

Subsoil compaction from tractor traffic in an olive (*Olea europea* L.) grove in Almería, Spain

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Abstract

This study was in an olive (*Olea europea* L.) grove in the Vélez Blanco District of Almería, Spain, where the soil is a typical Aridisol. The aim was to evaluate subsoil compaction caused by three different tractors currently used in olive groves. Measurements were made of (i) the cone index (CI), (ii) hydraulic conductivity (HC) and (iii) rut depth after passage of a light tractor (LT = 22.50 kN), a heavy tractor (HT = 42.60 kN) and a medium tractor (MT = 33.30 kN). The CI differed for the topsoil (0–200 mm) for each type of tractor after up to five passes. In this depth soil level, the CI was greatest for LT because the ground pressure (by narrow tyres) was greater than under the MT and HT. For deeper layers, there was a strong positive relationship between number of tractor passes and CI values, and the CI was greater for passes by the HT than the LT or MT. The HT resulted in shallower ruts up to the fifth pass, and the CI values were smaller because there was less ground pressure from this tractor than the others. In all treatments, tractor traffic caused varying decreases in HC in the 0–600 mm depth range. The main conclusion is that subsoil compaction is related directly to tractor weight. For the three tractors, topsoil compaction is caused by ground pressure and not on total axle load.

Keywords: Tractor traffic, cone index, track, axle load

Introduction

Soil compaction due to agricultural machinery is one of the major threats to soil quality. Compaction not only reduces pore volume, but also modifies pore geometry. This affects important soil properties and functions such as soil hydraulic properties, gas-phase transport and root growth. Soil compaction is therefore associated with many environmental and agronomic problems, such as erosion, leaching of agrochemicals, greenhouse gas emissions and crop yield losses (Keller & Lamandé, 2012). When soils are compacted, pore volume is reduced, aggregates crumble, and smaller interaggregate pores with unaccommodating faces are formed (Pagliai & Vignozzi, 2002). The major loss of the largest pores by soil compaction changes the pore size distribution and hence water retention (Dexter, 2004). Compaction is indicated by increases in the soil cone index

(CI) and bulk density and reductions in soil porosity, which has the effect of reducing root penetrability according to Botta *et al.* (2012) who also suggest that tractor traffic reduces total porosity and compresses large pores. This problem is more critical in groves for apples, almonds, citrus fruit and olives because tractors use the same tracks several times a year (Tolón-Becerra *et al.*, 2010).

Botta *et al.* (2002) identify two aspects of compaction that require investigation: (i) topsoil compaction within the cultivated (Ap) horizon and (ii) subsoil compaction below the tillage layer. The subsoil includes any plough pan in the upper part of the subsoil. Compaction of this pan can only be alleviated by subsoiling or natural processes of drying and wetting by shrinking and swelling, freezing and thawing, macrofauna activity, and root growth. These processes are slow, and evaluation of the persistence of subsoil compaction requires long-term experiments (Lamandé *et al.*, 2012).

According to Berisso *et al.* (2012), subsoil compaction is an important problem in agriculture and agricultural policy due to its persistence. However, experimental data on the persistency of subsoil compaction are scarce. Håkansson &

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Reeder (1994) state that when subsoil compaction is induced below the Ap horizon, it is difficult to alleviate it by mechanical loosening, is expensive and eventually becomes impossible. In addition, these authors demonstrate that subsoil compaction can cause a reduction in crop yield over a long period.

Taylor *et al.* (1966) report from their study that the number of cotton roots penetrating the soil was reduced drastically as penetration resistance approached 2000 kPa. At soils compacted to >2 MPa, root growth becomes virtually impossible. Botta (2000) states that soil with a high clay content in the east Pampas region of Argentina and compacted to a CI of >2200 kPa and a bulk density >1.7 Mg/m³ at a depth of 400–600 mm reduced peach (*Prunus persica* L.) yields by 29.6%. Threadgill (1982) notes that soils with a CI >2000 kPa reduced crop yields, and at >1500 kPa, there was reduced root growth in groves. Iancu *et al.* (1996) demonstrate that bulk density increased by 1.7%, soil penetration resistance increased by 15% and saturated hydraulic conductivity (HC) decreased by 31% with four different treatments with the crop grown along a contour and on lower, middle and upper terraces for two types of soil (brown colluvial and slightly eroded) in apple groves at a soil depth of 0–1.0 m. Nuñez-Moreno & Valdez-Gascon (1994) show that soil conditions affect yields and growing conditions in citric groves in a semiarid climate in northwestern Mexico. The mean orange yield was ca.162 kg/tree in the best area and 48 kg/tree in the worst. Comparison of soil data in the best and worst areas showed that in the worst soil, compaction was greater by 1500 kPa, the infiltration rate was lower, and there was an increase in silt content which reduced plant growth. Root growth was also affected by soil compaction.

Olive is a major crop in the Mediterranean basin and are grown on ca. 9.2 Mha (FAO, 2008). Olives are an important part of the Mediterranean diet and require relatively simple agricultural practices for their production (Gómez *et al.*, 2009). However, 3–7 tractor passes per year are necessary in olive groves for tillage and weed control,

and this can produce subsoil compaction. Soil compaction from the passage of machinery along with erosion as a result of steep slopes presents management challenges. Another problem is that soil compaction as expressed in a high CI as found in this study (>1500 kPa) impedes the growth of nitrogen-fixing legume cover crops sown in the rainy season between rows of olive trees. Moreover, soil cracks in the dry season, and compaction causes uneven growth of young olive tree roots.

Materials and methods

The objective of this study was to evaluate subsoil compaction caused by three different tractors which are used in olive groves in Almería. The hypothesis was that subsoil compaction due to tractors on tilled soils in olive groves depends on total axle load and number of tractor passes.

The site

The experiment was in the Vélez Blanco District of the Province of Almería in southeast Spain (37°41'N, 2°5'W) at an altitude of 828 m a.s.l. where there is a semiarid climate. Slope has a 30% gradient and is well drained (Drainage Class 3). The soil was an Aridisol (Soil Conservation Service, 1994) with an organic matter content ranging from 1.5% at the surface to 0.3% at a depth of 0.6 m. Soil properties are given in Table 1.

Experimental treatments

The experiments were in a 40-yr-old olive grove (*Olea europaea* L.). Plantation density was 156 olives/ha with 3- to 5-m-tall trees and 40-cm-diameter trunks. The treatment consisted of five tractor passes on 200-m-long by 4-m-wide plots, where there were 0, 1, 3, 5 and 7 tractor passes over the same path in three replications in completely randomized plots. The plots were ploughed once with a rotary tiller

Table 1 Soil physical and mechanical properties

Depth (mm)	0–180 A1	180–280 B21t	280–450 B22t	450–650 B3	+650 C
Optimum water content (%)	20.1 ± 0.14	21.2 ± 0.14	22.5 ± 0.19	23.0 ± 0.14	24.2 ± 0.16
Maximum dry BD (Mg/m ³)	1.45 ± 0.06	1.46 ± 0.02	1.49 ± 0.05	1.54 ± 0.04	1.62 ± 0.14
Soil organic carbon (g/kg)	8.1 ± 0.20	3.2 ± 0.2	4.0 ± 0.51	1.7 ± 0.50	1.8 ± 0.42
Total nitrogen (g/kg)	1.28 ± 0.04	0.8 ± 0.02	0.9 ± 0.10	0.4 ± 0.02	0.5 ± 0.01
C/N ratio	6.32	4.00	4.44	4.25	3.60
Clay (<2 m) g/kg	143 ± 2.34	251 ± 2.36	237 ± 2.68	173 ± 1.87	135 ± 2.64
Silt (20–50 m) g/kg	521 ± 3.30	525 ± 2.98	582 ± 3.12	691 ± 2.87	566 ± 1.91
Sand (g/kg)	336 ± 1.39	224 ± 1.87	181 ± 1.88	136 ± 0.96	299 ± 1.92
pH in H ₂ O (1: 2.5)	7.9 ± 0.03	8.1 ± 0.03	8.0 ± 0.02	8.3 ± 0.01	8.3 ± 0.05

(ASAE Standard, 1992a) 2 months before treatments were applied in a tillage system in common use within the region. Zero (Control plot), 1, 3, 5 and 7 inter-row passes were made by three tractors, light (LT), medium (MT) and heavy (HT), equipped with single front and rear tyres (Table 2). Tractor speed during the experiment was 5.5 km/h with no hitched load. The tractors were models commonly used on commercial farms in the experimental area, and the number of passes simulated typical traffic intensity over bare soil. In olive groves, there are from 3–7 tractor passes for tillage and weed control and another for applying N and K. The machinery used for this was a tractor, a sprayer with 2000-L tank capacity, mouldboard plough, rotary tiller and harrows (ASAE Standard, 1992a). Analysis of variance (ANOVA) using Statgraf ver. 7.1 was carried out with means compared using Duncan's multiple range test.

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, printed from there onto paper and measured with a planimeter. The average ground pressure was estimated as the total axle load divided by the tyre/soil contact area for both tyres on the axle. The tyre widths were measured in the field under working conditions (Botta *et al.*, 2008).

Table 2 Tractor characteristics

Tractor	Agrimac	Same TB 100	Fendt 312
	9800 4WD Light tractor	FWA Medium tractor	FWA Heavy tractor
Engine power (CV/kW)	82/60	99/73	110/81
Front tyres	300/70 R 20	320/70 R24	480/65 R24
Rear tyres	300/70 R 20	420/70 R28	540/65 R38
Inflation pressure, front tyre (kPa) ^a	60	60	60
Inflation pressure, rear tyre (kPa) ^a	60	60	60
Total weight (kN)	22.50	33.30	42.60
Axle front weight (kN)	14.64	13.30	17.05
Axle rear weight (kN)	7.90	20.00	25.60
Ground pressure front tyre (kPa)	110	98	45.5
Contact area front tyre (m ²)	0.0665	0.0678	0.1874
Ground pressure rear tyre (kPa)	59.8	74	52.4
Contact area rear tyre (m ²)	0.066	0.135	0.244

FWA, front-wheel-assist. ^aThe tyre inflation pressure was within the range recommended on the Goodyear Agricultural Tyre Division website.

Soil response variables

Soil water content (w/w), CI, HC and rut depth (RD) were measured on the same treatments immediately after the traffic treatments. The 'zero reference' for CI was not the soil surface but the depth at which there was no soil displacement. This was measured at the bottom of the RD on the centre lines of the tyre tracks because compression tends to be concentrated in this zone (Söhne, 1958). The soil water was measured with a gamma probe (Troloxer, 3440) at different depth ranges (0–200, 200–400 and 400–600 mm), at 100-mm intervals along the centre lines of the tractor tyre tracks. Every ten measurements, all of which were verified by gravimetric data using a 100-mm-high by 50-mm-diameter cylinder, were averaged. The CI was determined with a Rimick CP20 recording S313 penetrometer (ASAE Standards, 1992b). Twenty-five samples taken at a depth of 0–600 mm at 25-mm intervals were averaged for each plot. The CI was measured at random locations on all plots. HC was measured *in situ* at 0–600 mm depth with a TRIMS infiltrometer (Ankeny *et al.*, 1991). Ten measurements per tractor traffic treatment (LT), (MT) and (HT) were taken. The RD was measured using a profile meter consisting of a set of vertical metal rods (500 mm long and 5 mm diameter) spaced horizontally at 25-mm intervals by sliding them through holes in a 1-m-long iron plate. The plate was placed across the wheel tracks perpendicular to the direction of travel, and the rods were positioned to conform to the shape of the depression. The RD was calculated using the average depth of 60 sets of readings.

Results

Results from the CI measurements, RD and HC which were taken immediately after tractor passes are shown in Figures 1, 2 and 3, respectively. The relationships between the CI and tractor passes at 0–200 mm (topsoil) and 200–600 mm (subsoil) are illustrated in Figure 4a,b. Subsoil compaction related direct to tractor weight. For three different tractors, topsoil compaction was related to ground pressure and not total axle load.

In general, there were no significant differences ($P < 0.01$) in soil water between treatments when penetrometer resistance (or CI) was measured, and correction or allowance for this was not considered necessary. The water content (w/w) during tractor passes averaged 17.05% dry weight at a depth of 0–200 mm, 16.9 at 200–400 mm and 17.2% at 200–600 mm. Our research group had worked in this area for 5 yr prior to this experiment and found that tractors are driven between rows of trees at this soil water content. Therefore, the experiment to measure the impact of traffic was at this water content.

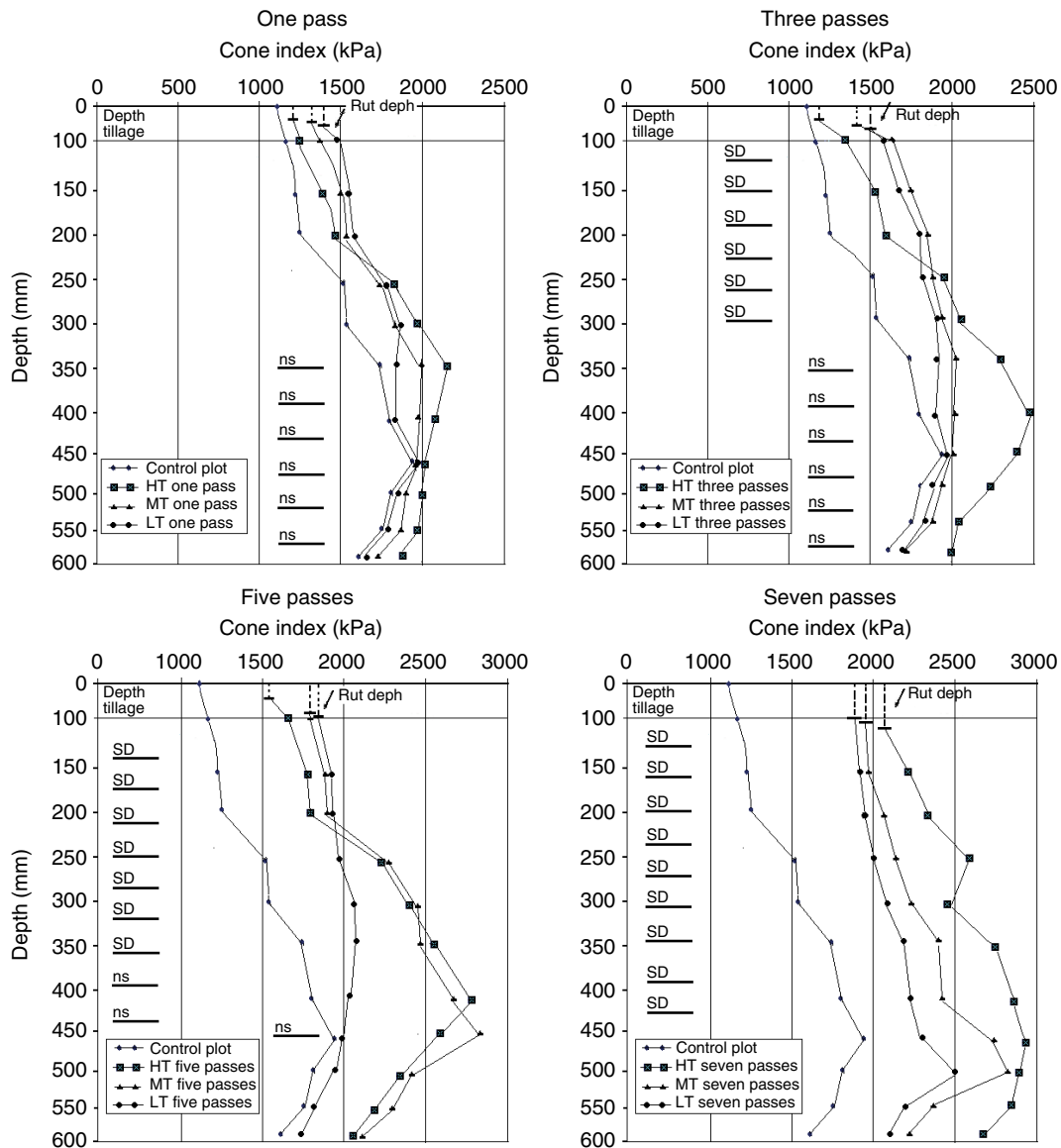


Figure 1 Cone index (kPa) measured on the centre lines of the tyre tracks of light (LT), medium (MT) and heavy (HT) tractors after one, three, five and seven passes. For each traffic treatment, control plot without traffic in black. SD, significant difference; ns, non-significant ($P < 0.01$) Duncan's multiple range test.

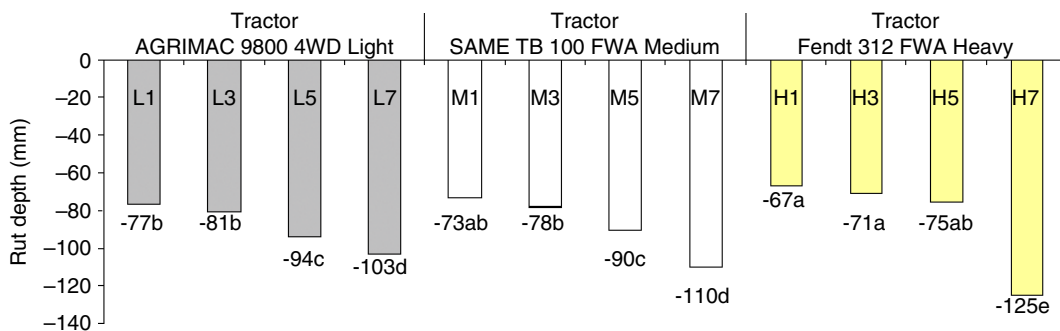


Figure 2 Light, medium and heavy tractor rut depth (mm) after traffic. (Values with different letters are significantly different ($P < 0.01$) Duncan's multiple range test).

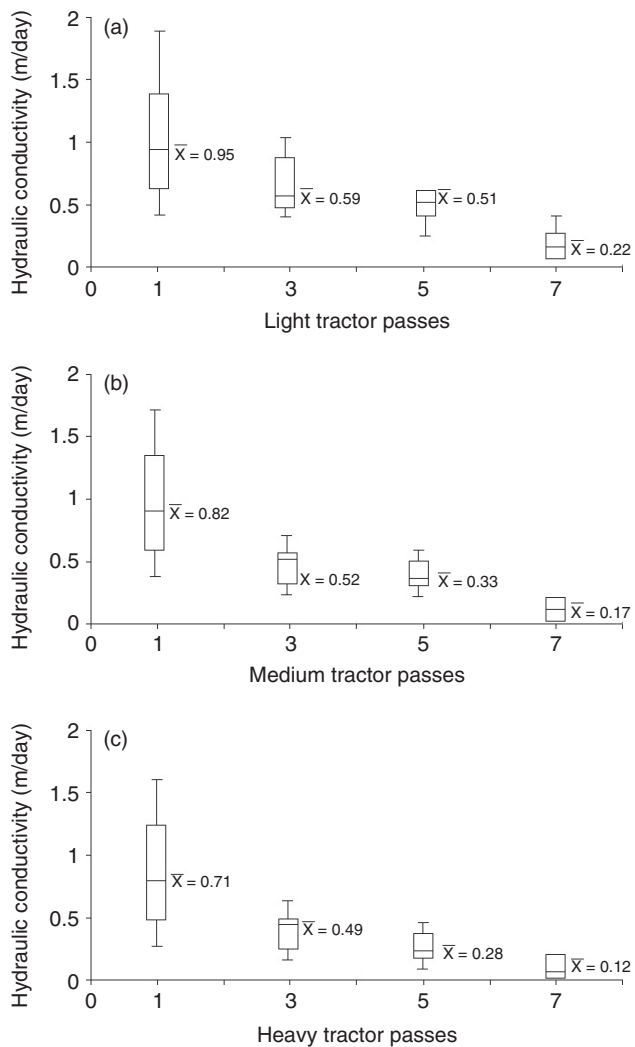


Figure 3 Hydraulic conductivity measured in a 0–600 mm depth range after tractor traffic by light tractor (a) medium tractor (b) and heavy tractor (c) after one, three, five and seven passes.

It is important to note that the “zero reference” for measuring the CI is not the soil surface but is at a depth where there was no soil displacement (on the bottom of the RD, in the centre lines of the tyre tracks (Söhne, 1958). The CI without tractor traffic increased with soil depth because lateral stress on the penetrometer cone increases with increasing depth and more force is needed for the cone to displace the soil. Resistance can also increase with depth because of changes in soil texture, gravel content, structure and agricultural traffic. Without traffic, there is an increase between 200 and 600 mm, probably as a result of differences in clay content (Table 1).

The CI differed for the topsoil (0–200 mm) for each type of tractor after five passes (Figure 1). The CI was greatest for light tractors (LTs) because the tyre/soil pressure contact (ground pressure) was greater than under the heavier

tractors. Results from the Standard Proctor (1933) compaction tests (Table 1) show a maximum bulk density of 1.45 Mg/m^3 at 20.1% soil water content for soil in the 0–180 mm depth range. Tractor passes were made at this soil water content (Table 1) and caused significant compaction.

The results on the behaviour of soil in the freshly tilled horizon as a result of traffic passes agree with those of Smith & Dickson (1990) and Botta *et al.* (2002, 2008) and thus confirm the direct relationship between topsoil compaction and ground pressure. In addition, under similar traffic conditions but with drier soil, narrower tyres cause more soil compaction than wider tyres because for the same number of passes according to Greene & Stuart (1985), narrower tyres produce higher pressure on soil because the tyre/soil contact area is smaller than with wider tyres to thus cause greater compaction. The light (LT) tractor had narrower tyres than the medium (MT) and heavy (HT) ones (Table 2), and, despite being lighter, caused greater pressure on the soil. However, all three tractors increased the CI in the topsoil.

Rut depth results at the centre line of the track for all tractors are shown in Figure 2. No significant ($P < 0.01$) differences were found in the RDs between medium and LTs when they passed one, three, five or seven times, but when the heavy tractor (HT) passed seven times (H7: 125-mm RD), it was significantly deeper, indicating that compaction was more concentrated and severe in the topsoil. However, the influence of RD on subsoil compaction is not clear. Up to the fifth pass, shallower RDs and lower CI were produced by the HT because the ground pressure from this tractor is less than from the light and medium ones. After five passes, tractor weight has a greater influence on RD than number of passes.

In all treatments, tractor traffic caused variable decreases in HC in the 0–600 mm depth range (Figure 3a–c). After five and seven passes by the LT, MT and HT, HC decreased significantly, probably due to decreased pore volume, aggregate collapse and formation of smaller interaggregate pores with unaccommodating faces (Pagliai & Vignozzi, 2002).

The results show that tractor weight and traffic frequency have a significant effect on topsoil and subsoil compaction. HC down to 600 mm was altered depending on weight and frequency of tractor traffic. The results for the topsoil (Figure 4a) show a strong positive relationship between number of tractor passes and the CI, and the HT caused higher CI values than from the light and medium tractors. It is important to note that HT caused higher CI values in subsoil (Figure 4b) than the topsoil (Figure 4a).

Discussion

Botta *et al.* (2002) report that the effect of traffic was to increase compaction in deeper layers (200–600 mm). In our study, at the 200–600 mm depth (Figure 4b), there is a

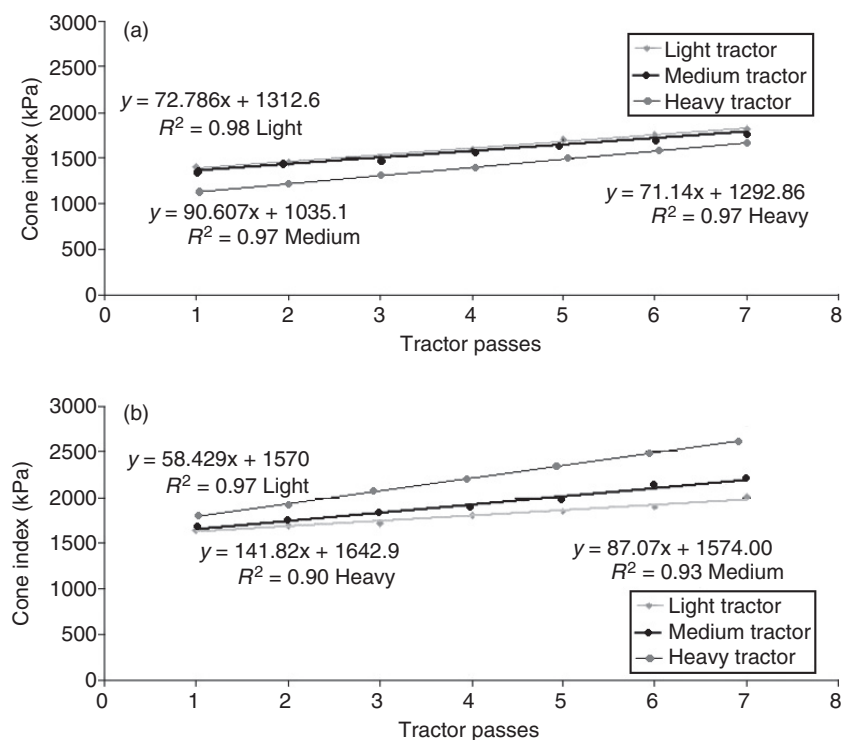


Figure 4 Relationships between the cone index and tractor passes for (a): 0–200 mm (topsoil), (b) 200–600 mm (subsoil).

strong positive relationship between the number of tractor passes and the CI, and the HT caused a higher CI than the light and medium ones. From this can be inferred that below 200 mm, the tractor load was responsible for subsoil compaction as also demonstrated by Håkansson & Reeder (1994). Hence, our data support the hypothesis that tractors as used in olive groves in Almería cause subsoil compaction. Induced soil compaction in this layer is cumulative, and no conventional tillage is performed below 250 mm. Only deep subsoiling can solve this problem. The maximum subsoiling depth which can be attained by conventional equipment is ca. 600 mm and requires not only high-powered tractors but also incurs substantial costs for fuel and labour.

It is important to note that from the fifth pass, the surface CI values did not respond to the ground pressure (Table 2), but were affected by the total tractor load. Our explanation for this is that after five tractor passes over the soil, the load destroys soil porosity causing its collapse. According to Raghavan & McKyes (1979) and Ljungars (1977), this is dependent upon the number of passes. According to Botta *et al.* (2004), seven tractor passes produce the highest CI. The CI data show that compaction by tractor traffic caused topsoil and subsoil properties to change considerably. These results are similar to those of Håkansson (1987), who demonstrated that the lasting effects of compaction under high axle loads are due to soil type, number of passes and number of years since compaction.

Muelqueen *et al.* (1977) conclude that the penetrometer is useful and fast for measuring compaction, but has

limitations. They point out that where the moisture content, apparent density, shear strength and structural condition vary markedly with depth, interpretation of penetrometer data is subject to much ambiguity because of differences between measured CI values and actual soil properties. Muelqueen *et al.* (1977) found that when the soil water content is low as was the case in our study (17.05%), compression underneath and around the penetrometer cone may be more important and the force of penetration is very dependent on soil density, so that measurements do not reflect the original soil properties. The trend in angle of internal friction is that as moisture content decreases, soil resistance rises. This is why the CI values as reported in this study show that soil compaction from tractor traffic could be less damaging for plant and tree roots than would appear from the measurements. In our study, the water content data were applied to the whole soil profile and were very similar in the topsoil and subsoil, which gives us confidence that the CI measurements are realistic.

Conclusion

Our study has shown that one pass of the FWA (front-wheel-assist) and 4WD tractors was sufficient to increase the CI in the topsoil layer (0–200 mm). Increases in subsoil CI (200–600) were slightly lower than in the shallower layer, but soil compaction in the subsoil tended to be more cumulative than in the topsoil, and mechanical loosening to alleviate

this compaction is extremely difficult. When the LT (22.5 kN) passed five and seven times, there were significant increases in the CI throughout the soil profile to a depth of 600 mm. HC was affected after five and seven passes of LT, MT and HT.

The results from this study show that in terms of soil management, farmers should minimize traffic on productive land and use lightweight tractors that exert less pressure on the tyre/soil contact area. It is this pressure that causes surface soil compaction. HTs also cause subsurface soil compaction, which can result in permanent cumulative effects that cannot easily be solved. In addition, olive groves in Almería on slopes up to 30% are highly susceptible to soil erosion and the ruts formed by machinery can further increase runoff. Soil compaction is a problem, which must be tackled before this land degradation issue becomes more difficult and expensive to solve.

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References

- Ankeny, D., Ahmed, M., Kaspar, T. & Horton, R. 1991. Simple field method for determining unsaturated hydraulic conductivity. *Soil Science Society of America Journal*, **55**, 467–470.
- ASAE Standard. 1992a. *Terminology and definitions for soils tillage and soil tool relationships engineering practice*, EP291, vol. 2. American Society of Agricultural Engineering, St. Joseph, MI, USA, 611 pp.
- ASAE Standards. 1992b. *Soil cone penetrometer S 313.2*. American Society of Agricultural Engineering, St. Joseph, MI, USA, 611 pp.
- Berisso, F. E., Keller, T., Lamandé, M., Iversen, B.V., Etana, A., Simojoki, A., Alakukku, I., Arvidsson, J., Forkman, J. & Schjønning, P. 2012. Persistence of subsoil compaction and its effects on pore characteristics and gas transport. In: *NJF Seminar 448 Soil compaction effects on soil functions and strategies for prevention*, vol. 8, No. 1, pp. 55–58. Helsinki, Finland.
- Botta, G. 2000. *Subsoil compaction distribution induced by agricultural traffic*. PhD Thesis. Luján University, Argentina, 230 p.
- 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. *Journal of Terramechanics*, **39**, 47–54.
- Botta, G., Jorajuria, D., Balbuena, R. & Rosatto, H. 2004. Mechanical and cropping behavior of direct drilled soil under different traffic intensities: effect on soybean (*Glycine max* L.) yields. *Soil & Tillage Research*, **78**, 53–58.
- 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 & Tillage Research*, **101**, 44–51.
- Botta, G. F., Tolón Becera, A., Vázquez, J., Balbuena, R. & Stadler, S. 2012. Soil compaction distribution under land clearing in calden (*Prosopis caldenia* Burkart) forest in Argentinean pampas. *Soil & Tillage Research*, **119**, 70–75.
- 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.
- FAO. 2008. Agricultural statistics. Available at: <http://faostat.fao.org>; accessed 01/22/2008.
- Gómez, J., Guzmán, M.G., Giradles, J.V. & Federes, E. 2009. The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. *Soil & Tillage Research*, **106**, 137–144.
- Greene, W.D. & Stuart, W.D. 1985. Skidder and tyre size effects on soil compaction. *Southern Journal of Applied Forestry*, **9**, 154–157.
- Häkansson, I. 1987. Long term effects of modern technology on productivity of arable land. *K. Skogs-o. Lantbr. Akad. Tidskr.*, **126**, 35–40.
- Häkansson, I. & Reeder, R.C. 1994. Subsoil compaction by vehicles with high axle load extent, persistence and crop response. *Soil & Tillage Research*, **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 Horticulture 451: VI International Symposium on Integrated Canopy, Rootstock, Environmental Physiology in Orchard Systems*.
- Keller, T. & Lamandé, M. 2012. From soil stress to soil deformation: current state of the research. In: *NJF Seminar 448 Soil compaction effects on soil functions and strategies for prevention*, vol. 8, No. 1, pp. 19–22. Helsinki, Finland.
- Lamandé, M., Berisso, F., Alakukku, L., Wildenschild, D. & Schjønning, P. 2012. Subsoil compaction of a clay soil persists three decades after heavy wheel traffic. In: *NJF Seminar 448 Soil compaction effects on soil functions and strategies for prevention*, vol. 8, No. 1, pp. 49–52. Helsinki, Finland.
- Ljungars, A. 1977. *Olika faktorers betydelse för tractorernas jordpackningsverkan*. Mätningar Agricultural College Sweden Department of Soil Science, Uppsala, Sweden.
- Muelqueen, J., Stafford, V. & Tanner, D. W. 1977. Evaluation of penetrometers for measuring soil strength. *Journal of Terramechanics*, **14**, 137–151.
- Núñez-Moreno, J.H. & Valdez-Gascon, B. 1994. Effect of Soil Conditions on Orange Trees. *Communications in Soil Science and Plant Analysis*, **25**, 1747–1753.
- Pagliai, M. & Vignozzi, N. 2002. Soil pore system as an indicator of soil quality. In: *Sustainable land management environmental protection a soil physical approach. Advances in geoecology*, vol. 35 (eds M. Pagliai & R. Jones), pp. 71–82. Catena Verlag, Reiskirchen.
- Proctor, R., 1933. *Fundamental principles of soil compaction*. Engineering News Record, pp. 245–248, 286–289, 348–351. McGraw Hills Companies Inc., New York, NY, USA.
- Raghavan, G. & McKyes, V. 1979. Vehicle compaction for agricultural tyres. *Transactions of the ASAE*, **202**, 218–220.
- Smith, D. & Dickson, J.W. 1990. Contributions of vehicle weight and ground pressure to soil compaction. *Journal of Agricultural Engineering Research*, **46**, 13–29.

- Söhne, W. 1958. Fundamentals of pressure distribution and soil compaction under tractors tyres. *Agricultural engineering*, **39**, 276–281.
- Soil Conservation Service. 1994. *Keys to soil taxonomy*, 6th edn. Soil Survey Staff USDA, Washington, DC.
- Taylor, H.M., Roberson, G.M. & Parker, J.J. 1966. Soil strength–root penetration relations for medium coarse-textured soil materials. *Soil Science*, **102**, 18–22.
- Threadgill, E. 1982. Residual tillage effects as determined by cone index. *Transactions of the ASAE*, **25**, 859–863, 867.
- Tolón-Becerra, A., Botta, G.F., Lastra-Bravo, X., Tourn, M., Bellora-Melcon, F., Vázquez, J., Rivero, D., Linares, P. & Nardon, G. 2010. Soil compaction distribution under tractor traffic in almond (*Prunus amygdalus* L.) orchard in Almería, España. *Soil & Tillage Research*, **107**, 49–58.