Soil & Tillage Research 107 (2010) 49–56

Contents lists available at ScienceDirect

Soil & Tillage Research

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

Soil compaction distribution under tractor traffic in almond (*Prunus amigdalus* L.) orchard in Almería España

A. Tolon Becerra [a,*], G.F. Botta [b,c], X. Lastra Bravo [a], M. Tourn [b], F. Bellora Melcon [b], J. Vazquez [c], D. Rivero [d], P. Linares [e], G. Nardon [f]

[a] *University of Almería, Ctra Sacramento s/n, La Cañada de San Urbano, 04120 Almería, Spain*
[b] *University of Buenos Aires, Agronomy Faculty, Av. San Martín 4453, Buenos Aires, Argentina*
[c] *National University of Luján Technology Department, 6700 Luján, Argentina*
[d] *Postgraduate Department, FCAF National University of La Plata, Argentina*
[e] *University Polytechnic of Madrid, E.T.S.I.A., Agrónomos, Spain*
[f] *School of Mechanics Engineering, Rosario University, Santa Fe, Argentina*

ARTICLE INFO

Article history:
Received 7 December 2009
Received in revised form 2 February 2010
Accepted 3 February 2010

Keywords:
Subsoil compaction
Orchard fruit
Axle load
Track

ABSTRACT

Almond orchards in Almería require frequent traffic with farm machinery, about 1–8 times a year. Our main objective was to evaluate the vertical distribution of soil compaction induced by traffic of two tractors with different weights, one light (LT = 15 kN) and one heavy (HT = 50 kN), passing 0, 1, 3, 5 and 8 times over the same track on Aridisol soil. The work was performed in the Vélez Blanco District of Almería in southeast Spain. Outlined hypothesis were: (a) subsoil compaction distribution due to tractor traffic on recently tilled soils in almond orchard depends on total axle load and tractor passes, (b) topsoil compaction produced by tractor traffic depends on tractor passes and ground pressure. Variables measured were (CI) cone index, (BD) bulk density, (TSP) total soil porosity and (RD) rut depth. The relevant results were: in topsoil (0–200 mm), 1, 3, 5 and 8 passes of a LT caused mean values of CI of 1420, 1825, 1950 and 2050 kPa respectively, while for the HT with the same number of passes the values were of 1235, 1520, 1630 and 2510 kPa respectively. BD mean values had a similar behavior: 1.35, 1.38, 1.51 and 1.55 Mg m^{-3} for 1, 3, 5 and 8 passes of a LT and 1.30, 1.32, 1.41 and 1.52 for the HT with the same number of passes. In the subsoil (200–600 mm) the HT caused higher CI and BD values than the LT. CI mean values of the LT were between 1705 and 2490 kPa, while the HT produced 2100–2790 kPa of CI. BD mean values were between 1.58 and 1.7 Mg m^{-3} for the LT and 1.65–1.77 Mg m^{-3} for the HT. Hence, the data support both hypotheses. No significant differences were found in RD between HT and LT when they passed 1, 3 or 5 times, but there was a difference when traffic raised up to 8 passes (143 mm RD for HT). The main conclusions were: (a) this work has shown that soil compaction resulting from tractor traffic increases CI and BD and decreases total soil porosity. The data of CI and BD indicated that Almond orchard soil is unable to limit subsoil compaction under moderate traffic intensity. (b) Up to the fifth pass of either a FWA or 2WD tractor, ground pressure is responsible for topsoil compaction.

1. Introduction and literature review

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

Compaction as evidenced by increased soil cone index and bulk density and reductions in soil porosity reduces the penetrability of the soil for roots (Botta et al., 2007). The altered pore size distribution brought about by tillage is very unstable and tends to change as the season progresses (Mapa et al., 1986). By loosening the soil, conventional tillage forms more macropores at the beginning of the season, but the persistence of these pores depends largely on the structural stability of the soil, the rainfall patterns after tillage, and the occurrence and timing of field traffic. Use of heavy equipment (e.g., manure spreaders or tankers) over a field can cause soil compaction, especially of heavy clay soil with high moisture content (Tessier et al., 1991; Jokela and Côte, 1994; Botta et al., 2008). From an agronomic point of view, compacted soils

---

[*] Corresponding author.
E-mail address: atolon@ual.es (A.T. Becerra).

doi:10.1016/j.still.2010.02.001

impede plant root development (Threadgill, 1982), delay overall plant growth and reduce yields (Gameda et al., 1985).

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

Botta et al. (2002) considered that it is advisable to divide soil compaction into two different problems: topsoil compaction, within range of depth corresponding to the cultivated horizon (Ap), and subsoil compaction, appearing at depths below the Ap depth limit. Håkansson and Reeder (1994), who stated that when subsoil compaction is induced below the Ap horizon, mechanical loosening to alleviate this compaction is very difficult, always expensive and eventually impossible. In addition, these authors demonstrated that subsoil compaction, at the quoted depths, can cause lasting reduction in crop yields.

On sandy loam of the Darvel series (Scotland, temperate climate) Smith and Dickson (1990) found a direct effect of ground pressure on topsoil compaction and of total axle load on subsoil compaction.

Tractor passes also caused soil compaction, Botta et al. (2006) reported that high traffic frequency (10 and 12 tractor passes in the same tracks equipped with 18.4–34 crossply tyre) of a light tractor (3.1 Mg) on Typical Argiudol soil in northeastern rolling Pampa region (Argentina, Humid subtropical climate) produced significant increases in cone index and dry bulk density in the topsoil and subsoil levels.

A very detailed study on the effect of multiple passes was made by Ljungars (1977) on eight soil types in Sweden (Oceanic climate). The effect was expressed by increase in degree of compactness. In same cases the increase rate declined after three to 6 passes whereas in other cases the responses was approximately linear up to nine or 18 passes.

In orchards, the constant movement of equipment between tree rows may cause topsoil and subsoil compaction and result in poor drainage. Botta (2000) found that on a soil with high clay content (Vertisol soil) in the east Pampas region (Argentina, Humid subtropical climate) soil compacted to a cone index of >2200 kPa and >1.7 Mg m^{-3} bulk density measured at a depth of 400–600 mm reduced peach (*Prunus persica* L.) yields by 29.6%. At this depth range, the assessed values by Botta (2000) were higher than the 1500 kPa (200 psi) limit mentioned by Threadgill (1982) to avoid root growth retardance.

Iancu et al. (1996) in Romania (Continental climate) found that with four different treatments (crop on contour line, lower, middle and upper terrace platform) to two types of soil (brown colluvial soil or slightly eroded soil) in apple orchards over the 0–1.0-m soil depth, bulk density increased significantly by 1.7%, soil penetration resistance increased by 15% and saturated hydraulic conductivity decreased by 31%. Soil humus content in the lower part of the terrace platform was significantly higher than the soil humus content in the middle (44% higher), the upper part of the terrace platform (91% higher), or contour line treatment (20% higher).

Nuñez Moreno and Valdez Gascon (1994) determined how soil conditions affect yields and growing conditions in citric orchards, in a semiarid climate in north-western Mexico. The mean yield, in the best area was about 162 and 48 kg/tree in the worst. By analyzing the soil in the worst areas, the authors verified that compaction was 15 bar higher than in the best soil, the infiltration rate was lower, and there was an increment in soil silt content, reducing plant growth. Root growth in many plants was also affected by compaction.

Outlined hypothesis were:

(1) Subsoil compaction distribution due to tractor traffic on recently tilled soils in Almond orchard depends on total axle load and tractor passes.
(2) Topsoil compaction produced by tractor traffic depends on tractor passes and ground pressure.

2. Objectives

The objectives of this study were to (a) evaluate the vertical distribution of soil compaction induced by traffic of two tractors with different weights and (b) quantify soil mechanical behavior due to compaction caused by tractor traffic currently in use in Almería almond (*Prunus amigdalus* L.) orchards.

3. Equipment and test procedure

3.1. The site

The experiment was conducted in the Vélez Blanco District of the Province of Almería in southeast Spain (37°41′N, 2°5′ W) at an altitude of 800 m asl. (semiarid climate). The no stone Class 2 Type 3 slope has a 30% gradient; and is well drained (Drainage Class 3). The soil is an Aridisol (Soil Conservation Service, 1994), with an organic matter content ranging from 1.5% (w/w) at the surface to 0.3% at a depth of 0.6 m. Soil physical and mechanical properties are given in Table 1.

3.2. Experimental treatments

Experiments were performed in a 20-year-old Marcona almond (*Prunus amigdalus* L.) orchard. Plantation density: 6 × 6 m, 4 and 5 m tall with a trunk that is about 20 cm in diameter.

Treatment consisted of five tractor traffic frequency on 200 m long by 4 m wide (800 m^2) plots, where the experimental variable

Table 1
Soil physical and mechanical properties.

Depth (mm)	0–130	130–280	280–450	450–650	+650
	A1	B21t	B22t	B3	C
Proctor					
Optimum water content (%, w/w)	19.1 ± 0.16	22.1 ± 0.13	22.3 ± 0.20	23.2 ± 0.16	24.0 ± 0.18
Maximum dry BD (Mg m^{-3})	1.41 ± 0.06	1.47 ± 0.05	1.51 ± 0.06	1.57 ± 0.02	1.60 ± 0.19
Soil organic carbon (kg^{-1})	8.6 ± 0.29	3.3 ± 0.2	4.1 ± 0.73	1.9 ± 0.56	1.7± 0.64
Total nitrogen (g kg^{-1})	1.30 ± 0.06	0.7 ± 0.03	0.8 ± 0.23	0.5 ± 0.01	0.6 ± 0.03
C/N ratio	6.67	4.71	5.12	4.0	2.83
Clay (<2 m) g kg^{-1}	140 ± 2.41	270 ± 2.41	240 ± 2.76	170 ± 1.99	140 ± 2.83
Silt (20–50 m) g kg^{-1}	540 ± 4.62	530 ± 3.00	590 ± 3.32	720 ± 2.98	570 ± 1.81
Sand (g kg^{-1})	320 ± 1.57	200 ± 1.91	170 ± 1.92	111 ± 0.98	290 ± 2.01
pH in H_2O (1:2.5)	8.0 ± 0.06	8.2 ± 0.02	8.2 ± 0.05	8.4 ± 0.02	8.4 ± 0.04

Table 2
Tractor characteristics.

Tractor	FWA Heavy	2WD Light
Engine power (CV/kW)	90/66	47/34.4
Front tyres	14.9R 24	650–16
Rear tyres	23.1R 26	12.4–28
Inflation pressure, front tyre (kPa)[a]	100	180
Inflation pressure, rear tyre (kPa)[a]	60	100
Total weight (kN)	50	15
Front weight (kN)	20	4.5
Rear weight (kN)	30	10.5
Front tyre—soil contact area (m^2)	0.53	0.10
Rear tyre—soil contact area (m^2)	0.453	0.140
Ground pressure front tyre (kPa)	18.8	22.5
Ground pressure rear tyre (kPa)	33.4	37.5
Forward speed when sowing ($km\,h^{-1}$)	5.5	5.5

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

was 0, 1, 3, 5 and 8 tractor passes over the same track in three replications in completely randomized plots. Before treatment, plots were plowed once with a rotary tiller (ASAE Standard EP291, 1992a). This treatment represents a tillage system commonly used in the region.

Zero (Control plot), 1, 3, 5 and 8 inter-row passes were made by two 2WD tractors, Light (L) and Heavy (H), equipped with single rear tyres (Table 2). Tractor speed during the experiment was 5.5 km h^{-1} with no hitch load.

Statistical analyses were performed by the Statgraf program ver. 7.1. An analysis of variance (ANOVA) was carried out, and means were analyzed by Duncan's multiple range test.

The tractors were models in common use on commercial farms in the experimental area. The number of passes simulated typical traffic intensity in the region under study. According to García et al. (2004) in Almond orchard there are from three to seven tractor passes for tillage practices and phytosanitary treatments per year and another one pass for soil fertilization (N and K) in the same period. In this practices are used: tractor, 2000 L tank, moldboard plow, rotary tiller and harrows (ASAE Standard EP291, 1992a).

The tyre/soil contact area was measured by reversing or driving the tractor into the experimental field and spraying the area around the tyre with paint. A hydraulic lift was then used to raise the tractor so that the tyre track could be transferred onto a sheet of glass, and printed from there onto paper, and measured with a planimeter. Average ground pressure was estimated as the total axle load divided by the tyre/soil contact area for both tyres on the axle. Finally tyre widths were measured in the field under working conditions (Botta et al., 2008).

3.3. *Soil response variables*

Soil water content (w/w), dry bulk density (BD), total soil porosity (TSP), cone index (CI) and rut depth (RD) were measured on the same day and immediately following the traffic treatments. It is important to note that "zero reference" to measure these parameters (CI and BD), is not the soil surface, it is located at a depth where there is no soil displacement. These parameters were measured on the bottom of the RD, in the centre lines of the tyre tracks, because in this zone the compressive effects tend to concentrate (Söhne, 1958).

BD and soil water content were measured with a gamma probe (Troxler, 3440), at different depth ranges (0–200, 200–400 and 400–600 mm) at 50 mm intervals along the tractor centre lines of tyre tracks. Each value of bulk density and soil water content was the average of ten measurements, all of which were verified by gravimetric data using a cylinder 100 mm high by 50 mm in diameter. Total soil porosity was calculated from bulk density using soil particle density.

The CI was determined with a Remick CP20 recording S313 penetrometer (ASAE Standard S313.2, 1992b). Twenty-five samples taken at a depth of 0–600 mm at intervals of 25 mm were averaged for each plot. Both BD and CI were measured at randomized locations on all plots.

Rut depth was measured using a profile meter consisting of a set of vertical metal rods (length 500 mm and diameter 5 mm), spaced at 25 mm horizontal intervals, sliding through holes in a 1-m long iron bar. The bar was placed across the wheel tracks perpendicular to the direction of travel and the rods positioned to conform to the shape of the depression. Rut depth was calculated using the average depth of 60 sets of readings.

4. Results and discussion

Water content (w/w) during traffic averaged 16% dry weight at a depth of 0–200 mm, 15.8% at 200–400 mm and 16.1% at 400–600 mm. In this area the agricultural traffic (between lines of trees) is commonly carried out when the soil has this water content. This was the reason why the work was carried out with this water content in order to measure the traffic impact in a real condition. Taking into account that soil wetness is a well established factor affecting the compaction and compressibility of soils (Proctor, 1933a; Terzaghi and Peck, 1967). The compressibility of soil decreases as it dries because of two processes. The effective stress increases as soil water potential decreases (Bishop and Blight, 1963), and direct contact between soil particles increases as the thickness of the water films around the soil particles becomes thinner (McNabb and Boersma, 1996).

Standard Proctor (1933b) compaction test results (Table 1) showed, for soil in the 0–130 mm depth range, a maximum bulk density of 1.41 Mg m^{-3} at 19.1% soil water content. Trafficking occurred at soil water contents close to this value (Table 1) causing significant compaction. For the initial bulk density, control plot for example, averaged 1.25 Mg m^{-3} in the 0–200 depth range (Fig. 1) and was raised to an average of around 1.41 Mg m^{-3}.

In general, there were no significant differences ($P < 0.01$) in soil water content between treatments when penetrometer resistance (or cone index) was measured and correction or allowance for this was not considered necessary.

Results of cone index (CI), bulk density (BD), rut depth (RD) and total soil (TSP) porosity are shown in Figs. 1 and 2, Table 3 and Figs. 4 and 5 respectively.

Cone index without tractor traffic increased with soil depth, because some resistance is from the weight of soil above the depth (Fig. 1). Lateral forces on the penetrometer cone increase with increasing depth therefore; more force is needed for the cone to displace soil. Resistance can also increase with depth because of changes in soil texture, gravel content, structure and agricultural traffic. Without traffic, increases between 325 and 600 mm ($\geq$1500 kPa), are probably as a result of clay content or previous machinery traffic.

In topsoil (0–200), up to 5 passes of the heavy and light tractors, as in 1 and 3 passes, the CI and BD values (Figs. 1 and 2) responded to the ground pressure being higher in absolute value for the light tractor. This is confirmed because, until fifth pass, as shown in Figs. 3 and 4a the light tractor caused in both soils has higher values in CI and BD than the heavy tractor, also in these figures, for heavy and light tractors, it can be seen that there is a strongly positive relationship between tractor passes and CI and BD values.

The behaviour of soil in this freshly tilled horizon following traffic agrees with results quoted by Smith and Dickson (1990) and Botta et al. (2002, 2006), confirming the direct relationship between topsoil compaction and ground pressure. Also, when

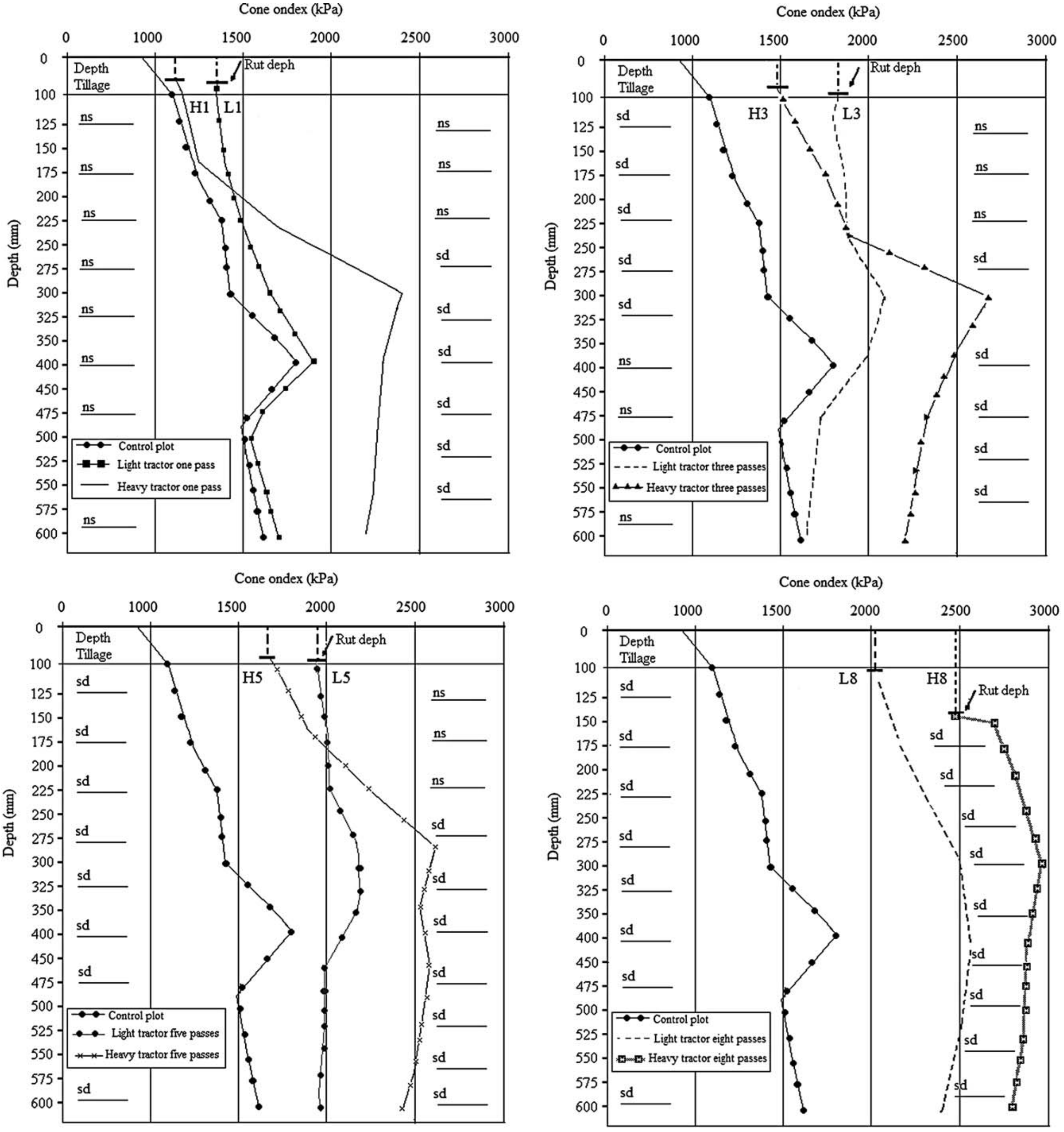

Fig. 1. Cone index values (kPa) measured in the centerlines of the tyre tracks for Light (L) and Heavy (H) tractor after 1, 3, 5 and 8 passes. For each traffic treatment, control plot without traffic in black. (sd): significant difference, (ns): not significant ($P < 0.01$) Duncan's multiple range test.

soils are dryer, like in this case, the water potential is lower, and narrower tyres will cause more soil compaction than wider tyres (Greene and Stuart, 1985). As a result, narrower tyres are expected to cause higher statistically significant soil compaction at this water content than wider tyres (Froehlich et al., 1980).

Is important to consider that from the fifth pass, the superficial cone index values did not respond to the ground pressure, but were affected by the total load of the used tractor. Our hypothesis for this is that after 5 tractor passes over the soil, the load destroys soil porosity causing its collapse and this would respond, according to Raghavan and McKyes (1979) and Ljungars (1977), to the number of passes.

After traffic the compaction took place, the gamma probe measurements revealed differences in BD between treatments to a depth of about 125–400 mm for light tractor and about 125–600 mm for heavy tractor (Fig. 2). However, only the effect on soil BD from the severe compaction procedure using 5 and 8 passes of heavy tractor on the plough bottom could be significantly ($P < 0.01$) distinguished from the control plot with the natural BD.

Examination of soil responses to traffic in deeper layers (200–600 mm) revealed that soil compaction increased as the traffic intensity increased, this result agree with those quoted by Botta et al. (2002). For the 200–400 mm (Figs. 3 and 4b) and 400–600 mm (Figs. 3 and 4c) depth ranges, respectively, shows that

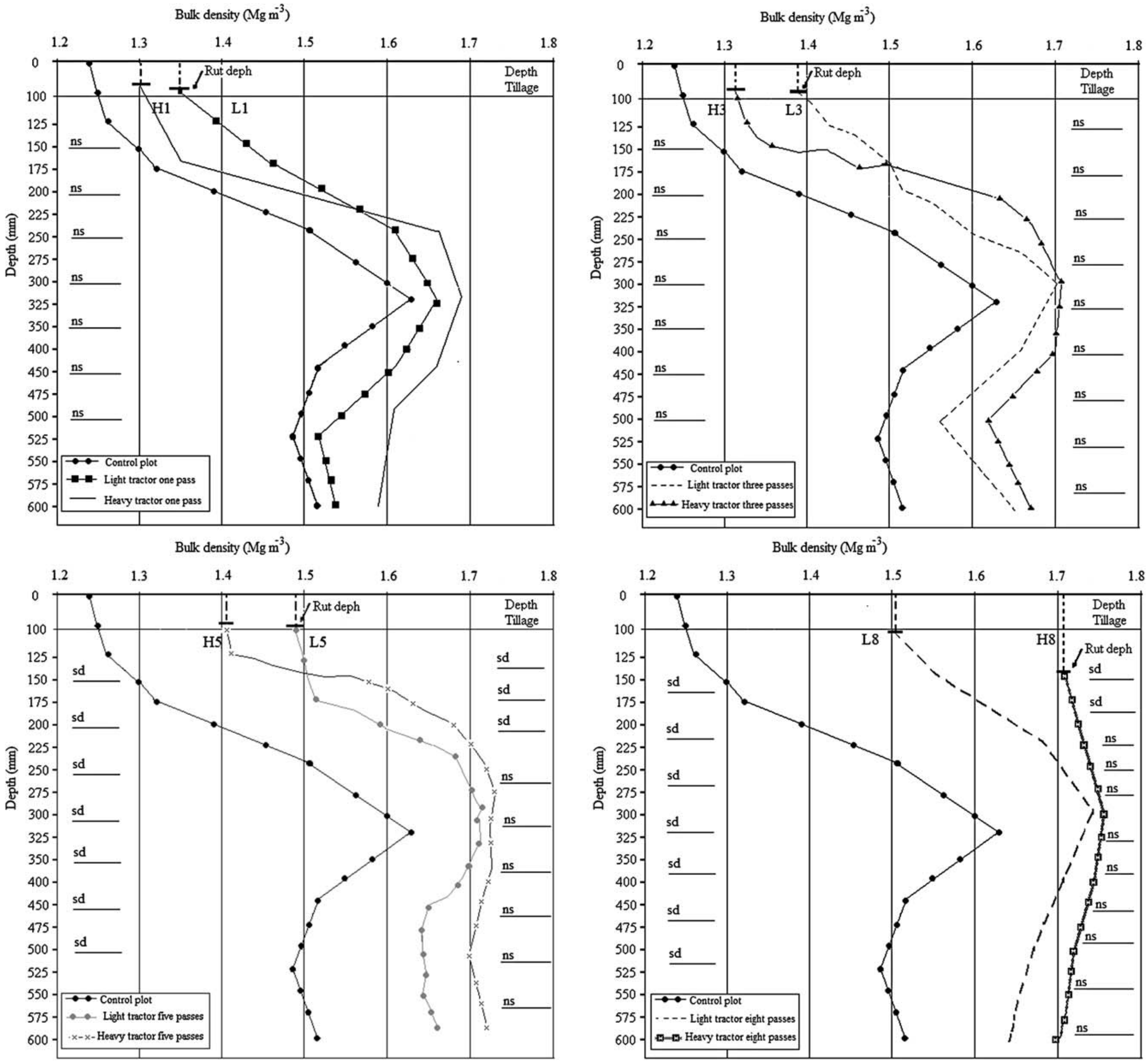

Fig. 2. Bulk density values (Mg m^{-3}) measured in the centerlines of the tyre tracks for Light (L) and Heavy (H) tractor after 1, 3, 5 and 8 passes. For each traffic treatment, control plot without traffic in black. (sd): significant difference, (ns): not significant ($P < 0.01$) Duncan's multiple range test.

Table 3
Light (L) and Heavy (H) tractor rut depth (mm) measurements for 1, 3, 5 and 8 passes.

Number of passes	L1	L3	L5	L8	H1	H3	H5	H8
Rut depth	80a	82a	97b	111c	72a	77a	91b	143d

Letters in depth row show significant differences between treatments $P < 0.01$ Duncan's Multiple range.

there is a strong positive relationship between tractor passes and CI and BD, and that the heavy tractor caused higher CI and BD values than the light tractor. From this, it can be inferred that after a depth of 200 mm, tractor load was responsible for subsoil compaction, as demonstrated by Håkansson and Reeder (1994).

BD and CI always increased with the number of passes, but BD tended to be less responsive than CI. Whereas BD increased to $\leq$8.8%, and differences between the control and 1 or 3 passes were not significant ($P < 0.01$), the corresponding average increase in CI was 42%. Differences between the control and 5 and 8 passes were significant at the 0–200 mm depth (Fig. 2).

In spite of this, the measured changes in bulk density are in agreement with the soil behaviour suggested by changes in cone index. Although bulk density changes due to tractor traffic tend to be less affected than cone index, if the same analysis is made considering the bulk density ratios due to greater axle loads, the same trend described above for cone index occurred.

BD was greater with 8 passes by the heavy tractor than with fewer (Fig. 2). Without traffic, BD at the surface exceeded the maximum 1.2 Mg m^{-3} recommended by Ressia et al. (1998) and Botta et al. (2004) for a depth of 200 mm, and from 200 to 400 mm, BD exceeded 1.6 Mg m^{-3} with or without traffic.

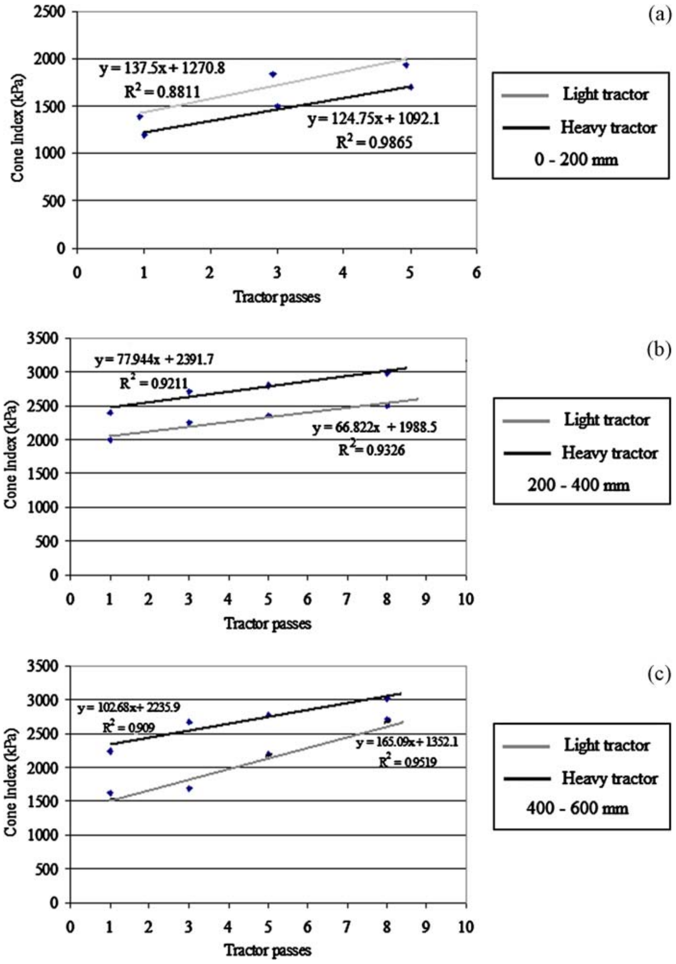

Fig. 3. Relationship between cone index and tractor passes for: (a) 0–200 mm, (b) 200–400 mm and (c) 400–600 mm depth range.

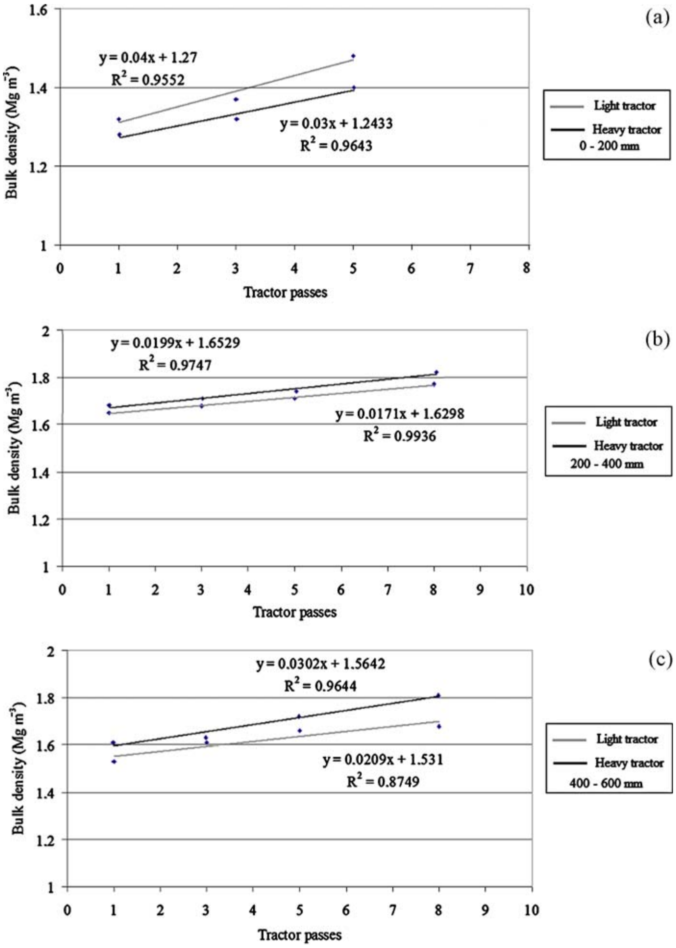

Fig. 4. Relationship between bulk density and tractor passes for: (a) 0–200 mm, (b) 200–400 mm and (c) 400–600 mm depth range.

Data from both parameters showed that compaction by tractor traffic caused considerable change to the topsoil and subsoil properties. These results are similar to those of Håkansson (1987), who indicated that the lasting effects of compaction at high axle load are related to soil type, the number of passes and the number of years since compaction. Hence, the data support both hypotheses.

In all traffic treatments, the tractor traffic caused variable decreases in total soil porosity respect to the control plots. Over all depth ranges the average porosity in all treatment control plots did not fall below 30% (Figs. 5 and 6).

Topsoil porosity in the 0–200 mm layer was significantly ($P < 0.01$) affected when the light tractor passed over it 5 and 8 times. Light tractor traffic caused a mean reduction in total soil

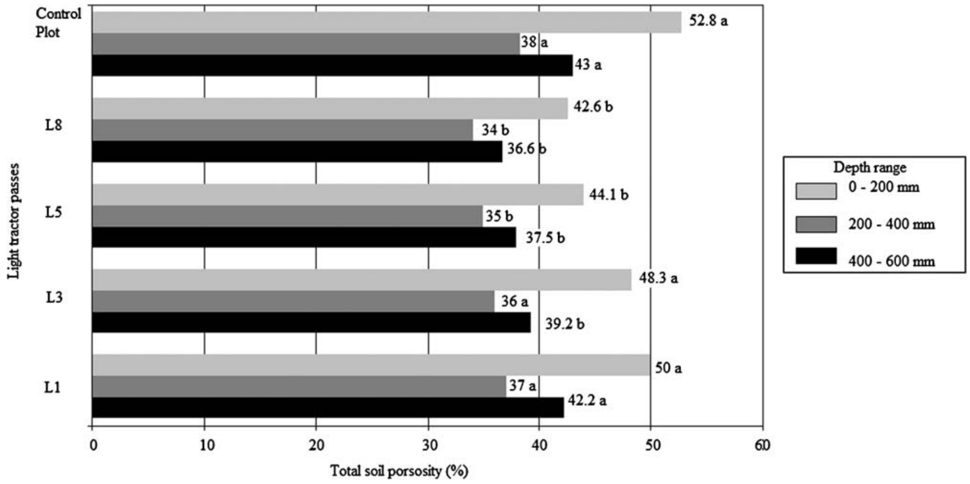

Fig. 5. Total soil porosity (%) in the track line after traffic for Light Tractor. (Values with different letters are significantly different ($P < 0.01$) Duncan's multiple range test.)

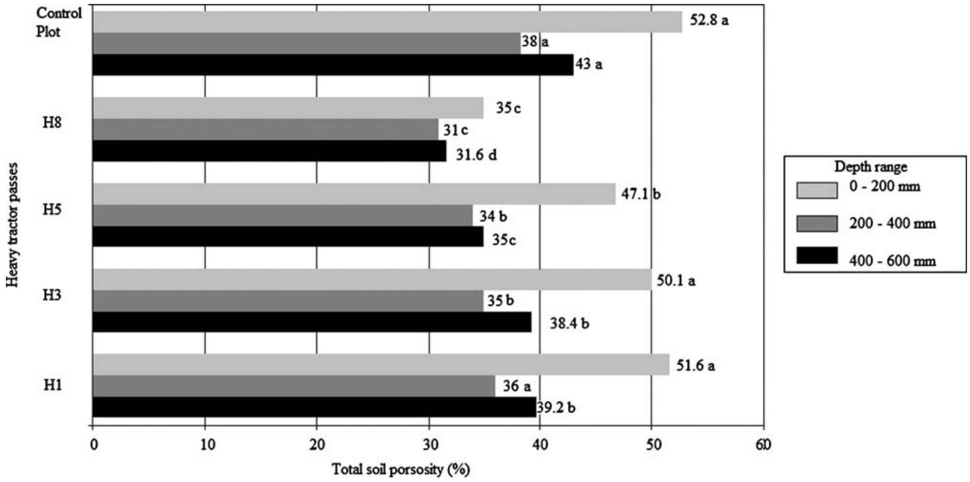

Fig. 6. Total soil porosity (%) in the track line after traffic for Heavy Tractor. (Values with different letters are significantly different ($P < 0.01$) Duncan's multiple range test.)

porosity of 10.2%, 8.7%, 4.5% and 2.8% with 8, 5, 3 and 1 pass, respectively. The heavy tractor also caused a significantly ($P < 0.01$) change in this parameter, when it passed 5 and 8 times. Reduction in total soil porosity was 17.8, 5.7, 2.7 and 1.2 for 8, 5, 3 and 1 passes, respectively.

The effect of this reduction in topsoil porosity on crop yield was significant and could be explained by the fact that the topsoil is where root development and nutrient uptake are concentrated. This corroborates other research suggesting that one pass of a tractor with different ground pressure can result in extensive topsoil compaction (Botta et al., 2002) and severe reduction in total soil porosity.

Soil porosity in the 200–400 mm profile was reduced to 1% by one pass of the light tractor, and with 3, 5 and 8 passes, the reduction in total soil porosity was 2%, 3% and 4%, respectively. The heavy tractor caused considerable changes in this parameter reducing total soil porosity by 7%, 4%, 3% and 2% for 8, 5, 3 and 1 passes, respectively.

In the 400–600 mm profile, average changes in total soil porosity after traffic were slightly smaller than in the shallower layer, and after light tractor traffic were reduced by 6.4%, 5.5%, 3.8% and 0.8% for 8, 5, 3 and 1 passes, respectively. The heavy tractor caused considerably more change, reducing total soil porosity by 11.4%, 8%, 4.6% and 3.8% with 8, 5, 3 and 1 passes, respectively.

Average rut depths are shown in Table 3. No significant ($P < 0.01$) differences were found in rut depths between heavy and light tractors when they passed 1, 3 or 5 times, but there was a difference when traffic raised up to 8 passes. H8 (143 mm rut depth) was significantly shallower indicating that the compaction was more concentrated and severe in the top soil; the influence of rut depth on subsoil compaction is not clear.

Up to the fifth pass, shallower rut depths and lower CI were produced by the heavy tractor, because the ground pressure from this tractor is less than the light one.

5. Conclusions

Within the limits of the experimental conditions, it may be concluded that:

- This work has shown that soil compaction resulting from tractor traffic increases CI and BD and decreases soil porosity. The data of CI and BD indicated that almond orchard soil is unable to limit subsoil compaction under moderate traffic intensity.
- One pass of heavy (50 kN total load) tractor produced an increase in bulk density and cone index in subsoil layers.
- There is a direct relationship between tractor weight and subsoil compaction which does not depend on vehicle ground pressure.
- Up to the fifth pass of either the front-wheel assist (FWA) tractor or two wheel drive (2WD) tractor, ground pressure is responsible for topsoil compaction.

References

ASAE Standard, 1992a. Terminology and Definitions for Soils Tillage and Soil Tool Relationships Engineering Practice, EP291, vol. 2. American Society of Agricultural Engineering, 611 pp.

ASAE Standards, 1992b. Soil cone penetrometer S 313.2. American Society of Agricultural Engineering, 611 pp.

Bishop, A.W., Blight, G.E., 1963. Some aspects of effective stress in saturated and partly saturated soils. Geotechnique 13, 177–197.

Botta, G., 2000. Subsoil compaction distribution induced by agricultural traffic, Thesis Doctor, Luján University, Argentina, p. 230.

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

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

Botta, G., Jorajuria, D., Rosatto, H., 2006. Light tractor frequency on soil compaction in the rolling Pampa region of Argentina. Soil Till. Res. 86, 14–19.

Botta, G., Pozzolo, O., Bomben, M., Rosatto, H., Rivero, D., Ressia, M., Tourn, M., Soza, E., Vázquez, J., 2007. Traffic alternatives in harvest of soybean (Glycine max L.): effect on yields and soil under direct sowing system. Soil Till. Res. 96, 145–154.

Botta, G., Rivero, D., Tourn, M., Bellora Melcon, F., Pozzolo, O., Nardon, G., Balbuena, R., Tolón Becera, A., Rosatto, H., Stadler, S., 2008. Soil compaction produced by tractor with radial and cross-ply tyres in two tillage regimes. Soil Till. Res. 101, 44–51.

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

Froehlich, H.A.J., Azevedo, P., Cafferata, L., 1980. Predicting soil compaction on forest land. Final Project Report, Coop. Agreement No. 228. U.S. Forest Service, Equipment Dev. Center, Missoula, MT.

Gameda, S., Raghavan, G., McKyes, E., Theriault, R., 1985. High axle load compaction and corn yield. Trans. ASAE 28 (6), 1759–1765.

García, J., Romero, P., Botía, P., García, F., 2004. Cost–benefit analysis of almond orchard under regulated deficit irrigation (RDI) in SE Spain. Spanish J. Agricul. Res. 2 (2), 157–165.

Greene, W.D., Stuart, W.D., 1985. Skidder and tyre size effects on soil compaction. South. J. Appl. For. 9, 154–157.

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

Håkansson, I., Reeder, R.C., 1994. Subsoil compaction by vehicles with high axle load extent, persistence and crop response. Soil Till. Res. 29, 277–304.

Iancu, M., Negoita, A., Neamtu, I., 1996. The effect of topographical modification of hill side apple orchards on the physical and chemical characteristics of the soil. In: ISHS Acta Horticulturae 451: VI International Symposium on Integrated Canopy, Rootstock, Environmental Physiology in Orchard Systems.

Jokela, W., Côte, D., 1994. Options for direct incorporation of liquid manure. In: Proceedings from the Liquid Manure Application Systems Conference. Rochester, New York. December 1–2, 1994. Northeast Regional Agricultural Engineering Service, Cooperative Extension, 152 Riley-Robb Hall, Ithaca, NY, pp. 14853–15701.

Ljungars, A., 1977. Olika faktorers betydelse for tractorernas jordpackningsverkan. Mätningar Agricultural College Sweden Dep. Soil Sci. 43 pp.

McNabb, D.H., Boersma, L., 1996. Nonlinear model for compressibility of partly saturated soils. Soil Sci. Soc. Am. J. 60, 333–341.

Mapa, B., Green, R.E., Santo, L., 1986. Temporal variability of soil hydraulic properties with wetting and drying subsequent to tillage. Soil Sci. Soc. Am. J. 50, 1133–1138.

Nuñez Moreno, J.H., Valdez Gascon, B., 1994. Effect of soil conditions on orange trees. Common Soil Sci. Plant. Anal. 25, 1747–1753.

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

Proctor, R.R., 1933a. Design and construction of rolled earth dams. Eng. News Rec. 111, 372–377.

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

Raghavan, G., McKyes, V., 1979. Vehicle compaction for agricultural tyres. Trans. ASAE 202, 218–220.

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

Smith, D., Dickson, J.W., 1990. Contributions of vehicle weight and ground pressure to soil compaction. J. Agric. Eng. Res. 46, 13–29.

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

Söhne, W., 1958. Fundamentals of pressure distribution and soil compaction under tractors tyres. Agric. Eng. 39, 276–281.

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

Terzaghi, K., Peck, R.B., 1967. Soil Mechanics in Engineering Practice, 2nd ed. John Wiley & Sons, New York, USA.

Tessier, S., Lague, C., Lambert, R., Tremblay, P., Brochu, Y., 1991. Soil compaction by liquid manure spreaders. CSAE paper No. 91-411. Saskatoon, Canada: CSAE.

Threadgill, E., 1982. Residual tillage effects as determined by cone index. Trans. ASAE 25 859–863, 867.