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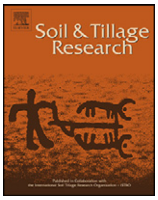

Soil compaction distribution under land clearing in calden (*Prosopis Caldenia Burkart*) forest in Argentinean pampas

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ABSTRACT

Although the virgin soil has a high organic matter content that reduces the soil's susceptibility to compaction, the high weight of the tractors used for land clearing cause a high degree of soil compaction. This study was performed in the Calden (*Prosopis Caldenia Burkart*) forest at La Pampa State, in West Argentina. The object of this study was to assess the soil compaction during mechanical land clearing with heavy machinery. Variables measured were (CI) cone index, (BD) dry bulk density, tractor rut depth (TRD) and Proctor test. The land clearing was performed with a Caterpillar tractor D6, with 0.7 × 2.3 m metallic tracks. The engine power was 300 kW and the weight was 18 Mg. The relevant results were as follows: in topsoil (0–0.2 m) 1 and 2 passes of a tractor caused mean CI values of 1833 and 2437 kPa, respectively. Dry bulk density mean values had a similar behaviour to those of CI, measuring 1.75 and 1.85 Mg m^{-3} for 1 and 2 passes, respectively. In the subsoil (0.2–0.9 m), two tractor passes caused higher CI and BD values than one tractor pass: CI mean values were between 1991 and 2439 kPa for one and two tractor passes, respectively. Dry bulk density mean values were between 1.81 and 1.89 Mg m^{-3} for 1 and 2 passes, respectively. Significant differences were found in TRD when the tractor passed one or two times, measuring 0.092 m TRD for one tractor pass and 0.111 m for two tractor passes. The main conclusions of this study are as follow: the level of soil compactability increases as the maximum BD attains a higher level and at a lower water content level. When soil with a moisture content level over the critical water content is compressed (for example, by one tractor pass with 18 Mg total load) it reaches saturation, and the compaction stress travels deeper in the soil than when the soil is drier. Then if the use of heavy machinery cannot be avoided, special attention should be given to traffic at a water content which the soil do not attain saturation by compression. Compared with most agricultural practices the high weight of the land clearing machinery generate greater compaction stresses in the soil, raising the maximum BD that develops at lower water content and subsequently reducing the work opportunities.

1. Introduction and literature review

The Calden (*Prosopis caldenia, Burkart*) forest is the typical wooded formation of the Argentinean central semiarid temperate region. In the last years, the Calden forest has been affected by land clearing, consisting of the total or partial removal of arboreal and shrubby vegetation that covers the soil to grow annual crops or create pastures.

Land clearing can be manual, chemical o mechanical. Mechanical clearing is the usual method due to the cost and time demanded by the other methods, but mechanical clearing depends on heavy machinery that compact the soil. Soil compaction is the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the BD (Soil Science Society of America, 1996). Soil compaction has been reported at soil depths of 0.7 m, after mechanical land clearing operations (Alegre et al., 1991). The compaction produced by mechanical land clearing can negatively affect the crop yields. Raghavan et al. (1977) recommend not exceeding 1.05 Mg m^3 BD to avoid yield decreases. Compaction of sandy soil to a BD of 1.35–1.6 g cm^{-3} caused an 87% decrease in the dry weight of roots of radiata pine seedlings (Sands and Bowen, 1978). Carter (1990), state that the maximum crop yields were attained at 80–90% of the maximum BD, with yield losses occurring at higher maximum BD values. Botta et al. (2006a), found that the sunflower yield (*Helianthus annus* L.), increases 24.5 and 12.8%

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after reducing the soil penetration resistance from 1.7 to 0.7 MPa, by passing a subsoiler at a depth of 0.280 m. Jorajuria et al. (1997) cited by Botta et al. (2006b) recommends not compacting the soil over a 1.5 MPa penetration resistance to avoid restricted root growth.

There are many soil factors that determine compactibility, but the water content is the only trait that can be managed to reduce soil compaction in the short term. The dependence of resistance of agricultural soils to compaction on soil water content were defined with the Proctor test, a widely accepted procedure to study compactibility of disturbed soils over a range of soil water contents under a standardised dynamic load (Aragón et al., 2000).

In the Proctor test, the BD is a function of soil water content, and it is used to determine the water content at which maximum BD, known as the optimum water content, occurs; in agriculture this is called ‘‘critical water content’’ because soil compaction is undesirable (Etana et al., 1997; Mapfumo and Chanasyk, 1998). The function described does not constitute a single characteristic curve for a given soil type, but a family of curves for different compaction efforts. For a greater compaction force, the curve is shifted upward and leftward, indicating higher attainable ‘‘maximum BD’’ at lower values of ‘‘critical moisture’’ (Hillel, 1998).

The Proctor's maximum BD used to be between 1.17 and 1.74 Mg m^{-3} and the critical water content between 15.0 and 43.1% (Aragón et al., 2000). Botta et al. (2004), found that Proctor's maximum BD was 1.5 Mg m^{-3} and the critical water content was 23.5%, in a direct drilled soil in the western part of the Rolling Pampas Region. However virgin soils with higher organic matter content were less susceptible to compaction: they reached lower ‘‘maximum BD’’ values at higher water levels than soils under cultivation or rotation. Quiroga et al. (1999) assessed 10 virgin soils in the Calden forest and found a mean maximum BD of 1.31 g/cm^3, attained at less than 70% degree of saturation and the critical water content 23.5%.

The critical water content defines dry and wet zones with different compaction patterns. When a soil is compacted at a lower than the critical water content it does not attain saturation during the compaction process and the stresses propagate on the particle scale only (i.e. through the solid particles and the network of interparticle contacts and not through the voids between them). The stress applied to the soil surface will induce particle movement to form a more compacted particle arrangement than before. The stress decrease with the soil depth and if the stress at a certain depth has become smaller than any previous stress acting on that soil element, there should not be any change in density of that element (Boussinesq, 1885; Fröhlich, 1934; Söhne, 1958, cited by Hadas, 1994). If the soil is compacted at a lesser water content than the critical value, it could be expected that the BD will decrease with depth following compression due to traffic.

In the case where the soil water content is greater than critical water content, the soil attains saturation during the compaction process. Saturated soil with the pores full of water cannot be compressed; then, the soil transfer the full compressive stress applied to the soil surface to deeper layers, acting as a hydraulic ram (Hadas, 1994). Soil compaction becomes more persistent the deeper it penetrates and causes persistent crop yield reductions (Håkansson and Reeder, 1994). It could be expected that the BD after the compaction in the layer acting like a ‘‘hydraulic ram’’ attains values of a saturated soil like in the wet side of the Proctor's curve.

The descending portions of the compaction curves tend to converge on a common line representing a degree of saturation of about 85–90% (Hillel, 1998), while the mean slope of the ascending part of the proctor curve expresses susceptibility to compaction (Quiroga et al., 1999).

Compaction curves differ when soil in cylindrical moulds is subjected to different numbers of blows by a standard proctor hammer. These curves correspond to compaction levels generated by tractors of different weights (Adekalu et al., 2007); thus, soil compressed by a heavier tractor will have a lower critical water content and will attain saturation under at a lower water content when under traffic.

The object of this study was to assess the soil compaction during mechanical land clearing with heavy machinery.

2. Materials and methods

2.1. The site

The study was performed in a Calden forest in La Pampa State, Argentina at 38°28′S, 65°20′W; altitude 290 m above sea level. The soil was an Entic Haplustoll (Soil Conservation Service, 1994). Typical profile characteristics are shown in Table 1. The area experiences a great water deficit from November to March (Fig. 1).

The land clearing was performed with a Caterpillar® tractor D6, with 0.7 m × 2.3 m metallic tracks. The engine power was 300 kW and the weight was 18 Mg (Fig. 2). This type of tractor is the usual for land clearing in Argentina and in many other parts of the world (Toledo and Morales, 1979; Alegre et al., 1989).

The tractor moved forward clearing; when it was stopped due to the resistance of the forest it moved back a few meters and then went over the forest again.

2.2. Experimental treatments and layout

There were two traffic treatments, one pass (when the tractor went forward) and two passes (when the tractor also went back). A control plot without traffic completes the experimental layout. The measurement points were taken completely randomized blocks, and five replications were performed.

An analysis of variance (ANOVA) was performed, and Tukey's test was used to analyse means ($P < 0.05$).

2.3. Assessed parameters

Maximum BD and critical water content (W) were determined according to the standard Proctor method (ASTM, 1992). Samples of air-dried and sieved (<2 mm) soil were taken from the soil top layer. After wetting in a 947 cm^3 cylinder, the soil sample was compacted, in three equal layers, by 25 compressions per layer using a mass of 2.5 kg from a height of 30.5 cm; this represents a compaction energy of 590 kJ m^{-3}. The weight of the wet compacted soil in the chamber was determined. Then, the samples were dried in an oven at 105 °C for 24 h and weighed again to estimate the water content and dry bulk density. The depth ranges were: 0–0.15, 0.15–0.30, 0.30–0.45, 0.45–0.60, 0.60–0.75 and 0.75–0.90 m.

Dry bulk density was measured with stainless steel soil cores according to Blake (1965), at the centre line of the tractor track

Table 1
Maximum BD (Mg m^{-3}) and critical water content values measured at six depth ranges.

Depth (m)	Maximum bulk density	Critical water content (%)
0–0.15	1.33	19.0
0.15–0.30	1.48	17.8
0.30–0.45	1.49	17.5
0.45–0.60	1.55	16.9
0.60–0.75	1.58	16.5
0.75–0.90	1.58	16.3

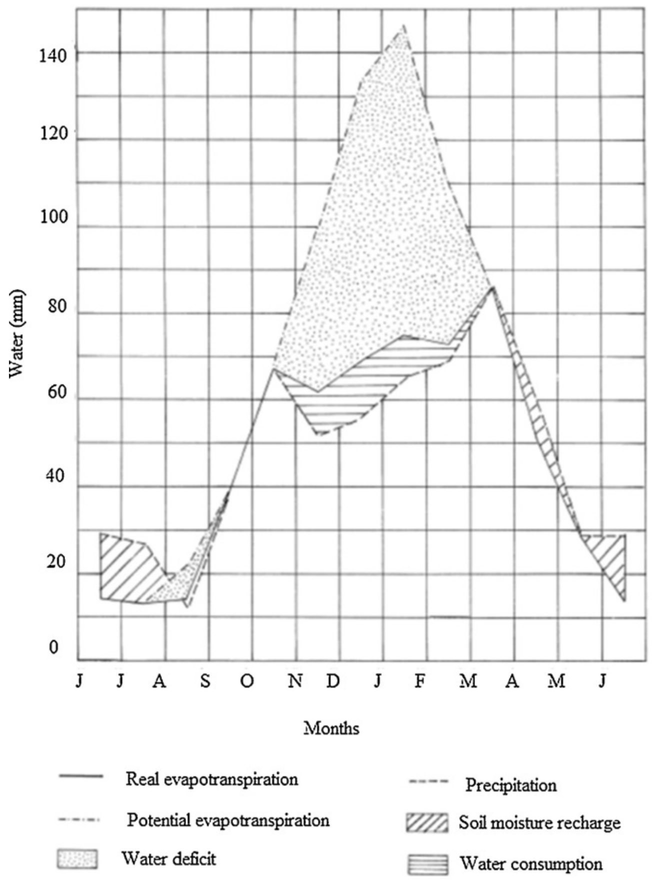

Fig. 1. Monthly water balance of the trial area.

according to the methodology proposed by Botta (2000). The depth ranges were: 0–0.15, 0.15–0.30, 0.30–0.45, 0.45–0.60, 0.60–0.75 and 0.75–0.90 m.

Gravimetric soil water content (w) was obtained from the same soil cores used to evaluate BD, at the same six depth ranges listed above.

To plot the saturation curve over the compaction curve in Fig. 4, the following equation was used (s is the degree of saturation):

$$\mathrm{BD} = \frac{1}{[0.377 + (w/s)]}\ (\mathrm{Mg\ m^{-3}})$$

Fig. 2. Crawler tractor used for land clearing.

Penetration resistance was determined with a Scout 900 recording penetrometer S 313 (ASAE Standards S 313.2, 1993). Each datum is the average of 25 samples for each plot in the depth range 0–0.90 m taken at intervals of 0.025 m. Dry bulk density and cone index were randomized measured on all the plots.

Tractor rut depth (TRD) was measured using a profile meter consisting of a set of vertical metals rods (length 0.5 m and diameter 0.5 m), sliding through holes spaced at horizontal intervals of 0.025 m in a 1-m iron bar. The bar was placed across the wheel traces perpendicular to the direction of travel, and rods were positioned to conform to the shape of the depression. TRD was calculated as the average depth of 60 reads on the 1-m bar.

3. Results and discussion

Soil water content (w/w) during traffic treatments averaged 16% dry weight from 0 to 0.15 m deep, 14.5% between 0.15 and 0.30 m deep, 13.8% between 0.30 and 0.45 m deep, 13.4% between 0.45 and 0.60 m deep, 13.1% between 0.60 and 0.75 m deep and 12.7% between 0.75 and 0.90 m. In general, there were no significant differences in soil water content between treatments when penetrometer resistance (or cone index) was measured, and correction or allowance for resistance (or cone index) was not considered necessary.

Maximum BD was 1.33 $\mathrm{Mg\,m^{-3}}$ at the 0–0.15 m layer and increase in deeper layers to 1.58 $\mathrm{Mg\,m^{-3}}$ at 0.75–0.90 m layer (Table 1). Critical water content was 19% at the 0–0.15 m layer and decrease in deeper layers to 16.3% (Table 1). These values were in the expected range of 1.17–1.74 $\mathrm{Mg\,m^{-3}}$ of maximum BD and 15.0–43.1% of critical water content, described by Aragón et al. (2000).

Because the soil susceptibility to compaction is related to the mean slope of the ascending part of the proctor curve, there must be considered that the upper part of the ascending portion of the curve, corresponding to the maximum BD, hence increases as the slope increase as the last increase too. Therefore, a low value of maximum BD like those determined at the 0–0.15 m soil layer indicates low susceptibility to compaction. This low susceptibility to compaction must be related to the higher organic matter content of virgin soils (Table 2). The soil susceptibility to compaction increase at deeper layers (Table 1).

The maximum BD was attained with a degree of saturation below 70%. These data agree with those of Quiroga (1999) and contrast with the observation that the peak of BD used to be at 80% saturation (Hillel, 1998). The fact that the virgin soils reach the maximum BD at a lower degree of saturation seems to be due to the higher organic matter content resulting in more air remaining trapped in the soil.

Dry bulk density and cone index (Tables 3 and 4) of soil exposed to traffic were always greater than the control plot (without traffic).

Table 3 shows the BD of the soil before the land clearing. These values were very high for soil that was never compressed by traffic. However, Rohand et al. (2004) stated that water suction during dry periods may have consolidated the soil to a higher degree than the compaction process caused by heavy agricultural traffic. In corroboration, Fig. 1 shows there was a severe water deficit in the summer around the trial area.

Despite of the high BD values before traffic, the BD increased at six depths assessed after the tractor's first pass, as shown in Table 3. After the second pass the BD increased again. The BD values exceeded the Proctor's maximum bulk density at each depth. To achieve this degree of compaction, the tractor had to apply a surface contact stress greater than the proctor's applied stress, corresponding to higher compaction curve. Furthermore, the soil reached 80–90% degree of saturation after the traffic. In the soil

Table 2
Typical soil profile.

Horizons	Ap	A	AC	C
Deep range (m)	0–0.12	0.15–0.30	0.35–0.65	0.71–1.20
Organic carbon (g kg^{-1})	12.3 ± 3.20	6.7 ± 2.00	5 ± 1.76	3 ± 1.90
Total nitrogen (g kg^{-1})	1.5 ± 0.04	0.8 ± 0.01	0.7 ± 0.00	0.3 ± 0.01
C/N ratio	8	8	7	5
Clay (<2 μm) (g kg^{-1})	161 ± 3.24	284 ± 2.45	184 ± 2.76	63 ± 3.1
Silt (2–20 μm) (g kg^{-1})	98 ± 4.1	63 ± 3.21	76 ± 3.56	99 ± 3.8
Silt (2–50 μm) (g kg^{-1})	176 ± 4.32	144 ± 4.0	131 ± 3.8	206 ± 2.7
Very fine sand (74–100 μm) (g kg^{-1})	402 ± 3.57	302 ± 3.01	398 ± 2.76	367 ± 2.21
Fine sand (100–250 μm) (g kg^{-1})	159 ± 1.4	201 ± 1.21	207 ± 0.98	261 ± 0.91
Medium sand (250–500 μm) (g kg^{-1})	4 ± 0.22	6 ± 0.98	4 ± 0.01	4 ± 0.10
pH in H$_2$O (1.2.5)	6.4 ± 0.01	6.6 ± 0.01	6.9 ± 0.02	6.9 ± 0.02

compaction curve for the stress applied by the tractor, these values only can belong to descending part of the compaction curve, because in the ascending part of the curve, the soil do not attain saturation. The maximum BD for the tractor's compaction curve must be at a lower water content than the Proctor's maximum bulk density, letting the soil water content of the trial site reside in the wet side of the curve.

Fig. 3 shows that the soil layer assessed after traffic (0–0.90 m) attained the degree of saturation that corresponds to the hydraulic ram effect. With the soil saturated, the applied surface stress would not decrease with increasing depth as previously stated by Boussinesq (1885), Fröhlich (1934) and Söhne (1958), as cited by Hadas (1994); the full compressive stress applied at the soil's surface would be transferred to a deeper layer (Hadas, 1994). The BD values (Table 3) do not decrease, but increase lightly with increasing depth through the six layers assessed (0–0.90 m). From the BD curve like function of water content, it was stated that in the wet side of the curve the soil cannot overcome the BD at which saturation occurs, and the last one depend on the soil water content. The increase in BD values with soil depth agree with the small reduction in soil water content from soil the surface, resulting in a small increase in the BD at which the soil attains saturation (Fig. 3). Therefore, it could be expected that in a soil under a load, with water content over the critical value, the BD will increase or decrease with depth depending upon the water content at each depth. As the soil can act as hydraulic ram (Hadas, 1994), it is expected that the full compressive stress applied to the soil surface was transferred under the 0.90 m soil layer, where the soil suffer a higher degree of compaction.

To avoid soil compaction at deeper layers during mechanical land clearing with heavy machinery, the soil must be compressed by traffic when the water content is lower than the critical value; this will avoid the soil reaching saturation during the traffic generated hydraulic ram effect. Due to the high weight of the land clearing tractor, it is expected that the corresponding critical water content was lower than the Proctor's content. Consequently, the advisable soil water range for traffic with these heavy land clearing tractors is lower than the soil water range below Proctor's critical water content.

Table 3
Dry bulk density mean values (Mg m^{-3}) measured for three treatments at six depth ranges.

Depth (m)	Control plot	1 pass	2 passes
0–0.15	1.63 a	1.72 b	1.84 c
0.15–0.30	1.67 a	1.78 b	1.87 c
0.30–0.45	1.72 a	1.80 b	1.89 c
0.45–0.60	1.76 a	1.82 a	1.89 a
0.60–0.75	1.80 a	1.83 a	1.89 a
0.75–0.90	1.80 a	1.82 a	1.89 a

Different letters in horizontal direction show significant differences ($P < 0.05$ Tukey).

All the BD values after traffic were greater than the quoted values described by Raghavan et al. (1977), Sands and Bowen (1978) and Czyz (2004) and recommended to avoid yield decreases. Furthermore, Carter (1990) stated that crops give their maximum yield at a BD of 80–90% of the Proctor maximum BD; the soil BD following land clearing was 42% greater. Therefore, it could be expected important yield losses after land clearing. However, it could be predicted a lower degree of damage will occur if the soil has been compressed at a water content lower than the critical value.

Cone index data collected after exposure to traffic gave a clear indication of the initial soil condition in each treatment. Table 4 (statistical analysis between treatments) shows that CI on the control plots was greater than the 1100 kPa (0 m) cone index quoted by Soza et al. (2003) as critical for normal seed emergence

Table 4
Cone index values (kPa), for all treatments, measured after traffic.

Depth (m)	Control plot	1 pass	2 passes
0	675 a	1003 b	2251 c
0.025	1135 a	1246 b	2427 c
0.050	1380 a	1563 b	2455 c
0.075	1487 a	1834 b	2500 c
0.100	1630 a	1962 b	2392 c
0.125	1747 a	2215 b	2452 c
0.150	1776 a	2308 b	2428 c
0.175	1788 a	2216 b	2401 c
0.200	1681 a	2156 b	2640 c
0.225	1636 a	2009 b	2558 c
0.250	1583 a	2018 b	2790 c
0.275	1540 a	1939 b	2865 c
0.300	1329 a	1926 b	2961 c
0.325	1352 a	1914 b	3069 c
0.350	1314 a	1949 b	3186 c
0.375	1463 a	1991 b	3322 c
0.400	1530 a	1995 b	3339 c
0.425	1682 a	1945 b	3284 c
0.450	1759 a	1919 b	3330 c
0.475	1829 a	1923 b	3289 c
0.500	1909 a	1932 b	3312 c
0.525	1989 a	1948 a	3282 b
0.550	2033 a	2033 a	3271 b
0.575	2147 a	2129 a	3115 b
0.600	2309 a	2214 a	3128 b
0.625	2303 a	2356 a	3066 b
0.650	2317 a	2378 a	3036 b
0.675	2341 a	2363 a	3027 b
0.700	2473 a	2478 a	2893 b
0.725	2553 a	2591 a	2824 b
0.750	2649 a	2679 a	2835 b
0.775	2835 a	2752 a	2814 a
0.800	2915 a	2881 a	2859 a
0.825	2922 a	2938 a	3007 a
0.850	3002 a	3016 a	3037 a
0.875	2996 a	3004 a	3068 a
0.900	3081 a	3089 a	3148 a

Values with different letters (horizontally) are significantly different at each depth ($P < 0.05$ Tukey's test).

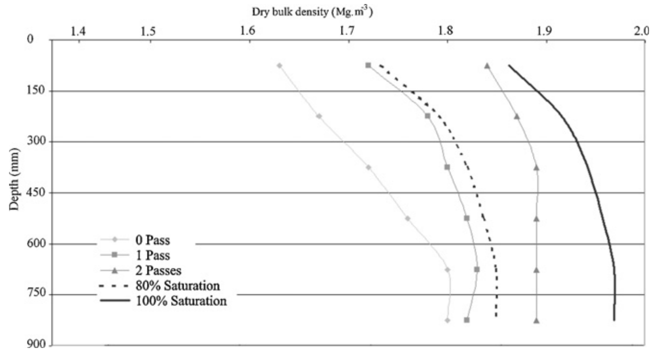

Fig. 3. Dry bulk density values for diferent treatments and two degrees of saturation at different depths.

Table 5
Tractor rut depth values (m) measured after one pass and two passes of the Crawler tractor.

1 pass	0.092 a
2 passes	0.111 b

Different letters in vertical direction, show significant differences ($P < 0.05$ Tukey).

of wheat in fine textured soils. At 0.75 m depth, cone resistance was again higher than the 1500 kPa limit mentioned by Jorajuria et al. (1997) to avoid restricted root growth. Cone index without tractor traffic increased with soil depth.

According to Botta et al. (2006a), a CI increase with increasing soil depth was expected because some resistance depends on the weight of soil above the point of measurement. 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 the cone index greatly increased between 0.50 and 0.90 m depth; the maximum CI was 2190 kPa recorded at 0.90 m depth. An additional effect of traffic at this depth was seen in the 1 and 2 tractor passes where the cone index was greater than the control.

In Table 4 the effect of a 1 pass and 2 passes are seen most obvious compared with the control plot. Results show that the depth range where CI was significantly different with respect to the control plot was different. After one tractor pass CI values were significantly different ($P < 0.01$) up to 0.50 m soil depth while CI values after two tractor passes were significantly different ($P < 0.01$) up to 0.75 m soil depth. Soil compaction in the subsoil tends to be cumulative, because conventional tillage is seldom carried out at that depth. Subsoiling operations are the only mechanical means capable of solving this problem. In spite of the fact that the maximum subsoiling depth attainable by conventional equipment is about 0.60 m, we agree with 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.

Finally, averages of TRD are shown in Table 5. TRD increased with tractor traffic frequency. The soil surface was the layer most vulnerable to both compression and displacement from the passage of tractors. The greatest TRD and significant differences ($P < 0.01$) were found when the tractor passed 1 and 2 times.

These findings for the use heavy machinery for land clearing could be extended to the use of other heavy machinery like forestry machinery, slurry tankers, grain and beet harvesters or construction machinery in agricultural land.

4. Conclusions

The maximum BD and critical water content can be used as an indicator of susceptibility to compaction. During the land clearing the virgin soils, with high organic matter content, have less susceptibility to compaction. Furthermore, critical water content limits the soil water ranges that produce different compaction patterns.

It is know that when the soil attain saturation by compression during the traffic, it act like a hydraulic ram, compacting deeper soil layers. But the soil attains saturation over the critical water content which depends on the tractor weight and it is lower than the Proctor's critical water content for heavy machinery. Then if the use of heavy machinery cannot be avoided, special attention should be given to traffic at a water content which the soil do not attain saturation by compression.

The results of this study indicated that one pass of equipment for land clearing operation (here a crawler tractor with 18 Mg total load) produced an increase on BD and CI in topsoil (0–0.20 m) and subsoil layers (0.20–0.90 m).

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