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RESEARCH ARTICLE

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Sunflower (*Helianthus annuus* L.) harvest: Tractor and grain chaser traffic effects on soil compaction and crop yields

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Abstract

Previous studies have defined compaction as an important degradation process of agricultural soils. However, there is very little information (under field conditions) on the effects of tractor and grain chaser traffic during harvest operations on soil cropped for 15 years under no-till cultivation methods. The aim of this study was to quantify the effects of two different total loads of tractor and grain chaser traffic on soil physical properties and sunflower (*Helianthus annuus* L.) yields. The treatments included a control plot with no tractor or grain chaser traffic (T1), a plot with tractor and grain chaser traffic with a total load of 275.8 kN (94.35 kN km^{-1} ha^{-1}; T2), and a plot with tractor and grain chaser traffic with a load of 332.2 kN (123 kN km^{-1} ha^{-1}; T3). Soil physical properties and sunflower yields were analysed over three growing seasons in the western part of the Pampa region, Argentina. In the topsoil (0 to 200 mm), the results showed that after one pass of T2 and T3, infiltration decreased significantly compared with that in T1; a similar trend was observed for total topsoil porosity. Cone index values in T3 were >2.5 MPa and between 3.33 and 4.90 MPa in the subsoil (200 to 600 mm). Dry bulk density values in T3 were >1.70 Mg m^{-3} in the topsoil and in the subsoil. This study also demonstrated that as the wheel load and ground contact pressure increase, sunflower yields decrease and subsoil compaction increases, even in soils with a high bearing capacity.

KEYWORDS
axle load, crop yield, soil compaction, sunflower cropping, wheel load

1 | INTRODUCTION

Sunflower (*Helianthus annuus* L.) is South America's fourth most important crop, with 1.56 Mha devoted to it. The main producers are Argentina and Paraguay, which together produced 3.77 million metric tonnes in the 2015/2016 season (United States Department of Agriculture, 2017). Argentina is the second largest exporter of sunflower after Ukraine.

In Argentina, sunflower is produced in the east-central part of the country, mainly in clayey soils (1.27 Mha by no-till cultivation methods) that suffer from very high compaction due to traffic from agricultural machinery.

It is known from numerous scientific contributions that compaction, in addition to water and wind erosion, is one of the main causes of soil degradation, to the extent that it is addressed in the European Soil Framework Directive (European Commission, 2006). As an example of the problem, it can currently be inferred that more than half of the land-surface erosion worldwide is caused by soil degradation from compaction and deformation due to incorrect soil management.

Soil compaction changes the soil's porosity and has harmful effects on an important range of soil functions, thereby reducing the biological quality of the soil (Naderi-Boldaji & Keller, 2016).

The harmful effects of agricultural traffic, high axle load, and high tyre ground contact pressure (GCP) on soil properties and crop production are well understood (Botta et al., 2013; Håkansson & Reeder, 1994).

It is important to note that when soils are compacted with CI values > 2 MPa, the roots of most annual crops practically stop growing (Botta, Jorajuria, Balbuena, & Rosatto, 2004). In addition, the same author supports this assertion, indicating that in clay soils, CI values of 2.2 MPa and dry bulk densities > 1.5 Mg m^{-3} reduce crop yields.

According to Raper (2005), deterioration of the soil produced by agricultural traffic can sometimes be visible above-ground as deformation of the soil or can be hidden below-ground. In any case, agricultural traffic can reduce crop production by causing a compacted soil condition that is not compatible with plant growth.

Additionally, the wheel load is directly correlated with subsoil compaction (Botta et al., 2008; Spoor, Tijink, & Weisskopf, 2003).

In a study by Botta et al. (2006), deep soil densification produced reduced root growth in sunflower, and this reduction did not benefit sunflower yields. Soil compaction by the repeated pass of tractors, grain chasers, combine harvesters, and planter machines is also one of the main causes for the reduction of soil pore distribution and thus affects crop production (Soane & Ouwerkerk, 1994). That is why the soil conditions at sunflower harvest must be taken into account and efforts made to reduce the subsoil compaction produced by the heavy machinery used in harvest operations.

In light of this situation and the sustained worldwide increase in no-till sunflower cultivation, and considering that there is a dearth of information on this particular aspect of machinery (tractors and grain chasers) interactions with soil within no-till cultivation methods during sunflower harvest, we believe that filling these knowledge gaps will be an important contribution.

The objectives of this work were to (a) quantify the changes in the physical properties of soil due to traffic from two different machines (tractor and grain chasers) during harvest operations on a Mollisol worked for 15 years under no-till cultivation methods and (b) ascertain the effects of tractor and grain chaser traffic (with different total loads) on sunflower yields.

The hypotheses were that (a) sunflower yields are negatively affected by one pass of a tractor and grain chaser and that this traffic impacts the subsoil and that (b) higher loads and GCP cause an increase in subsoil compaction compared with similar but lower loads and pressures.

2 | MATERIALS AND METHODS

2.1 | The site and soil characteristics

This work was conducted at an experimental farm, located in western Buenos Aires Province (36°04′33.18″ south and 62°29′14.57″ west) on a soil classified as a Mollisol (Soil Survey Staff, 2014). Table 1 shows the initial soil conditions and soil profile characteristics. Soil at the experimental site has been under no-till cultivation methods for 15 years with a common regional crop rotation: wheat/soya (*Triticum aestivum* L.)/(*Glycine max* L.) in winter followed by sunflower (*H. annuus* L.) in summer.

2.2 | Treatments

The treatments were applied to 50-m-long × 30-m-wide plots laid out in completely randomized blocks, with three replicates for each treatment and 10-m-wide buffer zones between plots to prevent interactions. The treatments consisted of a control with no tractor or grain chaser traffic and two treatments where total loads of 276 and 332 kN were imposed by the tractor and grain chaser, as detailed in Table 2.

The following tracks were exposed to traffic treatments: In Year 1, three separate sets of tracks were created (on March 25, 2013) by the combination of tractor and grain chaser along the 50-m length of the plots. In Year 2, two of these three tracks were run on again (on March 22, 2014), whereas in Year 3, only one of the tracks was used again (on March 24, 2015) during sunflower harvest. The proportion of the plot taken up by tracks including headland was 6% for Treatment 3 (T3), whereas for Treatment 2 (T2), the trampled percentage was 4.9%, totalizing for each plot 18% of its surface (6% × 3) for T3 and 14.7% (4.9% × 3) for T2.

For a correct interpretation of the results, it is important to note that the year in which the traffic treatments started, the contractors or owners of the machinery changed their equipment, choosing them in order to increase their work capacity. This new equipment had greater weight than that used during the years prior to the development of this work.

The timing (dates) of the treatments and soil measurements was adapted from the one proposed by Botta et al. (2007), which took into account that the study area was in the southern hemisphere.

Prior to the application of each treatment, all the equipment was weighed using electronic scales. The mean GCP were measured with a Tekscan device. Tyre inflation pressures were adjusted in accordance with the tyre manufacturers' recommendations for the load being carried and the speed of operation.

2.3 | Soil parameters monitored

Cone index (CI), dry bulk density (DBD), total topsoil porosity (TTP), soil water content (SWC), rut depth (RD), and infiltration (I) were measured on the same day as the traffic treatments were applied. The parameters (CI, DBD, SWC, and I) were measured along the wheel tracks on the bottom of the RD in the trafficked plots (which was taken into account at data analysis) and were taken across the entire plot for the untrafficked control.

The CI was measured with a Rimick CP20 recording penetrometer (American Society of Agricultural and Biological Engineers, 2013). Each datum is the average of 20 samples for each plot at the depth range of 0–600 mm, taken at intervals of 25 cm.

The procedure used to obtain the DBD and SWC values is described in Tolón-Becerra et al. (2010). Total topsoil porosity (0- to 200-mm depth range) was calculated from DBD using soil particle

TABLE 1 Soil conditions and soil profile characteristics

Horizon	Ap	A_{12}	AC	C
Depth range (mm)	0–150	150–300	300–650	650–1,200
Organic carbon (g kg^{-1})	12.30 ± 5.2	6.7 ± 1.2	5.2 ± 1.4	—
Clay (g kg^{-1})	173 ± 3.21	304 ± 2.5	190 ± 2.4	67 ± 2.31
Silt (g kg^{-1})	318 ± 3.02	280 ± 2.31	210 ± 2.33	305 ± 1.61
Sand (g kg^{-1})	509 ± 2.16	416 ± 2.11	600 ± 2.27	637 ± 2.01
pH in H_2O (1:2.5)	6.2 ± 0.04	6.3 ± 0.02	6.4 ± 0.02	6.7 ± 0.01

density. This value was computed only for the topsoil because crop root development and nutrient uptake are concentrated there.

Infiltration (I) was determined using the ring infiltrometer method. Rings were 0.25 m in diameter and 0.4 m height and were inserted 0.20 m deep in the soil to prevent lateral seepage loss. The average infiltration was determined from 20 locations per plot.

Rut depth: A description of the procedure used to determine RD is included in Botta et al. (2008).

2.4 | Crop measurements

Sunflowers were planted on October 14, 2012, in the first study year; on October 15, 2013, in the second year; and on October 14, 2014, in the third year. The plant density was five plants per square metre, and the sowing depth was 30 mm. The planter had a distance between rows of 525 mm, with individual pressure and depth control of each one of the soil opener blades. The average emergence was 90% in all treatments.

TABLE 2 Description of harvesting equipment characteristics

Tractor and grain chaser specifications (T2) Tractor FWA (Two axle and single wheels)		Grain Chaser 196 kN (Two axle and single wheels)	
Engine power (CV kW^{-1})	145/106.7	Front tyres	24.5R32
Front tyres	16.9R26	Front tyres inflation pressure (kPa)	120
Front tyres inflation pressure (kPa)	70	Rear tyres	24.5R32
Rear tyres	24.5R32	Rear tyres inflation pressure (kPa)	120
Rear tyres inflation pressure (kPa)	65	Total weight loaded (kN)	196.00
Total weight (kN)	79.80	Front axle weight (kN)	98.0
Front axle weight (kN)	31.75	Rear axle weight (kN)	98.0
Rear axle weight (kN)	48.05	Static load per front wheel (kN)	49.0
Static load per front wheel (kN)	15.875	Static load per rear wheel (kN)	49.0
Static load per rear wheel (kN)	24.025	Front wheel track width (mm)	2,800
Front wheel track width (mm)	2,800	Rear wheel track width (mm)	2,800
Rear wheel track width (mm)	2,800	Mean ground pressure per front tyre (kPa)	76.5
Mean ground pressure per front tyre (kPa)	38.72	Mean ground pressure per rear tyre (kPa)	76.5
Mean ground pressure per rear tyre (kPa)	39.38		
Distance between the tyres of the tractor and tyres of the grain chaser (mm)	3,380		
Tractor and grain chaser specifications (T3) Tractor FWA (Two axle and single wheels)		**Grain chaser 186 kN (One central axle and single wheels)**	
Engine power (CV kW^{-1})	315/231	Tyres	900/60R32T
Front tyres	600/70R30	Tyres inflation pressure (kPa)	190
Front tyres inflation pressure (kPa)	110	Total weight loaded (kN)	186.2
Rear tyres	710/70R42	Axle weight (one axle; kN)	186.2
Rear tyres inflation pressure (kPa)	100	Static load per wheel (kN)	93.1
Total weight (kN)	147.00	Wheel track width (mm)	2,800
Front weight (kN)	58.80	Mean ground pressure per tyre (kPa)	131.1
Rear weight (kN)	88.20		
Static load per front wheel (kN)	29.40		
Static load per rear wheel (kN)	44.10		
Front wheel track width (mm)	2,750		
Rear wheel track width (mm)	2,750		
Mean ground pressure per front tyre (kPa)	63.91		
Mean ground pressure per rear tyre (kPa)	80.91		
Distance between the tyres of the tractor and tyres of the grain chaser (mm)	4,100		

It is important to note that each row of the planter used to plant the traffic ruts increased the pressure on the soil. For the wider wheels (T3), the pressure on the ground was regulated on four openers, two per wheel, and for the T2, the pressure was regulated on two openers, one for each wheel (as shown in Figure 1). In this way, and together with the presence of stubble from the previous crop and soil moisture at the time of planting, very good soil removal was achieved. Regarding the uniformity in the depth of sowing, it was regulated by the levelling wheels of each body of the planter.

Fertilizer (40-kg ha^{-1} diammonium phosphate) was applied nominally along the seed line, as recommended, during each growing season, and weeds were controlled using postemergence herbicides. The same machinery was used for sowing and spraying the sunflower crop during every growing season of the trial, but the tractors and grain chasers were changed according to treatment.

Sunflower yield (SY) was determined by the method proposed by Tolón-Becerra, Tourn, Botta, and Lastra-Bravo (2011). In this method, the sunflower is harvested mechanically with tested systems and placed at the border of each plot. The whole plot was harvested with the same machine (a combine equipped with a 16-row sunflower header) in each growing season. Before the harvester passed, preharvest losses were determined (seeds in the soil and sunflower heads that could not be harvested by the harvester). After the harvester pass, any additional losses were also quantified. Finally, the total harvest losses were determined (preharvest loss + postharvest loss). To determine harvest losses, a count of 140 seeds on the ground per square metre was extrapolated to a loss of approximately 100 kg of seed per hectare from the harvester combine.

Root dry weight (RDW): A description of the procedure used to determine RDW is included in Botta et al. (2006).

2.5 | Meteorological data

Throughout the entire study period, meteorological data were recorded at an automatic weather station situated 500 m from the experiment site and within the trial premises on the farm.

The total rainfall, maximum air temperatures, average maximum temperatures, and total solar radiation from October 1 to March 31 for each year are shown in Table 3. The average maximum air temperature was within normal ranges for the proper implantation and growth and development of sunflowers. Rainfall during the critical period of sunflower growth (January 1–25) was below average in all three growing seasons. Rainfall was significant before harvest operations (the last 10 days of March) in each growing season, leading to high SWC values. The values of solar radiation were uniform during the study period. Because the seasonal weather conditions were relatively similar for every growing season, the variations in sunflower yield between the study years could be due to soil compaction produced by the traffic treatments.

2.6 | Statistical analyses

The soil parameter data were analysed by repeated-measures analysis of variance. Mean values were separated using Duncan's multiple range tests. For the three treatments, linear regression was used to study the relationship between CI and RD for two different depth ranges in the subsoil (200–400 and 400–600 mm). It is important to note that the study of the relationship between RD and the CI and DBD did not include the topsoil because of the high bearing capacity of soil (15 years under no-till cultivation methods); it was assumed that the increments in CI and DBD values in the topsoil were governed by the deformation of this layer (0 to 200 mm) produced by RD. Additionally, RD influence on topsoil compaction was well defined in a

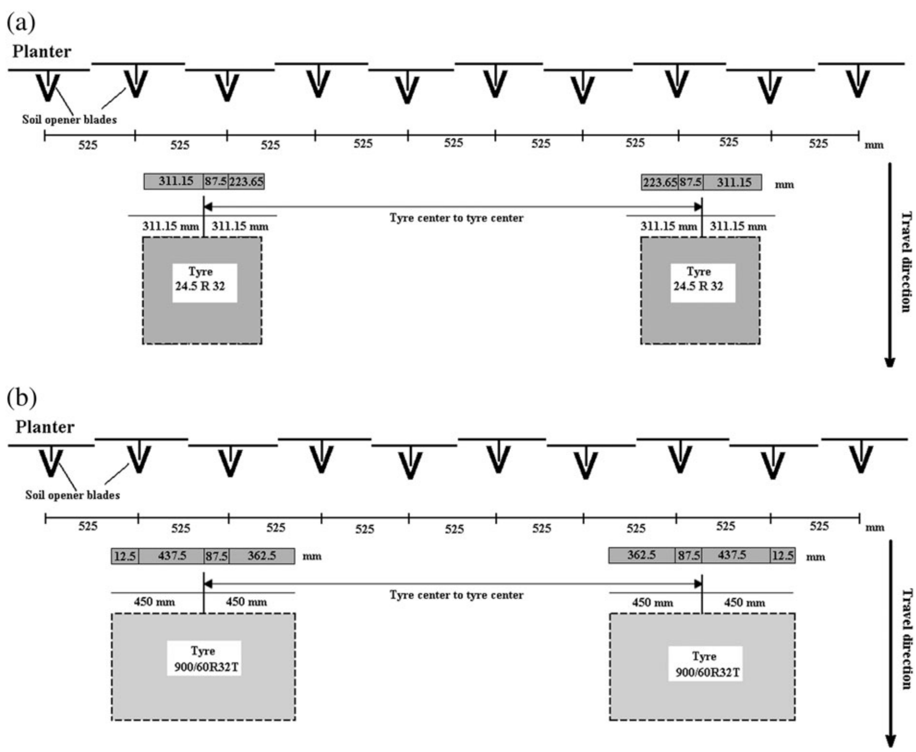

FIGURE 1 Diagram of the number of rows in the wheel tracks for each treatments: (a) Treatment 2 and (b) Treatment 3

TABLE 3 Meteorological data in the three growing seasons (October 1 to March 31) 2012 to 2015

October 1 to March 31	Max. air temp (°C)	Min. air temp (°C)	Average air temp (°C)	Total rainfall (mm)	Total solar radiation (kJ cm^{-2})
2012–2013	34.0	2.7	19.8	679.6	393.2
2013–2014	35.2	2.8	20.1	575.4	402.3
2014–2015	34.2	3.5	19.2	520.2	387.0

great number of previous scientific works (Botta et al., 2004, 2008; Stranks, 2006; Tolón-Becerra et al., 2011).

3 | RESULTS AND DISCUSSION

3.1 | Soil water content

The SWC, measured on traffic treatment days (March 25, 2013; March 22, 2014; and March 24, 2015), was 29% in the topsoil (0–200 mm), 28.5% at 200–400 mm, and 30.1% at 400–600 mm, and there was no significant difference in the SWC between interval depths. This high level of SWC was the result of 79.8-mm rainfall (on average for the three growing seasons) in the last 10 days of March before traffic treatments were applied. This situation is common in the study area at the time of the sunflower harvest and caused the soil to be, at the time of traffic, near but above the field capacity. Thus, it is important to note that soil water content is the most important factor influencing soil compaction processes. In the same sense, Botta et al. (2007) reported that the traffic in harvest operations should be as light as possible to avoid high soil compaction, particularly when working with soil under no-till cultivation methods and in wet conditions using machines with a high wheel load, as was the case in our study. At this point, it should be noted that the SWC did not significantly differ among the three growing seasons; therefore, we believe that the variations in the CI were not due to the SWC. Likewise, and in agreement with the findings of O'Flynn, Finnan, Curley, and McDonnell (2015), high soil water content makes soil susceptible to compaction when trafficking treatments are applied.

3.2 | Cone index and dry bulk density

The traffic treatments (T3 and T2) modified the characteristics of the topsoil and subsoil compared with the control plot with no traffic. Annually, repeated tractor and grain chaser traffic had a detrimental effect on soil CI and DBD; these parameters increased significantly from 2012 to 2015 in both the topsoil and the subsoil. Typical tillage depths in Argentina are approximately 200 mm, so the Ap horizon is considered to be in the 0- to 200-mm range of the topsoil layer; anything deeper is considered subsoil.

After three growing seasons, the CI and DBD values resulting from the T2 (275.8 kN) and T3 (333.2 kN) treatments were significantly different ($P < 0.01$) from the T1 treatment but at different soil depths (400 mm for T2 and 600 mm for T3; Figures 2 and 3). In the T3 treatment, the CI and DBD values were higher than 2.2 MPa and 1.68 Mg m^{-3} (Figures 2 and 3), respectively. Treatment 3 used one axle, which caused higher GCP on the topsoil (131.1 kPa) than the tandem axle. These results agree with those of Håkansson and Reeder (1994) and Botta et al. (2013), who indicated that compaction effects are related to soil bearing capacity, wheel load, GCP, and tyre inflation pressure. These results also agree with Lamandé and Schjønning (2011), who observed that the GCP and the distribution of pressure throughout the topsoil are linked to the tyre's attributes and are key factors to be used to control soil compaction. Thus, it could be said that the higher CI and DBD values observed in T3 were due to the treatment rather than the soil conditions. This agrees with previous studies by Håkansson and Reeder and Botta et al. (2007).

Treatment T2 caused a significant difference ($P < 0.01$) in soil compaction in the depth range from 200 to 400 mm compared with the control but had no significant effect from 400- to 600-mm depth. These CI values are indicative of high densification in the subsoil, exceeding the 2-MPa value indicated by Bengough, McKenzie, Hallett, and Valentine (2011) as responsible for losses in crop yield. The DBD values for T3 were higher than 1.74 and 1.77 Mg m^{-3} at depths of 200 to 400 and 400 to 600 mm, respectively. All values exceeded those quoted as critical for root growth retardation (Botta et al., 2004; Jorajuria, Draghi, & Aragon, 1997; Raghavan & McKyes, 1978).

The subsoil compaction produced by T3 is similar to levels observed by Alakuku et al. (2003), because there was a combination of a high average GCP (131.1 kPa), a high tyre inflation pressure (190 kPa), and a high wheel load (93.1 kN). This is not unusual, but what is striking and new is that the soil under continuous no-till cultivation methods (15 years) seems to behave, in terms of traffic, like tilled soil in that it is unable to bear machinery traffic with high wheel loads.

It can be seen (Figures 2 and 3) that when the soil was trafficked with tyres with high inflation pressure (T3) and a high load, the CI and DBD increased in the topsoil and subsoil, which agrees with Schjønning, Lamandé, Tøgersen, Arvidsson, and Keller (2008), Lamandé and Schjønning (2008), and Schjønning and Lamandé (2010). These authors found that the stresses at the tyre–soil interface—and hence the stresses to be transmitted down through the soil profile—for given soil conditions are directly related to the tyre inflation pressure. However, it is also important to consider that the load differences on the wheels on the same axles (particularly between the grain chasers) and the distance between the two tractor tyres and grain chasers are the underlying causes of the differences in the CI and DBD parameters. In this sense, it must be taken into account that when a tractor pulls a grain chaser (especially with one central axle, T3), the grain chaser transfers through the drawbar of the tractor a high load to the rear axle of the tractor, increasing the load on it. Consequently, the weight transferred by the T3 is greater than that transferred by the T2.

At 400 to 600 mm, the average CI and DBD values for the three seasons were highest in T3, and the peak values of these parameters occurred at progressively greater depths every year (Figures 2 and 3). The peak values of CI and DBD in this treatment (T3) were 4.81 MPa and 1.81 Mg m^{-3}, respectively.

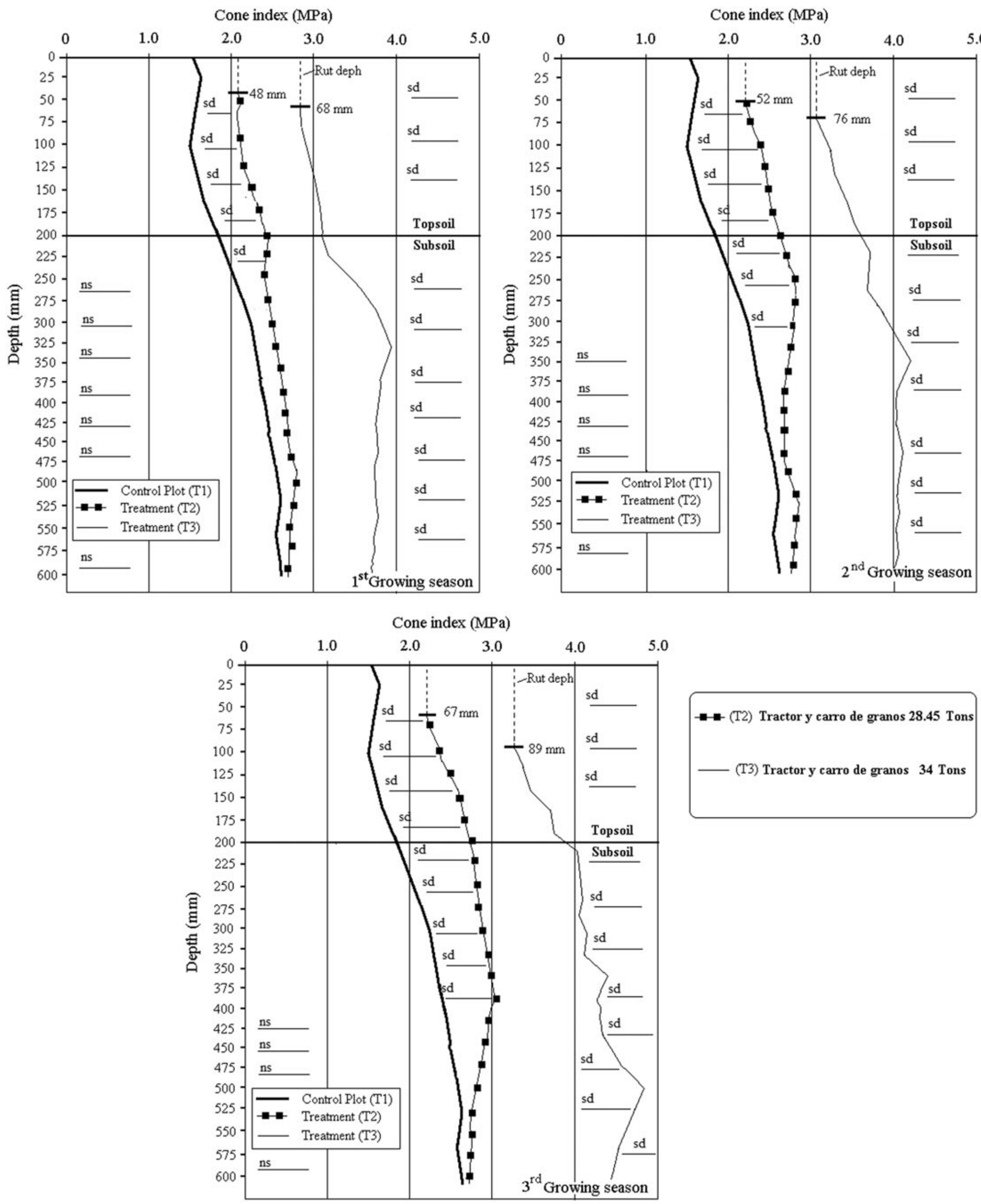

FIGURE 2 Cone index values (MPa) measured in the centrelines of the tyre tracks for treatments T2 and T3. For each traffic treatment, control plot without traffic in black. sd: significant difference; ns: not significant ($P < 0.01$) Duncan's multiple range test

3.2.1 | Total topsoil porosity

Total topsoil porosity (TTP) is considered to be an important indicator of compaction: The average TTP over the three growing seasons was 36.84.1% in T3, 40.94% in T2, and 43.94% in T1 (Table 4). The differences in TTP (0–200 mm) between the two traffic treatments, with respect to the control plot (T1), were statistically significant ($p < 0.01$) throughout the study period. Treatment 3 caused the greatest reduction in TTP; this soil response to traffic was due to high GCP (>130 kPa) and to the high load per wheel (>90 kPa), especially for the grain chaser that was part of this treatment.

It must be noted that this parameter was measured only in the topsoil because it is the sector of the soil where the sunflower roots most often develop and where nutrient uptake is concentrated in the first 60 days after sowing. Only T3 showed TTP values lower than 40%, which is considered to be the limit for affecting crop yields. In addition to the above, we must consider that the SWC was elevated at the time of traffic, which could cause the reduction in macropores and decrease in air-filled porosity that had a negative influence on crop yield. This result corroborates findings that suggest that one pass of machines with different GCPs can result in extensive topsoil compaction (Botta, Jorajuria, & Draghi, 2002) and a severe reduction in TTP.

3.3 | Rut depth

The T2 treatment resulted in a significantly shallower RD than did the T3 treatment (Figure 4). During all three growing seasons, RD for each

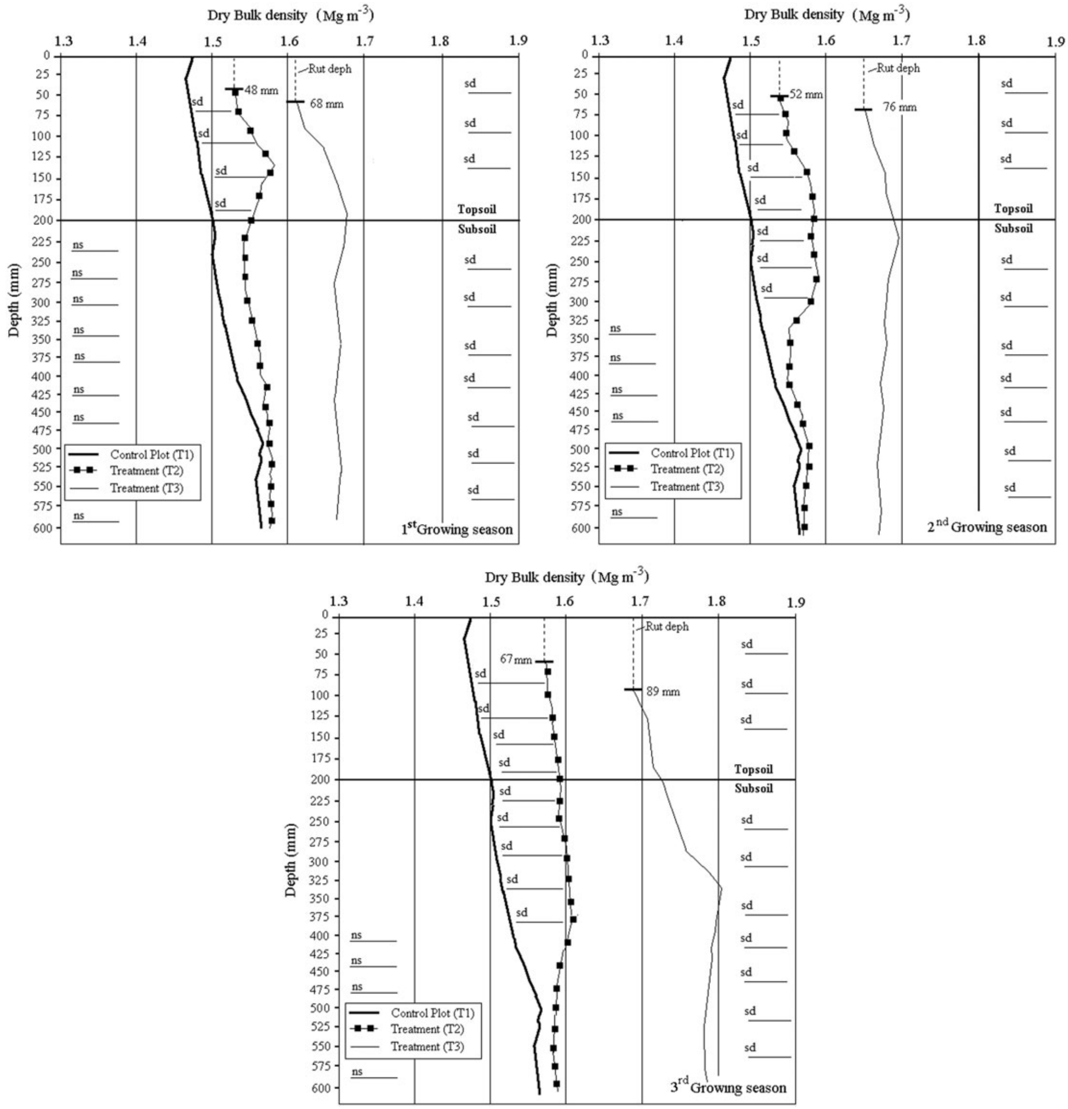

FIGURE 3 Dry bulk density (Mg m^{-3}) measured in the centrelines of the tyre tracks for treatments T2 and T3. For each traffic treatment, control plot without traffic in black. sd: significant difference; ns: not significant (P < 0.01) Duncan's multiple range test

traffic treatment significantly increased the stress on the topsoil (0 to 200 mm), but none of the treatments exceeded an RD of 89 mm. The RD was always greater for T3; this treatment had a higher GCP and wheel load than treatment (T2). In addition, for T3, in the deeper subsoil (200 to 600 mm), there was a clear or significant correlation between RD and soil compaction (R^2 values were between 0.83 and 0.91 for CI and between 0.81 and 0.93 for DBD [$p < 0.01$]). In the case of T2, this correlation was not clear (R^2 values were between 0.002 and 0.03 for CI and between 0.003 and 0.118 for DBD [$P < 0.01$]); in this treatment, the values of mean GCP per tyre and wheel load did not exceed 76.5 kPa and 49 kN, respectively.

3.4 | Infiltration

Both treatments T2 and T3 caused a statistically significant reduction in infiltration over the 0- to 200-mm depth profile compared with the control, whereas T3 resulted in the greatest average reduction over the three growing seasons (Figure 5). This result agrees with those obtained by numerous researchers (e.g., Arvidsson & Håkansson, 2014; Botta et al., 2004; Tolón-Becerra et al., 2011).

3.5 | Crop response

Two months after planting, large differences in sunflower growth rates (between 0- and 200-mm depth range) were observed among the treatments. Root dry weight (RDW) was negatively affected by soil compaction (Figure 6). The highest RDW values were found in the third growing season for T1 (5.1 g per plant), whereas the highest

TABLE 4 Total topsoil porosity values (%) calculated in the three growing seasons, after application of the two traffic treatments (0- to 200-mm depth range)

Treatments compared			
Total porosity (%)	**Control plot (T1)**	**Treatment 2**	**Treatment 3**
First growing season	43.90 a	41.70 b	37.83 c
Second growing season	43.95 a	40.75 b	36.98 c
Third growing season	43.98 a	40.37 b	35.72 c
Average	43.94 a	40.94 b	36.84 c

Note. Different letters within each treatment (horizontally) indicate a significant difference (P < 0.01 Duncan's multiple range test).

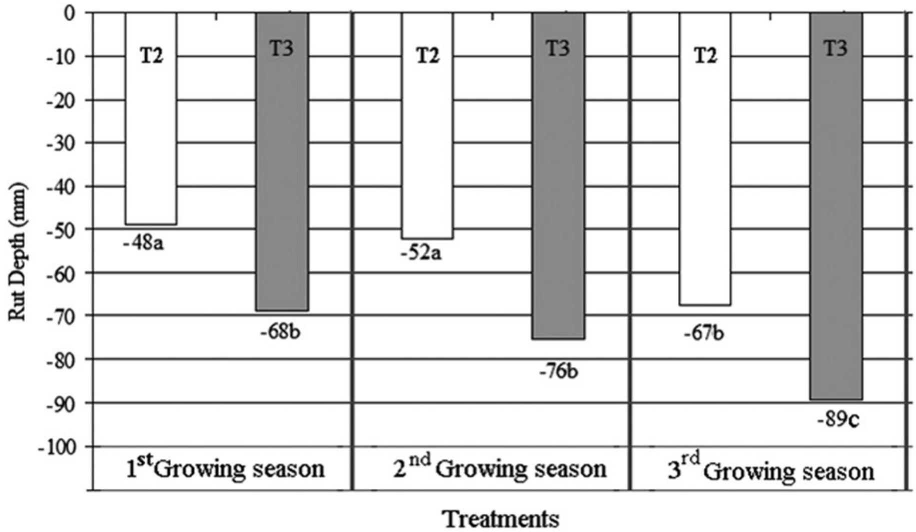

FIGURE 4 Rut depth (mm) measured after traffic of the treatments T2 and T3 during the three growing season. Bars with the same letter are not significantly different ($P < 0.01$) Duncan's multiple range test

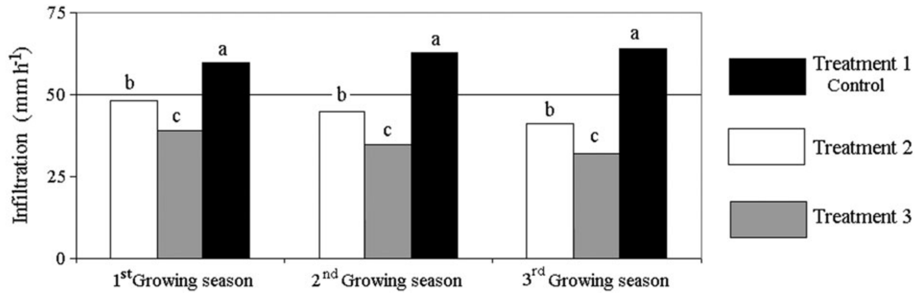

FIGURE 5 Average infiltration values (mm hr^{-1}) in the 0- to 200-mm depth range for the three treatments in the three growing seasons. Bars with the same letter are not significantly different ($P < 0.01$) Duncan's multiple

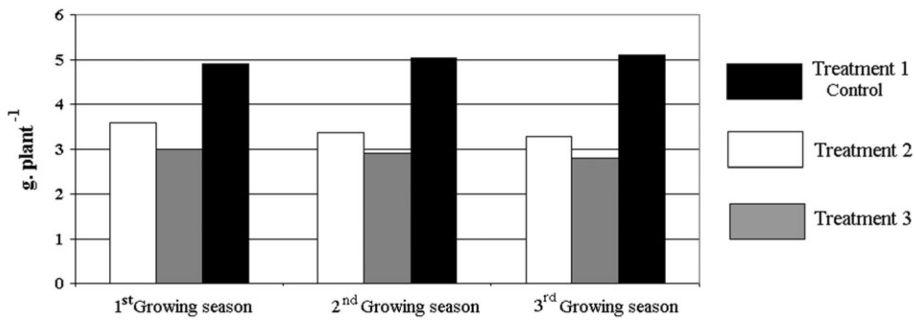

FIGURE 6 Root dry weight values (0- to 200-mm depth range) for three treatments in three growing seasons

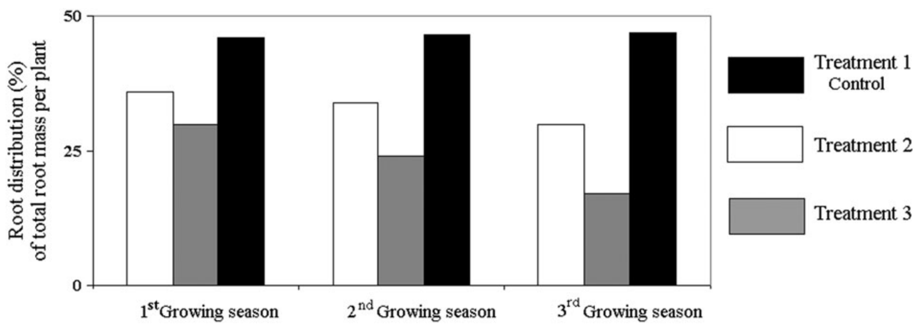

FIGURE 7 Mean of root distributions (0- to 300-mm depth range) for three treatments in three growing seasons

TABLE 5 Sunflower yields for different treatments in three growing seasons

	Treatments compared		
	T1 (control plot)	Treatment 2	Treatment 3
Crop yield (kg ha^{-1}) First growing season (Year 2013)	2,410 a	2,220 b	1,843.6 c
Yield (%)	—	**−7.20**	**−23.5**
Crop yield (kg ha^{-1}) Second growing season (Year 2014)	2,500 a	1,975 b	1,700 c
Yield (%)	—	**−21.00**	**−32.00**
Crop yield (kg ha^{-1}) Third growing season (Year 2015)	2,590 a	1,826.2 b	1,488.5 c
Yield (%)	—	**−29.49**	**−42.53**
Average yield	2,500 a	2,007 b	1,677.1 c

Note. Different letters within each year (horizontally) indicate a significant difference for the different depths of loosening ($P < 0.0$ Duncan's multiple range).

values in T3 and T2 were 3.0 and 3.6 g per plant, respectively, in the first growing season. For all seasons and traffic treatments, the root distribution was between 0 and 300 mm deep, 60 days after sunflower planting, as shown in Figure 7. This depth range zone contained, on average, approximately 47% of the final root biomass in the control plot, 30% in the T2 plot, and 17% in the T3 plot. These results are in accordance with those obtained by Stumpf, Pauletto, and Spinelli Pinto (2016), who observed a low root growth, below 100 mm (for all the species studied); this is the result of a high soil densification by compression below that level.

As shown in Table 5, treatments T3 and T2 caused a reduction in sunflower yield in relation to the control treatment (T1). In the third growing season, the control (T1) had a significantly higher SY than T2 and T3, with T3 being 42.53% and T2 29.49% less than T1, respectively. Therefore, SY decreased incrementally with GCP and equipment weight, resulting in T3 having the lowest SY. Thus, it was demonstrated that there was the greatest reduction in yield when the subsoil was impacted by the loads imposed by T3. Hence, the data support our two hypotheses: (a) Sunflower yields are negatively affected by one pass of a tractor and grain chaser and that this traffic impacts the subsoil, and (b) higher loads and GCP cause an increase in subsoil compaction compared with similar but lower loads and pressures.

We believe that this research could be considered the basis for a controlled traffic study, that is, a yearly reassessment of the same traffic lines with the goal of decreasing the total soil compaction in productive lots and achieving sustainable production that fundamentally avoids soil degradation.

4 | CONCLUSIONS

From our study, which was conducted over three sunflower growing seasons, we concluded the following:

- The soil compaction level is related to the wheel load and GCP. Tractors and grain chasers with a combined weight of 332.2 kN and a GCP between 63.91 and 131.1 kPa can compact soil up to 600 mm in depth. The same vehicles with a combined weight of 275.8 kN and a GCP of up to 60.3 kPa only influence to 300-mm depth.
- In addition, as the axle load and GCP increase, even in soils with no-till cultivation methods, subsoil compaction increases and sunflower yields decrease.
- Additionally, as in this case (soil with a high compaction level), for alleviation, farmers should evaluate deep tillage, work in the same traffic lines each year, and improve cover crops or drainage, especially in low ground within fields that experience high traffic or are worked in wet soil conditions.

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