Soil compaction caused by the impact of machinery traffic during corn (*Zea mays*) harvest

Compactación del suelo causado por el tránsito de maquinarias en la cosecha de maíz (*Zea mays*)

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Abstract

The aim of this work was to study soil compaction caused by the traffic of two types of combine harvesters and a tractor plus a grain cart with two loading conditions (fully loaded hoppers-empty hoppers) during corn harvest on vertic argiudoll soil by means of direct seeding system. Soil penetration resistance (PR) and soil bulk density (BD) were measured to a depth of 40 cm in five sampling sites. Response variables determinations were also analyzed. The tractor and the fully loaded grain cart traffic caused greater soil compaction in all the sampling depths, exceeding 60 cm on both sides of the footprint center. What is more, the values obtained from PR and BD measurements were higher than those values considered suitable for normal root growth. This was only evident in the tread width of the tires during the passing of the two fully loaded combine harvesters. The analysis of inflation pressures and tire loads used, indicated in some cases, poor concordance between these variables. The analysis also indicated that the tires were inflated to the limit of resistance.

Keywords

combine harvester • tractor • grain cart • penetration resistance • bulk density

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Resumen

El objetivo del trabajo fue estudiar la compactación causada por el tráfico de dos tipos de cosechadoras y equipo tractor más carro granelero con dos condiciones de carga (tolvas vacías-tolvas llenas) en la cosecha de maíz sobre un suelo argiudol vértico en sistema de siembra directa. Las determinaciones de las variables respuestas, resistencia a la penetración (RP) y densidad aparente (Da), se hicieron hasta los 40 cm de profundidad y en cinco sitios de muestreo. El tránsito del equipo tractor más carro granelero lleno fue el que mayor compactación causó en todas las profundidades de muestreo superando los 60 cm a ambos lados del centro de huella con datos de RP y Da superiores a los considerados crítico para el normal desarrollo radicular. Esta situación, en el pasaje de las dos cosechadoras en condiciones llenas, solamente se dio en el ancho de pisada de los neumáticos. El análisis de las presiones de inflado y cargas de los neumáticos usados indicaron, en algunos casos, una escasa concordancia entre estas variables y que las ruedas se encontraban en el límite de resistencia a las presiones utilizadas.

Palabras claves

cosechadora • tractor • carro granelero • resistencia a la penetración • densidad aparente

Introduction and background

Machinery traffic has a detrimental effect on soil. One of the major problems is soil compaction which leads to a variation in soil pore size and distribution since soil particles are tightly packed due to a reduction in the air volume with a consequent reduced rate of water infiltration and drainage. Consequently, there is a density and penetration resistance increase (3, 16)

Several factors are involved in soil compaction caused by tires: type, size, tire carcass type (conventional or radial) and its flexibility, load applied, contact pressure, soil moisture and number of passes (13).

Agricultural tires cause soil deformation at the soil-tire interface (19). This leads to a certain degree of compaction where the highest values are generally found at the tire footprint surface and below the tire footprint surface at its center (9). However, a single determination of bulk density at the footprint center at a single depth is probably not representative of the maximum value at each site located horizontally or vertically, in terms of conditions of low bearing capacity soils and the usage of R2 tires with deep tread (8).

Another important factor influencing soil compaction is tire inflation pressure since bulk density increases with high levels of inflation pressure (10). Studies carried out by Schjønning *et al.* (2008) examined two radial tires with a constant load on the tire but with inflation pressures that were below, equal to and higher than the pressure, recommended by tire manufacturers. These studies found that over inflated tires caused greater surface compaction.

Studies indicate that the specific pressure in the tire-soil contact area, closely linked to inflation pressure, causes ground strata compaction (17). Apart from that, loading accumulation causes compaction of the deepest soil layers at a depth of more than 30-50 cm regardless of the extent of the surface on which it is distributed (22).

Two methods can be used to determine compaction caused by farm equipment traffic considering bulk density (BD) and penetration resistance (PR). There are studies that determine certain critical BD values suitable for normal root growth: 1.45 Mg m^{-3} for clayey-textured soil horizons; 1.55 Mg m^{-3} for medium-textured soil horizons; and 1.65 Mg m^{-3} for sandy-textured soils (18). Corn is one of the major field crops prone to suffer root damage and suffer yield decreases, owed to compaction. This occurs since corn is sensitive to water stress, rising temperatures and factors resulting from compaction, that have a profound impact on crop yield and quality (20).

Studies carried out by Botta *et al.* (2018), regarding PR, analyzed the effect of compaction on crop yields. Those studies determined that soil-surface compaction and increasing penetration resistance, play a major role in crop yield decline. Penetration resistances exceeding values of 1.5 MPa in the first 20 cm depth inhibits normal root development. Besides, if the value is above 2.5 MPa, roots may stop growing.

To date, there is little information on the effect of combine harvesters, tractors and grain carts tires on compaction during corn harvest, mainly on vertic argiudoll soils. Hence, research on this problem would considerably benefit from rigorous studies.

Objective

To analyze the compaction effect caused by the passage of two types of combine harvesters and a tractor plus a grain cart with two loading conditions (fully loaded hoppers-empty hoppers) during corn harvest.

Hypothesis

The greater size and load capacity of machines and equipment used in harvesting increase the mass per axle, influencing the surface and subsurface compaction of the soil, even when using more buoyant radial tires.

Materials and methods

The study was carried out near the town of Sauce in the province of Corrientes, Argentina. The soil type is vertic argiudoll belonging to the series Paraje Francisco Gómez (11).

Morphological description: The soil horizons sequence is: Ap - A - Btss - BCss - Ck. It presents a 40 cm arable horizon which is thick, loam-textured, black, and porous. This horizon has strong biological activity but it is weakly structured owing to the action of tillage implements (discs) in the first 18 cm. The argillic horizon is visible at a depth of 40 cm to 68 cm. It is clayey, dark grey/black, strongly structured, plastic and sticky. From 68 cm, the clayey matrix (BCss) turns greyish-brown. The presence of calcium carbonate concretions is visible from 88 cm. This series presents high levels of organic matter and calcium, wich forms different salts.

Studies were carried out to evaluate the compaction effect caused by the combine harvesters and the tractor plus the grain cart traffic during the corn harvesting stage.

The experimental design was randomized complete block design with three repetitions where the blocks were constituted by the passes of the three machines under study. An analysis of variance was conducted and differences between means were determined by means of a Duncan test with a significance level of p<0.05.

The treatments were: Control treatment (T1); Combine harvester 1, John Deere 1450, empty (T2); Combine harvester 1, fully loaded (T3); Combine harvester 2, Claas Lexion 660, empty; Combine harvester 2, fully loaded (T5); Tractor Agco Allis 6.220A plus grain cart Cestari 20550 4R, empty (T6); Tractor Agco Allis 6.220A plus fully loaded grain cart (T7). Dry bulk density (BD) and penetration resistance (PR) were determined. Bulk density (BD) was measured directly after Hidalgo (2003) through the weighing of a known volume of soil taken with cylinders specially adapted to obtain the samples.

Penetration resistance determinations (PR) were made by using the ASAE standard penetrometer with the denominations S3133.2 (1). Samples for the two variables were taken at four depth ranges: 0-10; 10-20; 20-30; 30-40 cm, and at five sites: footprint center; 30-40 cm left and right of the footprint center coinciding with the tread edge; 60-80 cm to the left and to the right of the footprint center (figure 1). The first distance for tires with narrow tread width combined 1 front tires, tractor rear tires and grain cart tires. The second distance for the tire with the widest tread width combine harvester 2 front tires.

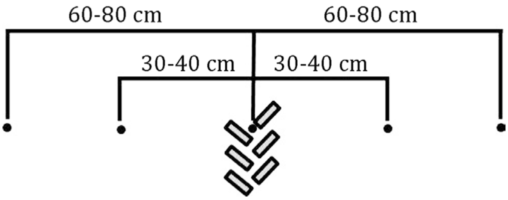

Figure 1. Sampling site for penetration resistance and bulk density.

Figura 1. Lugar de toma de muestra de resistencia a la penetración y densidad aparente.

Three trenches were dug by means of treatment and repetition for the collection of bulk density samples. This was done transversely to each pass. The trenches were 1.30 m and 1.70 m long for tires with a tread width of 60 and 80 cm respectively. The trenches had a width of 50 cm and a depth of approximately 50 cm.

Soil moisture was close to field capacity under test conditions. An additional study of this variable was carried out since it influences PR and BD values. Moisture data were also evaluated at all sampling sites when developing the method for determining the latter variable. An average was determined for each machine and loading condition as no clear differences were recorded in the values obtained.

The characteristics of the machines used are described in table 1 (page 165).

Table 1. Characteristics of the machinery used in the trial.
Tabla 1. Características de la maquinaria usada en el ensayo.

Machinery	Empty weight (kN)	Gross weight/ with ballast (kN)	Tire	Inflation pressure (kPa)	Recommended inflation pressure (kPa)	Difference of pressure (%)
Combine harvester 1 ED	91.2	132	24.5-32	206.8	200	+3
Combine harvester 1 ET	23	35	16.9-24	165.5	170	-3
Combine harvester 2 ED	116	184	800/70R32	220.6	240	-8
Combine harvester 2 ET	29	46	18.4-26	137.9	110	+20
Tractor ED	---	30.45	16.9-28	193.1	110	+43
Tractor ET	---	37.22	24.5-32	165.5	110	+33
Grain cart	44.13	189.76	23.1-30 R3	241.3	210*	+13

* Maximum pressure recommended by manufacturer. / * Presión máxima recomendada por fabricante.
ED front axle. ET rear axle. / ED eje delantero. ET eje trasero.

The method proposed by McKyes, 1985 cited by O' Sullivan *et al.* (1998), was used to determine tire-soil contact area and to estimate the contact pressure from the weight of the machine. This method has the advantage of its simplicity for data collection since it uses the measurements provided by the manufacturer, following this equation:

$$A = b * d / X$$

where:
A = contact area
X = constant whose value varies between 4 for rigid soils and 2 for loose soils. Coefficient 3 was used in this case
b = tire width;
d = tire diameter.

However, it is important to consider that this method underestimates the actual contact area as determined by Palancar *et al.* (2009). This may lead to an overestimation of the pressures exerted by the tires. The recommended pressures were obtained using the Tire-pressure-inflation-calculator (6).

Results and discussion

Contact areas: The exerted pressures exerted were estimated as shown in table 2 (page 166) by using this model the measurements provided by the manufacturers (4, 7).

Table 2. Tire dimensions and ground pressures.

Tabla 2. Medidas de los neumáticos y presiones ejercidas sobre el suelo.

Machines/ tires	Tire model	Tire width (mm)	Tire diameter (mm)	Contact surface (m^2)	Contact pressure (kPa)
C1 F	24.5-32	620	1826	0.3773	174.93
C1 R	16.9-34	429	1318	0.1885	92.84
C2 F	800/70R32	793	1936	0.5117	179.79
C2 R	18.4-26	467	1450	0.2257	101.90
Tractor F	16.9-28	429	1367	0.1955	155.75
Tractor R	24.5-32	620	1826	0.3773	97.94
Grain Cart	23.1-30	587	1707	0.3340	142.03

C1 F, combine harvester 1 front tire. C1 R, combine harvester 1 rear tire. C2 F, combine harvester 2 front tire. C2 R, combine harvester 2 rear tire. Tractor F, Tractor front tire. Tractor R, tractor rear tire.

C1 F, cosechadora 1 neumático delantero. C1 R, cosechadora 1 neumático trasero. C2 F, cosechadora 2 neumático delantero. C2 R, cosechadora 2 neumático trasero. Tractor F, Tractor neumático delantero. Tractor R, tractor neumático trasero.

It is important to note that both the combine harvester and the tractor had a high contact pressure at full load. These results are likely to provide an overestimation error derived from the use of the method proposed by McKyes 1985, as already mentioned.

Regardless, it is important to point out that the size of the tire used was close to the permitted load limits in the case of the C1 harvester. There is only one tire type, a 16 ply tire, capable of bearing the weight exerted on the front axle, at speeds of less than 10 $km.h^{-1}$. This tire is not nationally manufactured.

A similar situation occurred with the fully loaded grain cart and the use of tires that exceeded, by approximately 25%, the maximum load limit, recommended by the manufacturer. This situation was evidenced after finding that the used pressures, were 13% higher than the recommended maximum pressures.

The pressures used did not coincide with those recommended by the manufacturer, obtained through the calculation program (5).

The combine harvester 1 is the only machine whose values were close to optimum values. The other machines used pressures that differ from the pressures they should have been using by approximately 18%.

Penetration resistance

Significant differences were observed between machines and loading conditions as well as between sampling sites when analyzing the effect caused by the passage of the combine harvesters and the tractor plus the grain cart. The passing of the combine harvesters and the tractor plus the grain cart with both loading conditions (empty and fully loaded) caused greater penetration resistance in the center of the footprint. This contradicts other authors who point out that the greatest compaction using conventional tires occurs in the center of the footprint (9).

Machinery traffic caused greater compaction effect of 60-80 cm on both sides of the center of the footprint with values greater than the control treatment in the heaviest load condition. The increase in mass per axle in addition to pressures different from those recommended by the manufacturer may have been the cause of this effect. This coincides with studies carried out by Schjønning *et al.* (2008), who described that surface compaction was recorded only with pressures higher than those recommended by the manufacturers.

On the contrary, the passage of empty machinery did not generate compaction effects on the soil at the greatest distance (60-80 cm) on neither side of the center of the footprint, at depths of 0 to 10 cm (table 3). It is important to point out that, in the surface (0 to 10 cm), the values determined through penetrometer could be affected towards both sides of the center of the footprint by a lateral soil displacement effect. These values may be even lower values than the control treatment (15, 17).

At greater depths, the values were more consistent and always superior to the control treatment, even at 30-40 cm of depth (table 3; table 4, page 168; tables 5 and 6, page 169). These results would explain the increase in PR values even at the most distant sampling sites from the center of the footprint. This is directly related to the increase in machine masses by storing harvested grain in their hoppers.

Table 3. Depth 0-10 cm. Statistical analysis of penetration resistance. PR values expressed in MPa. Moisture values expressed as a percentage.

Tabla 3. Profundidad 0-10 cm. Análisis estadístico de resistencia a la penetración. Valores de RP expresados en MPa. Valores de humedad expresados en porcentaje.

Machines	Moisture (%)	C1 60 cm L	C1 30 cm L	Center	C1 30cm R	C1 60 cm R
		C2 80 cm L	C2 40 cm L		C2 40cm R	C2 80 cm R
		T+GC 60 cm L	T+GC 30cm L		T+GC 30cm R	T+GC 60 cm R
CH 1 E	19.7	0.840 p	1.130 jkl	1.270 g	1.150 hijk	0.880 o
CH 1 F	20.0	1.120 kl	1.380 e	1.470 d	1.380 e	1.190 h
CH 2 E	20.2	0.930 n	1.160 hij	1.390 e	1.170 hi	0.980 m
CH 2 F	19.6	1.090 l	1.540 c	1.610 b	1.540 c	1.140 ijk
T + GC E	20.4	0.980 m	1.310 f	1.48 0 d	1.300 fg	0.980 m
T + GC F	20.0	1.180 h	1.630 b	1.750 a	1.620 b	1.176 hi
Control Treatment	20.3	1.000 m	1.000 m	1.000 m	1.000 m	1.000 m

+Different letters present statistical differences. Duncan test p < 0.05.

+ Diferentes letras presentan diferencias estadísticas. Test de Duncan p < 0,05.

The highest values determined through the use of the penetrometer were observed in the passage of the tractor plus the grain cart, and in the harvester 2 in fully loaded hopper conditions (table 3, page 167; table 4, page 168; tables 5 and 6, page 169), coinciding with the highest contact pressures calculated for each machine.

Even with these increases, the data were inferior to the 2 MPa considered critical for root development in the first 20 cm of depth according to (2) (table 3, page 167 and table 4). It is noticeable how the effect of the successive passes, even using machines with low mass, turns important. This resulted in the highest compaction values evaluated with the penetrometer.

Bulk density

BD results, after the passes of the combine harvesters and the tractor plus the grain cart, resembled PR results. Statistical differences were observed between machines, loading conditions and sampling sites.

The passage of the combine harvesters and the tractor plus the fully loaded grain cart caused greater densification in the center of the footprint with a negative trend towards the sides. Nonetheless, it was higher than the control treatment value even at a distance of 60-80 cm on both sides of this sampling site. The maximum values were recorded with the tractor plus the grain cart (center of footprint, 30 cm on both sides), throwing data similar or superior to 1.45 - 1.46 Mg m^3.

These data were considered critical for root development of gramineae in clayey soils according to studies of Reinert *et al.* (2008) and Sadras and Calviño (2001) despite the fact that this equipment has the smallest mass.

Table 4. Depth 10-20 cm. Statistical analysis of penetration resistance. PR values expressed in MPa. Moisture values expressed as a percentage.

Tabla 4. Profundidad 10-20 cm. Análisis estadístico de resistencia a la penetración. Valores de RP expresados en MPa. Valores de humedad expresados en porcentaje.

Machines	Moisture (%)	C1 60 cm L	C1 30 cm L	Center	C1 30cm R	C1 60 cm R
		C2 80 cm L	C2 40 cm L		C2 40cm R	C2 80 cm R
		T+GC 60 cm L	T+GC 30cm L		T+GC 30cm R	T+GC 60 cm R
CH 1 E	20.8	1.268 qr	1.471 no	1.572 l	1.461 o	1.254 rs
CH 1 F	20.6	1.483 mn	1.737 fg	1.777 e	1.734 g	1.489 m
CH 2 E	20.3	1.241 s	1.491 m	1.669 h	1.493 m	1.241 s
CH 2 F	20.8	1.600 k	1.839 d	1.936 b	1.832 d	1.600 k
T + GC E	20.5	1.283 pq	1.610 k	1.753 f	1.628 j	1.279 pq
T + GC F	20.3	1.654 hi	1.878 c	1.974 a	1.874 c	1.635 ij
Control Treatment	20.4	1.291 p	1.291 p	1.291 p	1.291 p	1.291 p

Different letters present statistical differences. Duncan test $p < 0.05$.

Diferentes letras presentan diferencias estadísticas. Test de Duncan $p < 0,05$.

Table 5. Depth 20-30 cm. Statistical analysis of penetration resistance. PR values expressed in MPa. Moisture values expressed as a percentage.

Tabla 5. Profundidad 20-30 cm. Análisis estadístico de resistencia a la penetración. Valores de RP expresados en MPa. Valores de humedad expresados en porcentaje.

Machines	Moisture (%)	C1 60 cm L	C1 30 cm L	Center	C1 30cm R	C1 60 cm R
		C2 80 cm L	**C2 40 cm L**		**C2 40cm R**	**C2 80 cm R**
		T+GC 60cm L	**T+GC 30cm L**		**T+GC 30cm R**	**T+GC 60 cm R**
CH 1 E	20.6	1.502 q	1.587 no	1.699 l	1.594 n	1.508 q
CH 1 F	20.8	1.704 l	1.814 gh	1.870 e	1.834 fj	1.664 m
CH 2 E	21.0	1.533 p	1.732 k	1.856 ef	1.757 ij	1.507 q
CH 2 F	21.2	1.745 jk	1.846 f	2.000 b	1.852 ef	1.752 ijk
T + GC E	20.7	1.774 i	1.798 h	1.900 d	1.812 gh	1.751 ijk
T + GC F	21.3	1.853 ef	1.967 c	2.080 a	1.962 c	1.857 ef
Control Treatment	20.8	1.363 r	1.363 r	1.363 r	1.363 r	1.363 r

Different letters present statistical differences. Duncan test p < 0.05.

Diferentes letras presentan diferencias estadísticas. Test de Duncan p < 0,05.

Table 6. Depth 30-40 cm. Statistical analysis of penetration resistance. PR values expressed in MPa, moisture values expressed as a percentage.

Tabla 6. Profundidad 30-40 cm. Análisis estadístico de resistencia a la penetración. Valores de RP expresados en MPa. Valores de humedad expresados en porcentaje.

Machines	Moisture (%)	C1 60 cm L	C1 30 cm L	Center	C1 30cm R	C1 60 cm R
		C2 80 cm L	**C2 40 cm L**		**C2 40cm R**	**C2 80 cm R**
		T+GC 60 cm L	**T+GC 30cm L**		**T+GC 30cm R**	**T+GC 60 cm R**
CH 1 E	21.5	1.396 p	1.470 n	1.572 jk	1.507 m	1.357 q
CH 1 F	20.8	1.507 m	1.630 hi	1.727 g	1.612 i	1.532 l
CH 2 E	21.3	1.403 p	1.564 k	1.624 hi	1.567 k	1.400 p
CH 2 F	21.4	1.610 i	1.820 e	1.943 a	1.813 e	1.613 i
T + GC E	21.5	1.424 o	1.630 hi	1.774 f	1.638 h	1.421 o
T + GC F	21.0	1.850 cd	1.874 b	1.953 a	1.858 bc	1.830 de
Control Treatment	21.6	1.429 o	1.429 o	1.429 o	1.429 o	1.429 o

Different letters present statistical differences. Duncan test p < 0.05.

Diferentes letras presentan diferencias estadísticas. Test de Duncan p < 0,05.

This situation indicates that the double-passage effect on the same footprint, *i.e.* the 4-axis passage, was more important than the mass involved, in a similar way to that observed with a penetrometer. These effects were evident for all evaluated depths (table 7, tables 8 and 9, page 171 and table 10, page 172).

Combines 1 and 2 affected the soil bulk density differently in both full and empty conditions at all depths measured at the sides of the center of the footprint, even though estimated contact pressure values were not very different (table 2, page 166). This indicates that contact pressure value alone, cannot predict compaction risks due to traffic.

The greatest effects of densification caused by traffic were at 20-30 cm depth and on both sides of the center of the footprint (table 9, page 171). A negative trend towards the sides was observed for all cases following the same trends evaluated with the penetrometer.

Table 7. Depth 0-10 cm. Statistical analysis of bulk density. BD values expressed in Mg m^{-3}. Moisture values expressed as a percentage.

Tabla 7. Profundidad 0-10 cm. Análisis estadístico de densidad aparente. Valores de Da expresados en Mg m^{-3}. Valores de humedad expresados en porcentaje.

Machines	Moisture (%)	C1 60 cm L	C1 30 cm L	Center	C1 30cm R	C1 60 cm R
		C2 80 cm L	C2 40 cm L		C2 40cm R	C2 80 cm R
		T+GC 60 cm L	T+GC 30cm L		T+GC 30cm R	T+GC 60 cm R
CH 1 E	19.7	0.977 m	1.231 i	1.272 h	1.192 j	1.056 l
CH 1 F	20.0	1.178 j	1.328 f	1.380 de	1.329 f	1.173 j
CH 2 E	20.2	1.131 k	1.270 h	1.420 c	1.270 h	1.120 k
CH 2 F	19.6	1.316 fg	1.382 de	1.472 b	1.387 de	1.314 fg
T + GC E	20.4	1.050 l	1.280 h	1.367 e	1.290 gh	1.070 l
T + GC F	20.0	1.383 de	1.464 b	1.531 a	1.454 b	1.409 cd
Control Treatment	20.3	1.124 k	1.124 k	1.124 k	1.124 k	1.124 k

Different letters present statistical differences. Duncan test $p < 0.05$.

Diferentes letras presentan diferencias estadísticas. Test de Duncan p < 0,05.

Table 8. Depth 10-20 cm. Statistical analysis of bulk density. BD values expressed in Mg m^{-3}. Moisture values expressed as a percentage.

Tabla 8. Profundidad 10-20 cm. Análisis estadístico de densidad aparente. Valores de Da expresados en Mg m^{-3}. Valores de humedad expresados en porcentaje.

Machines	Moisture (%)	C1 60 cm L	C1 30 cm L	Center	C1 30cm R	C1 60 cm R
		C2 80 cm L	C2 40 cm L		C2 40cm R	C2 80 cm R
		T+GC 60 cm L	T+GC 30 cm L		T+GC 30cm R	T+GC 60 cm R
CH 1 E	20.8	1.170 q	1.267 p	1.331 m	1.282 o	1.171 q
CH 1 F	20.6	1.302 n	1.457 g	1.506 f	1.440 h	1.279 o
CH 2 E	20.3	1.167 q	1.360 l	1.441 h	1.379 k	1.164 q
CH 2 F	20.8	1.400 j	1.553 d	1.582 c	1.538 e	1.418 i
T + GC E	20.5	1.143 r	1.378 k	1.466 g	1.393 j	1.151 r
T + GC F	20.3	1.461 g	1.578 c	1.694 a	1.603 b	1.460 g
Control Treatment	20.4	1.170 q	1.170 q	1.170 q	1.170 q	1.170 q

Different letters present statistical differences. Duncan test $p < 0.05$.

Diferentes letras presentan diferencias estadísticas. Test de Duncan $p < 0,05$.

Table 9. Depth 20-30 cm. Statistical analysis of bulk density. BD values expressed in Mg m^{-3}. Moisture values expressed as a percentage.

Tabla 9. Profundidad 20-30 cm. Análisis estadístico de densidad aparente. Valores de Da expresados en Mg m^{-3}. Valores de humedad expresados en porcentaje.

Machines	Moisture (%)	C1 60 cm L	C1 30 cm L	Center	C1 30cm R	C1 60 cm R
		C2 80 cm L	C2 40 cm L		C2 40cm R	C2 80 cm R
		T+GC 60 cm L	T+GC 30 cm L		T+GC 30cm R	T+GC 60 cm R
CH 1 E	20.6	1.342 q	1.404 n	1.500 i	1.398 n	1.358 p
CH 1 F	20.8	1.384 o	1.550 h	1.61 f	1.549 h	1.399 n
CH 2 E	21.0	1.354 p	1.469 l	1.562 g	1.483 jk	1.336 q
CH 2 F	21.2	1.426 m	1.627 e	1.691 c	1.647 d	1.407 n
T + GC E	20.7	1.406 n	1.570 g	1.631 e	1.568 g	1.384 o
T + GC F	21.3	1.479 k	1.702 b	1.768 a	1.711 b	1.492 ij
Control Treatment	20.8	1.262 r	1.262 r	1.262 r	1.262 r	1.262 r

Different letters present statistical differences. Duncan test $p < 0.05$.

Diferentes letras presentan diferencias estadísticas. Test de Duncan $p < 0,05$.

Table 10. Depth 30-40 cm. Statistical analysis of bulk density. BD values expressed in Mg m^{-3}. Moisture values expressed as a percentage.

Tabla 10. Profundidad 30-40 cm. Análisis estadístico de densidad aparente. Valores de Da expresados en Mg $^{m-3}$. Valores de humedad expresados en porcentaje.

Machines	Moisture (%)	C1 60 cm L	C1 30 cm L	Center	C1 30cm R	C1 60 cm R
		C2 80 cm L	C2 40 cm L		C2 40cm R	C2 80 cm R
		T+GC 60 cm L	T+GC 30cm L		T+GC 30cm R	T+GC 60 cm R
CH 1 E	21.5	1.287 r	1.357 o	1.399 m	1.354 o	1.300 pq
CH 1 F	20.8	1.369 n	1.510 i	1.581 e	1.514 i	1.362 no
CH 2 E	21.3	1.309 p	1.438 k	1.464 j	1.437 k	1.301 pq
CH 2 F	21.4	1.421 l	1.583 e	1.672 b	1.602 d	1.430 kl
T + GC E	21.5	1.293 qr	1.548 g	1.644 c	1.537 h	1.290 qr
T + GC F	21.0	1.554 fg	1.674 b	1.734 a	1.670 b	1.564 r
Control Treatment	21.6	1.298 pqr	1.298 pqr	1.298 pqr	1.298 pqr	1.298 pq

Different letters present statistical differences. Duncan test $p < 0.05$.

Diferentes letras presentan diferencias estadísticas. Test de Duncan $p < 0,05$.

References to tables 3 to 10

Center (Center of the footprint); C1 30 cm L (Combine harvester 1 30 cm to the left of the center of the footprint); 30 cm R C1 (Combine harvester 1.30 cm to the right of the center of the footprint); C1 60 cm L (Combine harvester 1.60 cm to the left of the center of the footprint); 60 cm R C1 (Combine harvester 1.60 cm to the right of the center of the footprint); C2 40 cm L (Combine harvester 2.40 cm to the left of the center of the footprint); C2 40 cm R (Combine harvester 2.40 cm to the right of the center of the footprint); C2 80 cm L (Combine harvester 2.80 cm to the left of the center of the footprint); C2 80 cm R (Combine harvester 2.80 cm to the right of the center of the footprint); T plus GC 30 cm L (Tractor plus grain cart 30 cm to the left of the center of the footprint); T plus GC 30 cm R (Tractor plus grain cart 30 cm to the right of the center of the footprint); T plus GC 60 cm L (Tractor plus grain cart 60 cm to the left of the center of the footprint); T plus GC 60 cm R (Tractor plus grain cart 30 cm to the right of the center of the footprint). CH 1 E, combine harvester 1 empty; CH 1 F, combine harvester 1 fully loaded; CH 2 E, combine harvester 2 empty; CH 2 F, combine harvester 2 fully loaded; T plus GC E, Tractor plus grain cart; T plus GC F, Tractor plus fully loaded grain cart.

Referencias para tablas 3 a 10

Centro (centro de huella); C1 30 cm L (Cosechadora 1 30 cm a la izquierda del centro de huella); C1 30 cm R (Cosechadora 1 30 cm a la derecha del centro de huella); C1 60 cm L (Cosechadora 1 60 cm a la izquierda del centro de huella); C1 60 cm R (Cosechadora 1 60 cm a la derecha del centro de huella); C2 40 cm L (Cosechadora 2 40 cm a la izquierda del centro de huella); C2 40 cm R (Cosechadora 2 40 cm a la derecha del centro de huella); C2 80 cm L (Cosechadora 2 80 cm a la izquierda del centro de huella); C2 80 cm R (Cosechadora 2 80 cm a la derecha del centro de huella); T más BC 30 cm L (Tractor más carro granelero 30 cm a la izquierda del centro de huella); T más BC 30 cm R (Tractor más carro granelero 30 cm a la derecha del centro de huella); T más BC 60 cm L (Tractor más carro granelero 60 cm a la izquierda del centro de huella); T más BC 60 cm R (Tractor más carro granelero 30 cm a la derecha del centro de huella). CH 1 E, cosechadora 1 vacía; CH 1 F, cosechadora 1 llena; CH 2 E, cosechadora 2 vacía; CH 2 F, cosechadora 2 llena; T más BC E, tractor más carro granelero vacío; T más BC F, tractor más carro granelero lleno.

Conclusions

The passage of the tractor plus the fully loaded grain cart caused the greatest compaction at all sampling depths, exceeding 60 cm on both sides of the center of the footprint. The values obtained were close to or higher than the those suitable for crop development.

The compaction effect caused by the passage of the two combined harvesters in fully loaded condition is considered critical for crop development up to 30 cm on both sides of the center of the footprint.

The tractor plus the grain cart traffic within crop lots is neither convenient nor advisable according to the obtained results. To design a strategy for harvesting with controlled traffic becomes necessary. Nevertheless, if the detected levels of compaction remain the same in the next crop cycle should be verified.

To verify that tires used in harvesting equipment can withstand the stresses, turns important. Inflation pressure should also be verified since a tire's load carrying capacity is related to this pressure.

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