine power (CV/kW)	325/238.3	480/352
Rotors	One	one
Front tyres	900/60 R 32	900/60 R32
Front tyres inflation pressure (kPa)	200	240
Rear tyres	28 L - 26	750/65 R 26
Rear tyres inflation pressure (kPa)	120	120
Total weight loaded (Mg)	16.67	21.10
Front axle weight (Mg)	11.66	13.72
Rear axle weight (Mg)	5.10	7.38
Static load per front wheel (Mg)	5.83	6.86
Static load per rear wheel (Mg)	2.55	3.69
Front wheel track width (mm)	3300	3450
Rear wheel track width (mm)	3300	3450
Front tyre - soil contact area (m^2)	0.845	0.924
Rear tyre - soil contact area (m^2)	0.800	0.862
Tyre ground pressure per front tyre (kPa)	67.61	77.99
Tyre ground pressure per rear tyre (kPa)	31.23	83.90

Fifteen 200 m x 80 m plots were randomly assigned to traffic treatments with five replicates for each treatment and 20 m wide buffer zones between plots to prevent interactions. Prior to the application of each treatment, all the combine harvesters was weighed (with electronic scale) to obtain its total, individual axle loads and wheel load (figure 1).

Harvest operations were the same for both the traffic treatments (figure 2, page 90) but were not in the same place each growing season because local commercial practice employs random traffic.

The same machinery was used for sowing and spraying the maize crop during the three growing seasons of the trial, but the harvest equipment was changed according to treatment.

The tyre-soil contact area (TSC) and tyre ground pressure was estimated as the ratio between total axle load and total tyre-soil contact area (5).

Parameters monitored

Cone index (CI), soil water content (SWC), rut depth (RD), root dry matter per plant (RDM) and maize yields (MY) were measured. Soil sampling was done at seven points across the tyre track, described as: centre line of the tyre track (0) and at 70, 140 and 210 cm cm to either side of it, denoted "inside" and "outside" (figure 3, page 90).

Figure 1. Weight of the machinery prior to the test.

Figura 1. Peso de la maquinaria previo al ensayo.

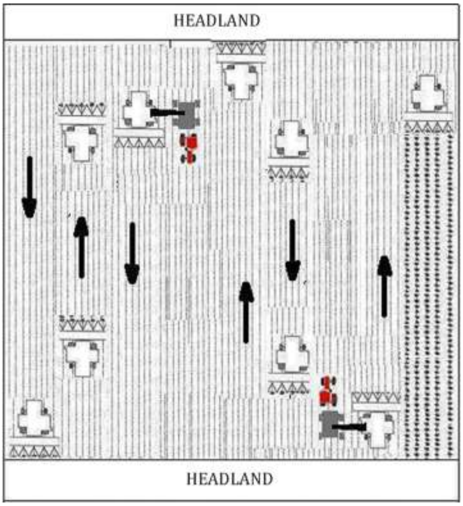


Figure 2. Schematic for the harvest traffic. Source: Botta *et al.* (2007).

Figura 2. Esquema para el tráfico de cosecha. Fuente: Botta *et al.* (2007).

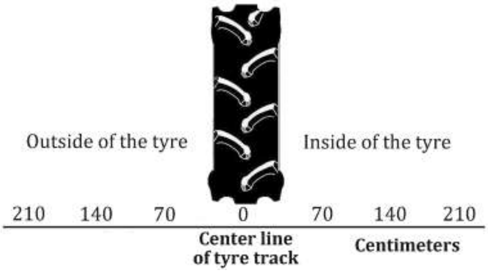


Figure 3. Soil and crop sampling points across the tyre track.

Figura 3. Puntos de muestreo del suelo y cultivo a través de la pisada del neumático.

Each of the points was selected at random within the sectors described by the passage of each of the treatments (figure 2, page 90). Cone index (CI) was measured after harvest at three depth ranges, 0-20-20-40 and 40-60 cm using a Rimick CP20 recording S313 penetrometer (3). Data for studying the impact of harvester passes on the CI, SWC and TD, were taken at the beginning (before sowing date) and end (harvest day) of each season, and averaged for the three growing seasons of study. On each measuring occasion, each datum was the mean of thirty soil samples for each of the plots per treatment, as proposed by Botta (2000). SWC was measured with a gamma probe at depths of 0-20 cm, 20-40 cm, and 40-60 cm. Each quoted value of SWC is the average of thirty measurements. Rut depths (RD) were measured using a profile meter consisting of a set of vertical metals rods (length 50 cm and diameter 0.5 cm), spaced 2.5 cm apart horizontally and sliding through holes in a 1-m long iron bar.

The bar was levelled across the wheel tracks perpendicular to the direction of travel and the rods pushed down to conform to the shape of the depression. The track depth was calculated from the average depth of 60 reads on the 1 metre bar.

Root dry matter (RDM) was measured 8 weeks after seedling emergence (during tasseling). Roots were sampled in the 0 to 30 cm depth range because most of the roots were concentrated in the first 25 cm.

A total of 70 samples were taken per treatment and after washing to remove all soil particles, the roots were dried at 104°C in a conventional oven to constant weight, which was recorded. To determine maize yield (MY), each plot was divided into 160 m^2 isolated quadrants in accordance with the method proposed by Tolón Becerra *et al.* (2011).

Statistical analysis

Data for yield and maize parameters for each growing season were analyzed by ANOVA considering a randomized block design. For all parameters, mean values were separated using the Duncan's multiple range tests with a significance level of 5%. Statistical analyses were carried out using Statgraph 7.1.

Results and discussion

Weather conditions

The ten-day total rainfall and average maximum temperatures from September 25 to April 30 for each year were registered. The average maximum air temperature was within normal ranges for the proper implantation and growth and development of maize. Rainfall during the critical period of maize growth (1st - 25th January) was below average in the three growing seasons. Rainfall was significant before harvest operations (last 10 days of April) in the third year causing high SWC. Because seasonal weather conditions were rather similar in all the growing seasons, variations in maize yields between seasons could be due to soil compaction produced by the different combine harvester.

Soil water content and Cone index

Over the whole period of the study (October 2014-April 2017), there was no significant difference in the SWC between depths (0 to 60 cm) seasons or treatments, although there was a small increase in absolute values with sampling depth. Topsoil compaction (0-20 cm) by treatment 3 (combine harvest with high tyre ground pressure) caused greater changes in the topsoil properties (CI > 2.7 Mpa) than treatment 2 (harvest with low tyre ground pressure). With respect to the CI values (figure 4, page 92), the combine harvester (T2) caused the least increase in soil impedance, with minimal horizontal transfer of compaction in the 0 to 20 cm depth range, showing significant differences from the control only in the centre of the track. In contrast, (T3) caused the greatest increase in CI at all points analyzed, and was differentiated significantly from treatments T2 and T1 (control).

Compaction by the high tyre ground pressure treatment (T3) caused greater changes to the topsoil and subsoil properties than the low pressure treatment (T2). These results are in accord with those of Botta *et al.* (2016) and Håkansson and Reeder (1994), who indicated that compaction effects at high axle load are related to soil type, number of passes, tyre ground pressure and the number of years since compaction.

The CI values resulting from the T2 (low pressure) and T3 (high pressure) treatments were significantly different ($P < 0.01$) from the control plot (T1), but at different soil depths (as expected), *i.e.* 40 cm for T2 and 60 cm for T3.

In addition, the CI values were higher for T3 than for T2. It is likely that this higher CI, which caused densification of the subsoil, was due to passage of the heavier machinery during harvest operations (T2 = 21.10 Mg) rather than to the qualities of the ground itself. This mirrors studies by Arvidsson and Håkansson (2014), Botta *et al.* (2007) and Håkansson and Reeder (1994).

For the tyre low pressure treatment (T2), in the first depth range (0-20 cm) there were strong differences in the data from the sampling points, with maximum CI in the centre of the tracks and diminishing toward the sides, but always higher than the control plot, and up to 70 cm either side of the centre line of the tyre track (figure 4, page 92).

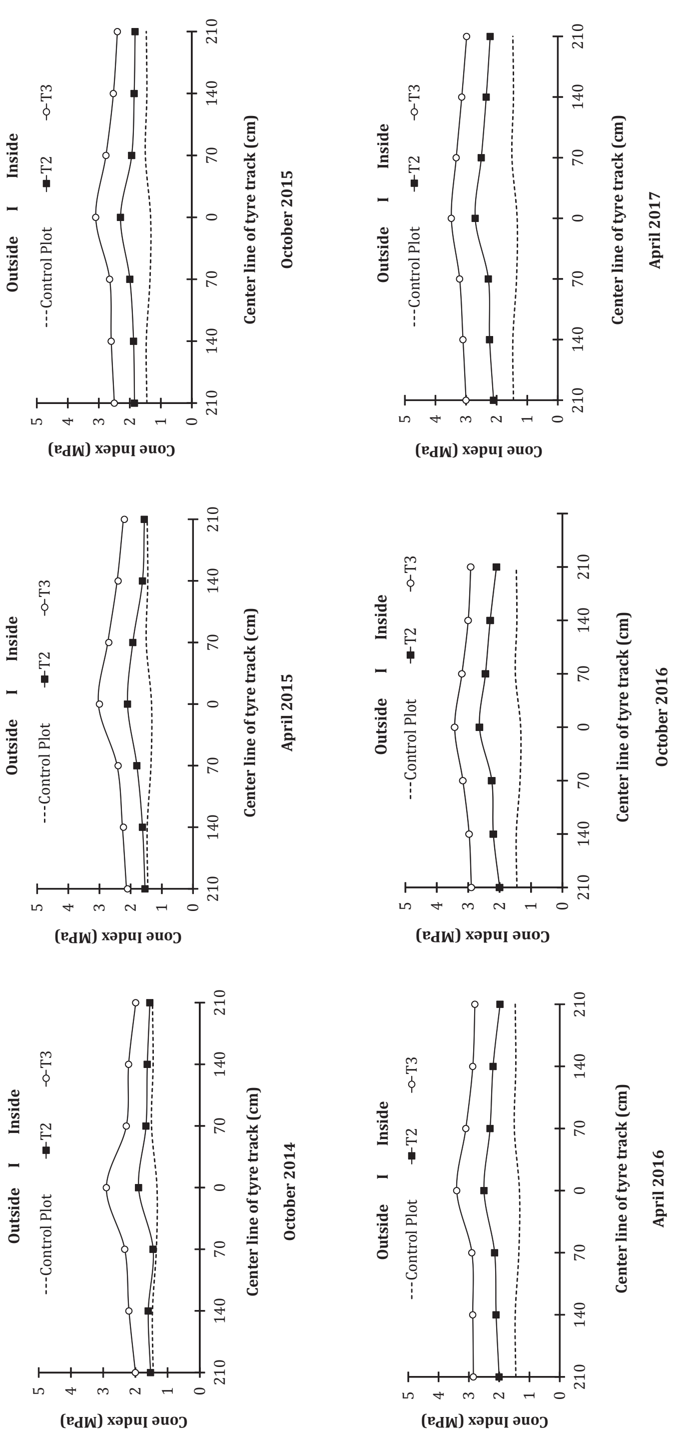


Figure 4. Cone index values (MPa) measured, between 0 to 20 cm depth range for two combine harvest in the three growing seasons at the start and end of testing.

Figura 4. Valores del índice de cono (MPa) medidos, entre 0 a 20 cm de profundidad para las dos cosechadoras durante las tres estaciones de crecimiento, al inicio y al final de la prueba.

For the high tyre ground pressure treatment (T3) CI values measured at 0, 70, 140 and 210 cm, to either side of the track centre, were significantly different to T1 (control) and T2 (low pressure) and higher than 2.5 MPa. For the three experimental growing seasons, the tyre ground pressure reflected in CI was always higher for treatment T3 (figure 4, page 92).

In the 20 to 40 cm depth range, T2 (low pressure) caused an increase in soil impedance compared with the control, but this difference was only significant ($P< 0.01$) at 70 cm, both on the inside and outside of the center line of the tyre track (figure 5, page 94; figure 6, page 95). Cone index values for the T3 treatment CI were higher than 3 MPa at the centre of the track between depths of 0 to 20 and 20 to 60 cm (figure 5, page 94; figure 6, page 95). These CI values indicate that over-compaction occurred in the subsoil and were greater than the limit of 2.0 MPa suggested by Botta *et al.* (2004) and Botta *et al.* (2009), to avoid yield decreases.

For treatments 2 and 3, the CI values measured at 70, 140 and 210 cm, to either side of the the tyre track centre were lower than at the centre.

The results for T3 in particular (tyre inflation pressures of up to 220 kPa in front tyres) are in accord with those of Jun *et al.* (1998) who indicated that the maximum normal stress occurred near the centre line of tyres at high inflation pressure. This was also observed by Hidalgo *et al.* (2016), Keller and Arvidsson (2004), Keller (2005), Lamandé and Schjønning (2011) and Schjønning (2015), who additionally noted that tyre inflation pressure significantly affects the vertical stress not only in the topsoil, but also in the subsoil.

Jun *et al.* (1998) also observed that the maximum tangential stress occurred near the tyre centre line and decreased as the position moved towards the edge of the tyre.

For tretamnet 2, in the 40 to 60 cm depth range CI values at 210 cm to the outside and inside of the tyre track did not differ significantly from the control plot. There were no significant differences for this treatment (T2) compared with the control in the 40 to 60 cm depth range.

In this level depth range, average CI values for the three growing seasons were higher for (T3) than for (T2). Of particular note is the fact that T3 (in last season) caused CI values between 3.4 and 4.25 Mpa in the subsoil.

Rut depth (RD)

The RD for the two treatments were of different magnitudes. During all three growing seasons, RD at constant wheel load significantly increased the stress in the topsoil (0 to 20 cm) and upper subsoil (figure 7, page 96).

This figure also shows that RD was always greater for the high tyre ground pressure treatment (T3) than those of the equivalent low pressure. Also, the high axle load machines caused a higher pressure on the topsoil than (T2).

However, the influence of RD on subsoil compaction is not clear. Also, it can be seen (figure 7) that when the soil was trafficked with tyre ground pressures of 77.99 to 83.90 kPa and high load (Eg.: T3 = 21.10 Mg), the cone index increased in the topsoil and subsoil, but there was no effect of the RD on subsoil compaction (20 to 60 cm).

Root dry matter (RDM) and maize yields (MY)

In each of the three growing seasons, there were significant differences in RDM between all the traffic treatments as well as the control (table 3, page 97).

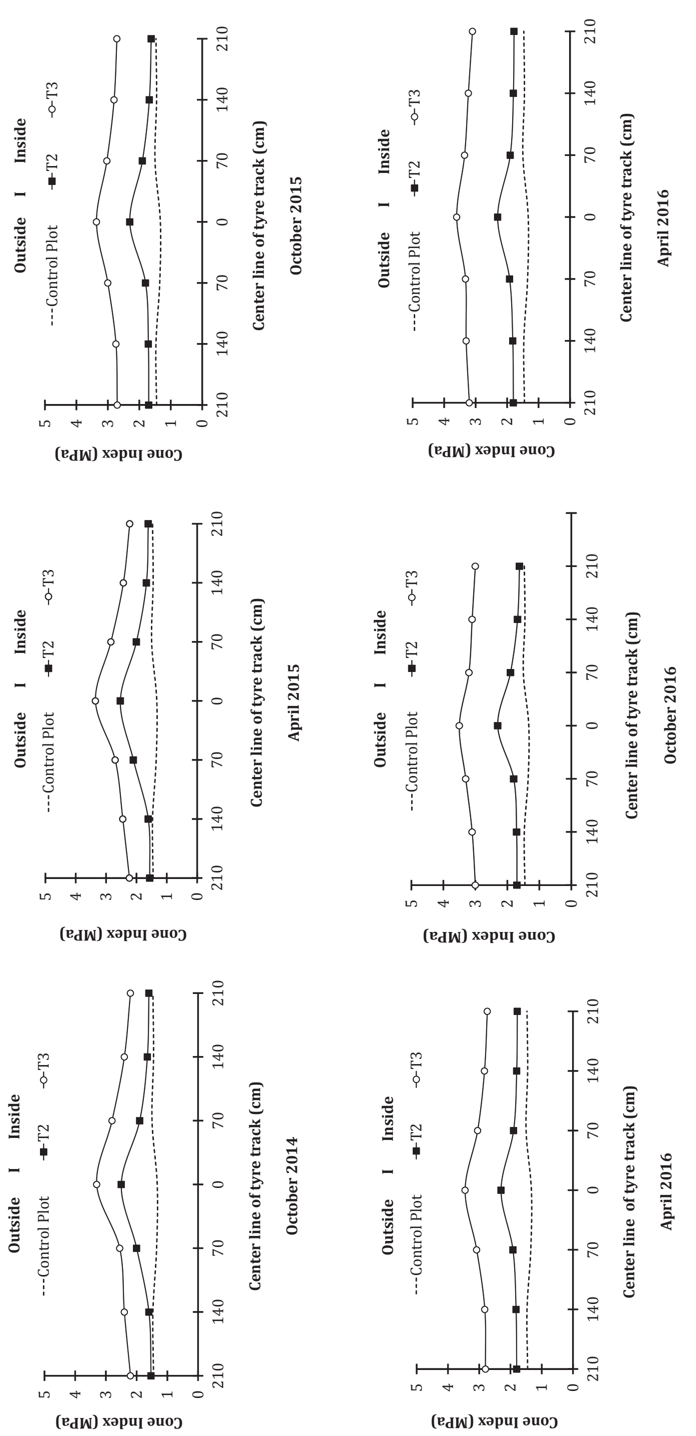


Figure 5. Cone index values (MPa) measured, between 20 to 40 cm depth range for two combine harvest in the three growing seasons at the start and end of testing.

Figura 5. Valores del índice de cono (MPa) medidos, entre 20 a 40 cm de profundidad para las dos cosechadoras durante las tres estaciones de crecimiento, al inicio y al final de la prueba.

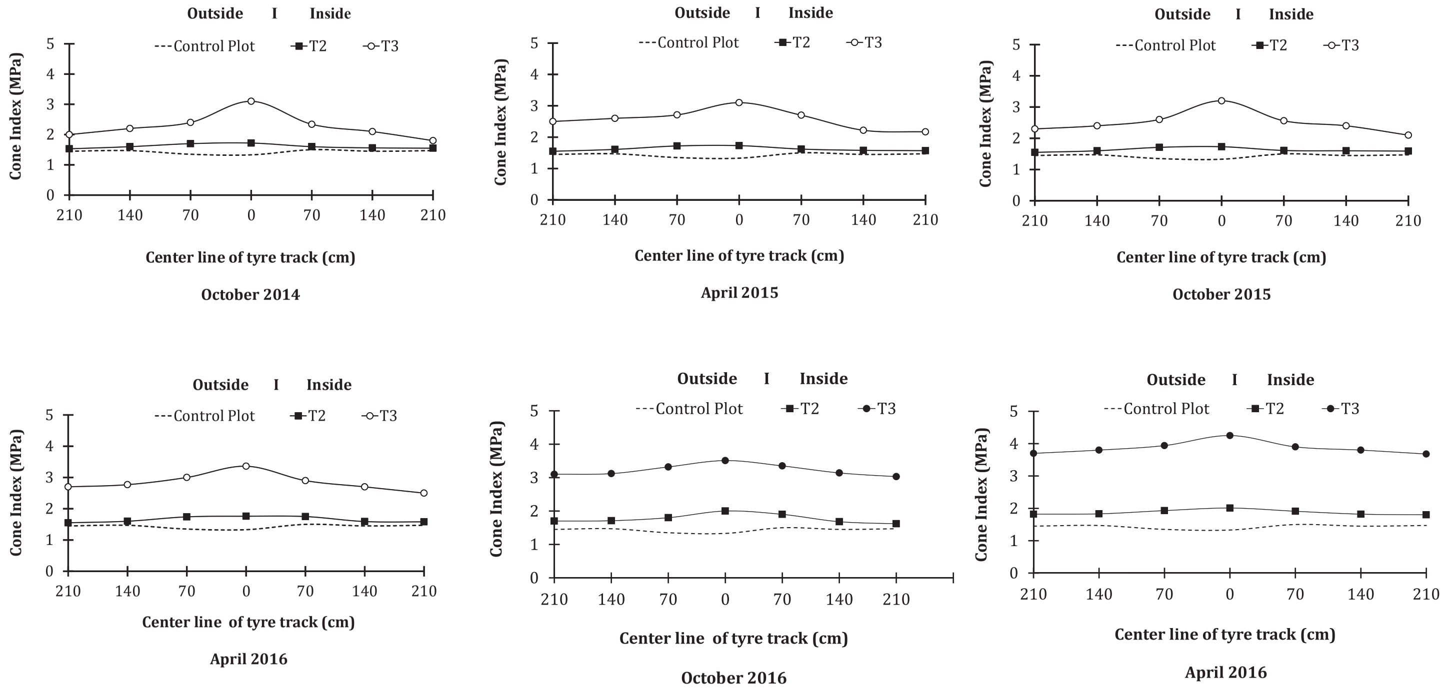
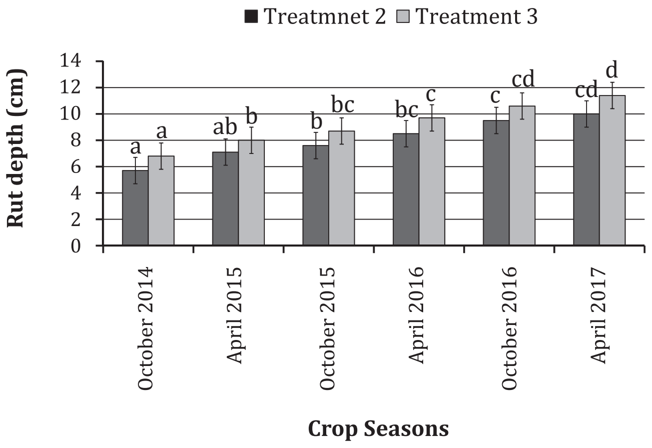


Figure 6. Cone index values (MPa) measured, between 40 to 60 cm depth range for two combine harvest in the three growing seasons at the start and end of testing.

Figura 6. Valores del índice de cono (MPa) medidos, entre 40 a 60 cm de profundidad para las dos cosechadoras durante las tres estaciones de crecimiento, al inicio y al final de la prueba.



Error bars indicate standard errors. (Values with different letters are significantly different ($P < 0.01$) Duncan's multiple range test).

Las barras de error indican errores estándar. (Los valores con letras diferentes son significativamente diferentes ($P < 0,01$) prueba de rango múltiple de Duncan).

Figure 7. Rut depth (cm) measured for two combine harvesters after traffic in the three growing seasons.

Figura 7. Profundidad de huella (cm) medida para los dos tratamientos después del tráfico en las tres estaciones de crecimiento del cultivo.

As the axle load increased, the RDM values decreased. Root dry matter (RDM) was affected negatively by soil compaction.

The highest RDM values were found in the 1rst Growing season for T2 (46.6 g $plant^{-1}$) at the 210 cm position outside the track centre line, whereas the highest value in T3 was 41.9 g $plant^{-1}$ in the 1st Growing season (again at 210 cm outside the track centre line).

These results mirror those of Nunes *et al.* (2015) and Botta *et al.* (2009) who indicated that a decrease in root development of all species below the 0-10 cm layer reflected a restrictive soil physical condition. This was due to the presence of aggregates formed originally by compression, with high soil bulk density and low soil macroporosity. Also, according to Botta *et al.* (2016), roots are biologically responsive indicators and tend to grow more vigorously in zones that show least physical resistance.

In all treatments, RDM values were directly proportional to maize yields which were greater in treatment 2 than treatment 3. Lower values of soil compaction were associated with greater maize yields and RDM (table 3, page 97 and table 4, page 98).

For the three growing seasons, in treatments T2 and T3, traffic caused variable decreases in maize yields. After one pass of the equipment, MY decreased significantly with respect to the control plot (T1 = 8.2 Mg ha^{-1}). The MY over the three growing seasons was significantly lower in the (T3) treatment, followed by (T2) (table 4, page 98).

Table 3. Root dry matter per plant (g plant^{-1}) for three growing seasons.
Tabla 3. Materia seca de raíz por planta (g planta^{-1}) en tres temporadas de crecimiento.

1st Growing season							
Treatments	210 cm Outside	140 cm Outside	70 cm Outside	Center line of tyre track	70 cm Inside	140 cm Inside	210 cm Inside
(T3)	41.8 Cc	41.5 Cc	41.1 Cc	40.5 Cc	41.6 Cc	41.4 Cc	41.9 Cc
(T2)	46.6 Bb	46.1 Bb	46.2 Bb	45.2 Bb	46.1 Bb	46.1 Bb	46.3 Bb
Control plot **(T1)**	50.1 Aa	50.3.1 Aa	49.7 Aa	50.2 Aa	50.0 Aa	49.4 Aa	50.1 Aa
2nd Growing season							
Treatments	210 cm Outside	140 cm Outside	70 cm Outside	Center line of tyre track	70 cm Inside	140 cm Inside	210 cm Inside
(T3)	41.5 Cc	41.1 Cc	41.0 Cc	40.0 Cc	41.3 Cc	41.5 Cc	41.7 Cc
(T2)	45.8 Bb	45.7 Bb	45.5 Bb	44.7 Bb	45.1 Bb	45.6 Bb	45.5 Bb
Control plot **(T1)**	50.1 Aa	50.3.1 Aa	49.7 Aa	50.2 Aa	50.0 Aa	49.4 Aa	50.1 Aa
3rd Growing season							
Treatments	210 cm Outside	140 cm Outside	70 cm Outside	Center line of tyre track	70 cm Inside	140 cm Inside	210 cm Inside
(T3)	40.8 Cc	40.2 Cc	40.0 Cc	39.7 Cc	40.4 Cc	40.6 Cc	40.7 Cc
(T2)	45.0 Bb	45.2 Bb	45.1 Bb	43.9 Bb	45.0 Bb	45.2 Bb	45.2 Bb
Control plot **(T1)**	50.1 Aa	50.3.1 Aa	49.7 Aa	50.2 Aa	50.0 Aa	49.4 Aa	50.1 Aa

Means with different capital letters show significant differences between treatment (vertically) and lowercase letters show significant difference between sampling site (horizontally) ($P < 0.01$).

Medias con letras mayúsculas diferentes muestran diferencias significativas entre los tratamientos (verticalmente) y letras minúsculas muestran una diferencia significativa entre los sitios de muestreo (horizontalmente) ($P < 0,01$).

The effect of harvester traffic (T2 and T3) on maize yield was found to be important, with yields decreasing with increased axle load and tyre ground pressure.

The minimum of 4.7 Mg ha^{-1} was observed in the 3rd Growing season in the centre line of the tyre track in T3 treatment, but increased with distance from the centre, reaching 5.10 Mg ha^{-1} at 210 cm on either side (table 4, page 98). Also, in the 3rd growing season, a minimum of 6.25 Mg ha^{-1} was found in the centre line of the T2, increasing toward the sides, and reaching 6.70 and 6.71 Mg ha^{-1} at 210 cm on the inside and the outside of the track centre line respectively (table 4, page 98). Treatment 3 resulted in a significantly lower maize yield than from T2 and the control (T1).

Percentage decreases ranged from 42.69% (at the track centre line for T3 in the 3rd Growing season) to 16.82% (at 210 cm from the inside of the track centre line for T2 in the 1rst Growing season).

Maize yields decreased with increasing tyre ground pressure and vehicle weight, with (T3), being the treatment with the lowest yield. It is probable that most of the yield reduction for T3 was caused by damage to the topsoil structure resulting from the higher tyre ground pressure produced by the combine harvester (> 80 kPa) and the high total load of T3 (21.10 Mg). This result is in agreement with those obtained by numerous researchers (2, 6, 14, 30, 31).

Table 4. Maize yields (t ha^{-1}) measured after harvesters traffic in three growing seasons.

Tabla 4. Rendimientos del maíz (t ha^{-1}) medido después del tráfico de las cosechadoras en las tres estaciones de crecimiento.

1 rst Growing season			
Sampling site	**Control plot (T1)**	**Treatment 2**	**Treatment 3**
210 Outside	8.20 Aa	6.81 Ab	5.56 Ac
140 Outside	8.20 Aa	6.73 Ab	5.45 Ac
70 Outside	8.20 Aa	6.59 Ab	5.38 Ab
Center line of tyre track	8.20 Aa	6.50 Ab	5.10 Ac
70 Inside	8.20 Aa	6.63 Ab	5.40 Ab
140 Inside	8.20 Aa	6.74 Ab	5.52 Ac
210 Inside	8.20 Aa	6.82 Ab	5.58 Ac
2 nd Growing season			
Sampling site	**Control plot (T1)**	**Treatment 2**	**Treatment 3**
210 Outside	8.20 Aa	6.73 Ab	5.33 Ac
140 Outside	8.20 Aa	6.40 Ab	5.25 Ac
70 Outside	8.20 Aa	6.32 Ab	5.11 Ab
Center line of tyre track	8.20 Aa	6.35 Ab	5.03 Ac
70 Inside	8.20 Aa	6.42 Ab	5.15 Ab
140 Inside	8.20 Aa	6.51 Ab	5.26 Ac
210 Inside	8.20 Aa	6.75 Ab	5.38 Ac
3rd Growing season			
Sampling site	**Control plot (T1)**	**Treatment 2**	**Treatment 3**
210 Outside	8.20 Aa	6.70 Ab	5.10 Ac
140 Outside	8.20 Aa	6.30 Ab	5.05 Ac
70 Outside	8.20 Aa	6.20 Ab	5.01 Ab
Center line of tyre track	8.20 Aa	6.25 Ab	4.70 Ac
70 Inside	8.20 Aa	6.17 Ab	5.03 Ab
140 Inside	8.20 Aa	6.43 Ab	5.08 Ac
210 Inside	8.20 Aa	6.71 Ab	5.10 Ac

Means with different lowercase letters show significant differences between treatment (horizontally) and capital letters show significant difference between sampling site (vertically) ($P < 0.01$).

Medias con diferentes letras minúsculas muestran diferencias significativas entre tratamientos (horizontalmente) y mayúsculas muestran una diferencia significativa entre los sitios de muestreo (verticalmente) ($P < 0,01$).

Conclusions

In general, the degree of soil compaction is dependent upon the axle load, tyre inflation pressure and the tyre ground pressure.

Combine harvesters weighing 21.10 Mg with high inflation pressure tyres (240 kPa) compact the soil to 60 cm depth both below their track centres and to 210 cm either side. Combine harvesters weighing 16.67 Mg and with low tyre ground pressure (31.23 - 67.61 kPa) have impact on the subsoil and only influence soil under the wheel centre and have limited or no influence on either side of it.

This study also demonstrated that if the wheel load and tyre inflation pressures and ground pressure increases, even in soils with a high bearing capacity (soil in long term direct sowing), maize yields decrease (in the machinery track and 210 cm to either side of it) and subsoil compaction increases.

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