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Soil Compaction Due to Sugarcane (*Saccharum officinarum*) Mechanical Harvesting and the Effects of Subsoiling on the Improvement of Soil Physical Properties

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Abstract: The main purpose of this study was to shed light on the soil behaviour from compaction point of view before and after harvesting traffic and on the reaction to the subsoiling operation. In this regard two different experiments were conducted and to provide an alternative tool for this evaluation, High Resolution Computed Tomography (HRCT-Scan) was also used. The results showed positive correlation of clay with maximum dry bulk density, but it was found that sand and silt were more positively correlated with optimum moisture content than clay. These results indicated that in this region, the soils are most susceptible to compaction and harvesting traffic make them compacted. The maximum compaction occurred in the first layer (0-20 cm depth) and minimum or no compaction happened in the layer, beyond the 60 cm depth. These results also showed that subsoiling the soil can improve the soil physical properties. Furthermore, CT-Scan results indicated that compaction can be treated by subsoiling and soil physical properties can be improved. This type of managing soil compaction has been used in the field and high harvested sugarcane (*Saccharum officinarum*) yield indicates that it is a successful operation.

Key words: Bulk density, proctor, HRCT-Scan, subsoiling, sugarcane

INTRODUCTION

In the Khuzestan province of Iran, sugarcane (*Saccharum officinarum*) cultivation started with the establishment of Haft Tappeh Sugarcane Project in 12000 hectares in 1958. Development of sugarcane cultivation in this province was continued by the establishment of Karoon Project in 26000 hectares in 1973. The cultivation methods in these two projects were similar and developed by Hawaii Agricultural Experiment Station based on the experimental works in the field as explained by Sund and Clements (1974). Under this current cane growing system, there is a mis-match between crop row spacing (1.5 m) and track width of the harvesting equipment (1.83 m). Therefore, some traffic occurs very close to the row and occasionally directly over the row, resulting in yield decline in the next years crop. A problem, similar to this, has been described by Braunack *et al.* (2006). Furthermore, due to attention to using fully mechanized cultivation in the new sugarcane development projects, this method of cultivation has been rejected in about 84000 hectares and a new method has been developed and used since 1984. This new method of cultivation is fully mechanized. However, it is well known that in mechanized agriculture, soil compaction also reduces crop yields (Lindstrom and Voorhees, 1994). Therefore, it was necessary that a system of cultivation with minimum soil compaction be developed. In the new cultivation method, sugarcane is planted in two rows inside the furrows spaced at 1.83 m. The space between the two rows in each furrow is 0.50 m. When the sugarcane stalk height reaches about 0.5 m, the furrow is replaced with the hill. As a result, sugarcane growth zone is on the hill and inside the furrow specialized for irrigation and the necessary traffic (Fig. 1). In such conditions, the space has been divided in two parts, one for minimum tillage and the other for traffic compaction. Many industries have already recognized this and have adopted a system of controlled traffic whereby crop growth zones and traffic zones are physically separated (Mullins *et al.*, 1977; Williford, 1985; Lamers *et al.*, 1986; Gerik *et al.*, 1987; Wesley and Smith, 1991). This kind of plant configuration was first used in Queensland of Australia and the results also indicated that the development of a controlled traffic system is practical and would not result in yield loss (Robotham *et al.*, 2005). The

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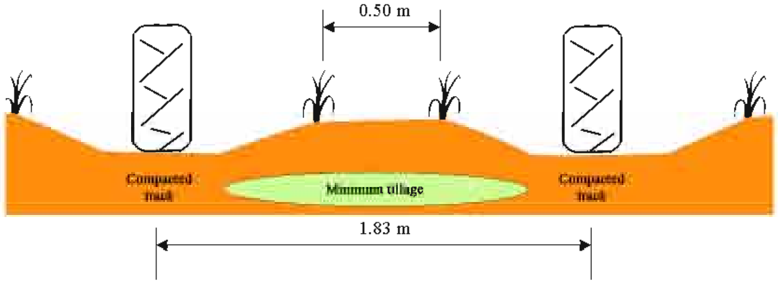

Fig. 1: Relation between track width of vehicles and crop row spacing

crop grows for 12-15 months before mechanical harvesting by cutting stalks at the ground level. A ratoon crop regrows from the underground nudes again and is mechanically harvested after a period of between 10 and 12 months. Several harvests are taken from the initial planting. Thus, a crop cycle consists of a plant crop and on average four ratoon crops. A pair row is harvested simultaneously with a haulout unit tracking alongside the harvester collecting the cut canes for transportation out of the field. The traffic, at each harvest is intense. Each furrow is trafficked with a minimum of four passes, two by the harvester and two by the haulout. Some furrows are trafficked more depending on row length and crop yield. A proportion of each furrow is trafficked by empty, partially loaded and fully loaded haulouts. Since the harvesters weigh up to 20 tones and fully loaded haulouts up to 30 tones and since harvesting traffic is often applied under wet soil conditions, there is great potential for soil compaction. Barzegar *et al.* (2000) have also indicated that soil compatibility under sugarcane cultivation may arise during land preparation, planting, cultural practices and, particularly, harvesting operation. Intense soil cultivation causes several alterations to soil physical properties, resulting in structural degradation (Tisdall and Oades, 1982; Wood, 1985; Bramley *et al.*, 1996). Sugarcane continuous cropping, together with inadequate management practices, as intense traffic of machinery and the absence of crop rotation, can result in soil degradation and reduce productivity (Masilaca *et al.*, 1986; McGarry *et al.*, 1996; Braunack *et al.*, 1999; Bell *et al.*, 2001).

Generally soil compaction is the reduction in the volume of the pores due to an external force. In such conditions, the distribution and the size of the pores are altered, reducing the permeability and hydraulic conductivity. As a result of this, bad ventilation of soil, increase of bulk density and yield reduction is resulted. The yield reduction occurs due to limitation of root growth and so declining their efficiency to absorb nutrients. This problem is much more important for phosphorous and potassium nutrients (Pankhurst *et al.*, 2003).

Although hill and furrow has been divided in two parts one dealing with traffic and the other with the root zone, traffic compaction may affect the whole area, reducing infiltration and limiting root development to small area. This may happen, because the soil transmits the applied pressure to the lower layers and eventually provides the possibility of deep layers formation with a high bulk density (McGarry and Bristow, 2001) and low permeability. Therefore, it is necessary to find a proper way to reduce bulk density by mechanical means.

Subsoiling the soil using a single shank tractor with a mounted oscillating subsoiler may increase the soil macro-porosity resulting in a lower bulk density (Bandalan *et al.*, 1999). Subsoiling the soil, especially after harvesting when heavy trucks transport the cut canes from the field to the sugar factory, to break hardpan and minimize the compaction affects, could be a suitable way to improve soil physical properties. This may decrease the bulk density and therefore, the soil infiltration improves and the root has enough space to develop. Therefore, the main purpose of this paper is to shed light on the soil behaviour from compaction point of view before and after harvesting and on the reaction of the soil to the subsoiling operation. However, it was also necessary to study the relation of maximum dry bulk density with both, particle size distribution and optimum moisture content by Proctor test to study the potential of soil compactibility.

Furthermore, two field and laboratory experiments were conducted to evaluate the effect of subsoiling on the improvement of the soil physical properties. Methods for evaluating soil conditions as influenced by tillage are often limited to analysis of bulk samples. The application of medical High Resolution Computed Tomography (HRCT-scan) to characterize the tillage effects on soil properties provides an alternative tool to measure soil density, since it is at a more detailed scale (Ketcham and

Carlson, 2001). Using this method in this study provides more information about the density distribution within a soil sample. The advantage of using this method is to shed light on the soil behaviour, when subsoiled with such tools and to provide more comparisons.

MATERIALS AND METHODS

In this study two different experiments were conducted to evaluate the potential of soil compactibility and to improve soil physical properties due to subsoiling treatment after harvesting traffic compaction during 2004 to 2006.

Site description: This field study was conducted in Amir Kabir and Mirza Kochakkhan Plantations, South Western Iran (longitude 48° 15′ 42′′ E, latitude 32° 58′′ 09½N). Figure 2 shows the location of the field study in Iran. This region has a mean annual rainfall of about 168 mm. The rainfall distribution is bimodal with peaks in January and February. The dry season extends from March to October. The average of minimum and maximum air temperature are 15.3 and 32.9, respectively and a mean annual air temperature of 24.1°C. However, the average air temperature of the coldest and the hottest month of the year are 6 and 46°C, respectively.

Parent materials of this area are derived mainly from a continuation of the Mesopotamian plain and is developed on an alluvial deposit. It has a level to nearly a topography level, where the possibility of water standing is greater than in adjacent areas. The local elevation ranges from 4 to 6 m above the sea level. The mean annual evaporation (from a class A pan) is around 3000 mm annually. Accordingly, the soil moisture and temperature regimes are Xeric and Hyperthermic, respectively (Anonymous, 1999). The soils were classified as: fine, carbonatic, hyperthermic, calcic haploxerepts (Anonymous, 1999).

Sugarcane production has covered about 24000 ha of this region since 1994. The production of mill-able stalk has averaged 100 ton per ha per year. Approximately 30000 m^3 per ha (or 3000 mm depth) irrigation water are applied annually for sugarcane production in this region. Row spacing was 1.83 m for sugarcane. Subsurface drainage system was installed for all of this area.

Field experiment: This research has been carried out in three fields with different cultivation ages as follows: (i) the first field was under the first year of cultivation (plant); (ii) the second field was under the second year of cultivation (ratoon 1) and (iii) and the third field was under the third year of cultivation (ratoon 2). These fields were harvested at 15% moisture (w/w).

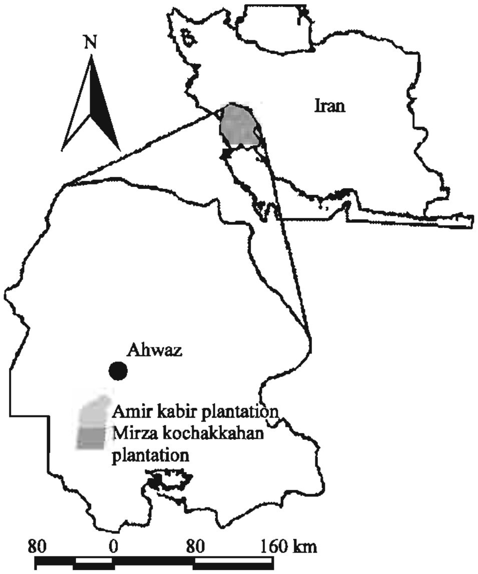

Fig. 2: Location of the fields study in Khuzestan province

The length of each field was 1000 m with 250 m width resulting in a 25 ha area. The harvesting traffic compaction was obtained by bulk density measurement. This measurement was conducted in three different times: before harvesting operation, after two traffic passes by the harvester and two by the haulout through the furrow and finally and after subsoiling treatment (ratooning). In the last stage, the bulk density was measured after two irrigations following the subsoiling treatment, when enough soil consolidation was happened inside the furrow. Samples were taken from 0.25, 0.5 and 0.75 length of each furrow. In every location, the soil profile was digged out to more than one meter. Then, using the metal cylinders (50 mm in height and in diameter), undisturbed samples were taken from these profiles to determine the bulk density. These samples were taken from the depths of 0-20, 20-40, 40-60, 60-80 and 80-100 cm. Three core samples were taken at each depth for the determination of pre-compression load before and after mechanical harvesting traffic (harvester and haulout). In addition to these samples, enough soil was taken from each depth for the laboratory chemical analysis.

Furthermore, CT-Scan method was used to provide more comparison between soils under traffic compaction and soil after subsoiling. The micro-CT-Scan, EVS-MS8 model, was used for this purpose. See Perret *et al.* (1999), Ketcham and Carlson (2001), Pierret *et al.* (2002) and Pires *et al.* (2003) for a complete listing of articles and researchers currently involved in CT-scan and soil research. Two undisturbed soil samples were taken from the surface layer for these analysis. Using sample from the surface layer was due to critical compaction, happening in this layer. X-rays were generated at 100 kv, 0.5 mA and with a 65 μm focal spot on the X-ray anode tube. Images were collected at 10 μm slice intervals and scale of analyses was at 10 μm^3 voxel (volume element) size.

Laboratory experiment: To determine soil properties, the soil samples were collected from three different fields of the above mentioned sugarcane plantations. Soil physico-chemical properties were measured in disturbed soil samples. These samples were collected from the soil surface (0-60 cm), air-dried and ground to pass a 2 mm sieve. Then soil samples from each field were mixed together to obtain a homogeneous sample. Particle size analyses were conducted using the modified Bonyoucous hydrometer method (Lambe, 1951). Electrical Conductivity (EC) of saturated soil extract and pH of soil saturated paste were also measured using standard methods (Anonymous, 1954). Organic matter content was determined using the Walkley and Black procedure (Jackson, 1975).

To study the potential of soil compactibility, it was necessary to obtain the particle size distribution, optimum moisture content and maximum dry bulk density using Proctor test (Adekalu and Osunbitan, 2001). The soils with initial moisture contents from 5-8%, were each brought to five moisture levels (10, 12, 14, 16 and 18%) on a percentage wet mass basis. The soil was subjected to 25 blows of a standard Proctor hammer at each moisture content (Lambe, 1951). Soil dry bulk density at the different moisture contents was determined at each compaction level (Lambe, 1951).

The dry bulk density measurements were repeated for different soil texture at each moisture content. The moisture content were plotted with the soil dry bulk density to determine the optimum moisture content (the moisture content corresponding to maximum dry bulk density). Also, the optimum moisture content and maximum dry bulk density were correlated with soil particle size distribution.

RESULTS AND DISCUSSION

Proctor test: The proctor test was used to study the potential of soil compactibility. Table 1 shows the results of particle size distribution, optimum moisture content and maximum density of the soil samples. According to this Table 2 when clay content of the soil increased, the maximum dry density also increased. This coefficients illustrate that there was a positive correlation between the clay content and the maximum dry density. However, sand and silt were negatively correlated to the maximum dry density, meaning that with increased sand or silt content of the soil the maximum dry density decreased slightly.

The results showed that sand and silt were positively correlated with optimum moisture content, whereas clay had negative correlation. The determination coefficient (R^2) of the relationship between clay and optimum moisture content was higher than the coefficient (R^2) of the relationship between silt particle and optimum moisture content (Table 2).

Table 1: Effect of particle size distribution on optimum moisture content and maximum dry bulk density[a]

Field No.	OM (g kg^{-1})	C (%)	Si (%)	S (%)	Texture	OMC (%)	MBD (mg m^{-3})
1	6.2	41	43	16	SiC	18.3	1.71
2	5.3	39	47	14	SiCL	17.5	1.73
3	6.1	35	36	29	CL	17.2	1.76
4	5.2	43	47	10	SiC	18.7	1.73
5	6.3	31	33	36	CL	15.9	1.79
6	5.3	37	41	22	CL	17.2	1.71
7	5.4	29	25	46	SiCL	15.1	1.83
8	5.1	36	35	29	CL	15.9	1.74
9	6.8	29	23	48	SiCL	14.7	1.86
10	6.3	33	31	36	CL	15.8	1.79
11	6.2	19	24	57	SL	13.1	1.92
12	6.1	31	31	38	CL	15.7	1.77
13	5.9	27	38	35	CL	15.3	1.81
14	5.7	21	25	54	SCL	14.1	1.90
15	5.6	25	27	48	SCL	14.3	1.89
16	6.1	29	27	44	CL	15.9	1.81
17	5.8	31	45	24	CL	16.1	1.73
18	5.4	19	25	56	SL	13.0	1.91

[a] OM: Organic Mater; OMC: Optimum Moisture Content; MBD: Maximum Bulk Density; S: Sand; Si: Silt; C: Clay

Table 2: Parameter of linear regression equation of soil optimum moisture content (y) and maximum dry density (y) on soil components (x). The linear equation of this regression is $y = \alpha x + \beta$

Soil components (x) (%)	Optimum moisture content (y) (%)			Maximum dry density (y) ($g\ cm^{-3}$)		
	α	β	R^2	α	β	R^2
Sand	0.2203	8.9727	0.9317	-0.0094	2.0878	0.8502
Silt	0.1617	10.3490	0.7086	-0.0074	2.0458	0.7418
Clay	-0.1042	19.4840	0.8974	0.0046	1.6359	0.8791

Table 3: Mean of optimum moisture contents and maximum dry bulk densities for different soil textures[a]

Texture	MDBD ($mg\ m^{-3}$)	OMC (%)
SL	1.91	13.1
SCL	1.89	14.2
CL	1.77	16.1
SiCL	1.81	15.8
SiC	1.72	18.5

[a]: S, Sand; Si, Silt; C: Clay; MDBD: Maximum Dry Bulk Density; OMC, Optimum Moisture Content

Table 4: Some physico-chemical characteristics of the soil samples[a]

Depth (cm)	Ece ($d\ S\ m^{-1}$)	pH	OM ($g\ kg^{-1}$)	CCE ($g\ kg^{-1}$)	SARe	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	Texture
0-20	2.9	7.3	3.6	424	6.5	192	475	333	SiCL
20-40	2.5	7.5	3.8	428	5.8	204	388	408	CL
40-60	2.4	7.7	4.4	413	4.8	175	255	570	CL
60-80	2.3	7.8	2.8	421	4.2	160	262	578	CL
80-100	2.4	7.7	3.1	431	3.8	151	281	568	CL

[a]EC: Electrical Conductivity; OM: Organic Matter; SAR: Sodium Absorption Ratio; CCE: Calcium Carbonate Equivalent; S: Sand; Si: Silt; C: Clay

Such results may be due to the effect of clay specific surface and higher porosity. Ohu *et al.* (1989) observed a similar positive correlation of sand with maximum dry bulk density, but found clay to be more negatively correlated with optimum moisture content than silt. This might be, due to small textural differences in the soils used in this study which have wider variation in silt content. Such results also have been reported by Lambe and Whitman (1979) and Adekalu and Osunbitan (2001).

The maximum dry bulk density for sandy loam, sandy clay loam, clay loam, silty clay loam and silty clay textures were 1.91, 1.89, 1.77, 1.81 and 1.72 mg m^{-3}, respectively and their corresponding optimum moisture contents were 13.1, 14.2, 16.1, 15.8. and 18.5% (Table 3).

There are small differences between the soil value of maximum dry densities and the value of optimum moisture content due to their textural disparity (Table 3). The silty clay soil had the lowest dry bulk density and highest optimum moisture content. The heaviest textures are able to hold greater quantity of water at the same potential. Hence they have higher optimum moisture contents and lower densities.

Clay soils are most susceptible to compaction because their fine particles hold more water for a longer period than a sand or a loam soil. Clay soils remain in a plastic state, most of the year, which make them compactable when harvesting traffic load is applied. Soil texture seems to have the overriding influences on these parameters. Similar overriding influences of texture were obtained by Barzegar *et al.* (2000).

Field experiment: The physico-chemical properties for different depths are presented in Table 4. The ECe of the soil extract was in the range of 2.3-2.9 dS m^{-1} and the SARe was also between 2.8 and 4.4. This indicates that the soil is neither saline nor sodic. Furthermore, all the soil layers texture were clay loam, except the surface layer which was silty clay loam. According to the results, the Organic Matter (OM) was between 3.8 and 6.5 g kg^{-1} indicating a negligible amount of organic matter (Table 4).

The changes in the dry bulk density due to traffic compaction and subsoiling treatment in the three different fields showing the same trends for plant, Ratoon 1 and Ratoon 2 fields due to harvesting traffic (Fig. 3).

Furthermore, the effect of subsoiling in most conditions was higher than the effect of compaction. However, this compaction also indicated that there was no noticeable changes in the fourth layer (deeper than 60 cm). This may be because of penetration depth of the subsoiler (deep plough), used in the subsoiling operation, which is often about 60 cm. From this layer, neither traffic compaction, nor subsoiling can affect the soil porosity and ventilation. Therefore, no obvious changes have been observed in the bulk densities of the soil. It can also be seen from this figure, that there was no significant differences between the initial dry bulk densities in these different plantation conditions. However, after harvesting, the dry bulk density dramatically increased in all different sites. The dry bulk density for plant, ratoon 1 and ratoon 2 fields increased from 1.39, 1.42 and 1.45 to 1.55, 1.67 and 1.68 mg m^{-3},

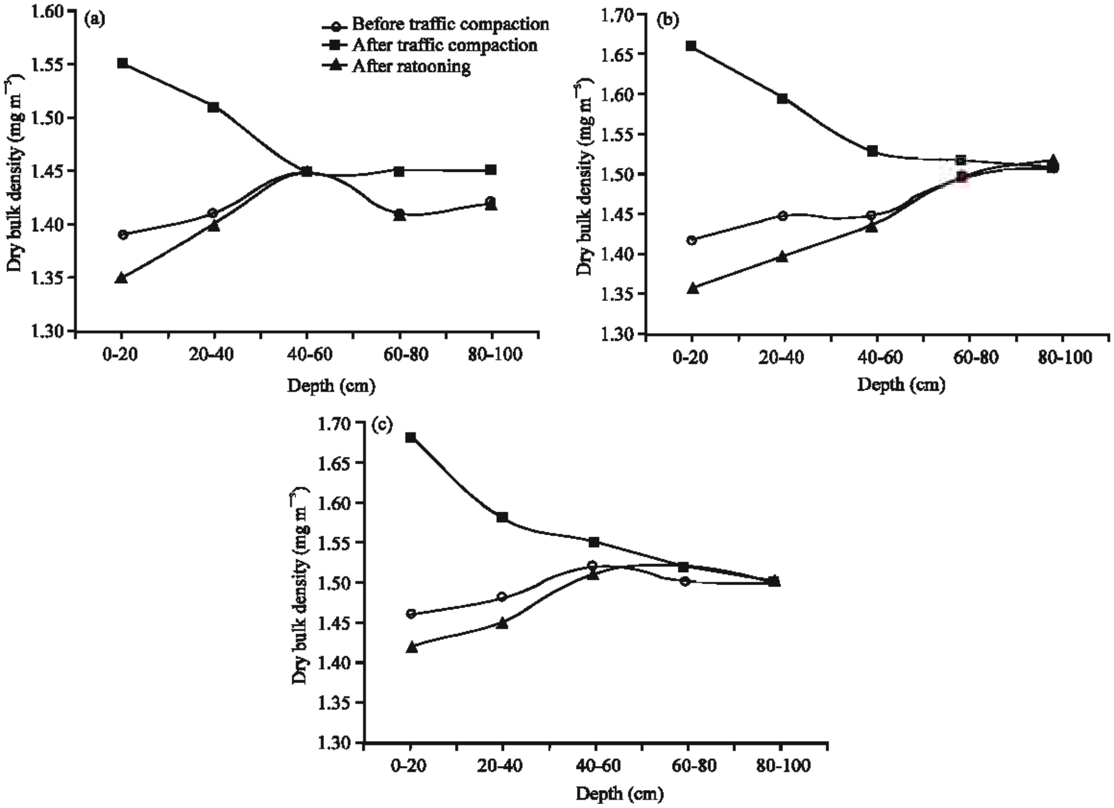

Fig. 3: Effect of traffic and ratooning practice on dry bulk density of soil in (a) Plant, (b) Ratoon 1 and (c) Ratoon 2 fields

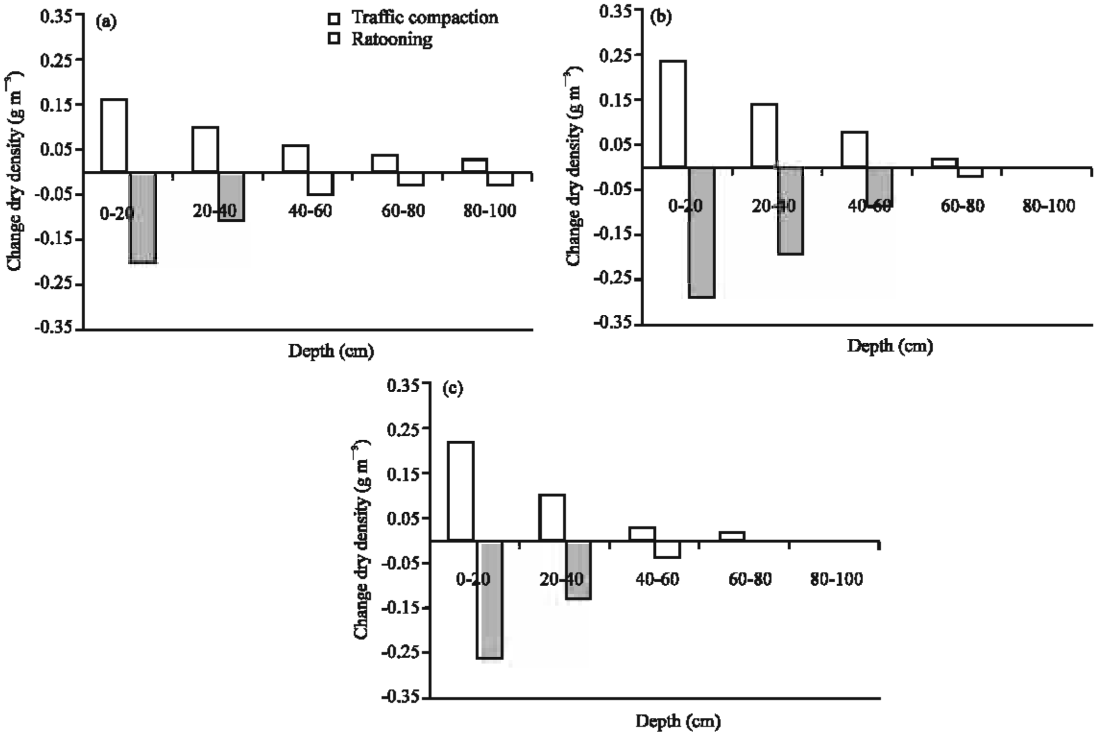

Fig. 4: Changes in dry bulk density affected by harvester and haulout traffic in (a) Plant, (b) Ratoon 1 and (c) Ratoon 2 fields

respectively (Fig. 3). The amounts of these increases for plant, Ratoon 1 and Ratoon 2 fields are shown in Fig. 4.

The maximum increase was related to the first layer (0-20 cm depth). The minimum increase in dry bulk density occurred in layers beyond 60 cm depth, indicating that the most traffic compaction effects is related to the soil layers between 0-60 cm depth. Due to the high content of clay and low quantity of organic matter in the top layers of the soil, compaction was clearly predictable. Slight amount of organic matter, a heavy textured soil and enough moisture content provide suitable conditions for the soil compaction. In Columbia in soil with similar conditions of texture and moisture content but with suitable rate of organic matter (Mollisol order), the compaction took place only on the top layer (0-25 cm) (Torres and Pantoja, 2005). Compaction effects were limited to the top 40 cm soil layer and were concentrated in the inter-row spacing.

However, subsoiling can improve the soil physical properties. As it is clear from Fig. 4, subsoiling and other tillering operations (despite the fact that dry bulk density was measured after two times of irrigation) may significantly decrease the soil dry bulk density and improve it's porosity. The increase of dry bulk density in ratoon 2 was less than other plantation conditions. This is probably due to the presence of the last years remained trash and also due to the changes in soil structures, becoming more stable under last years tillering operation.

CT-Scan: The compaction in the soil particle, due to harvesting traffic is clearly shown. Figure 5b shows the loose soil particles, after subsoiling and the improvement of soil physical properties. This trend is similar to changes in dry bulk density due to improving the soil physical properties by subsoiling and ratooning.

Images, created with Hounsfild Value greater than 1800 (CT-density or CTD) illustrated new images of voxels for compacted soil due to harvesting (Fig. 6a) and subsoiling (Fig. 6b). These images confirm the distribution of soil porosity in both situations. There are differences in the density of both soils, especially some voids with very low density are prominent. The macropores volume in the surface layer (0-20 cm) decline, possibly due to traffic (Fig. 6a). Figure 6b also illustrates that subsoiling after harvesting makes the soil structure loose with a wide range of densities. The detailed image of the internal distribution of densities in soil can be related to soil physical parameters like bulk density and porosity. The same trend was reported by Olsen and Borresen (1997).

The Hounsfild Values (CTD) histograms are shown in Fig. 7a and b for after harvesting and before ratooning. These results indicates the compaction differences between the two situations. In compacted soil (after harvesting), the mean normal distribution of Hounsfild Value is greater than 2200 whereas this value is 1600 after subsoiling (after ratooning). Present investigation indicates that subsoiling loosens the soil structure with a wide range of density, but harvesting, makes

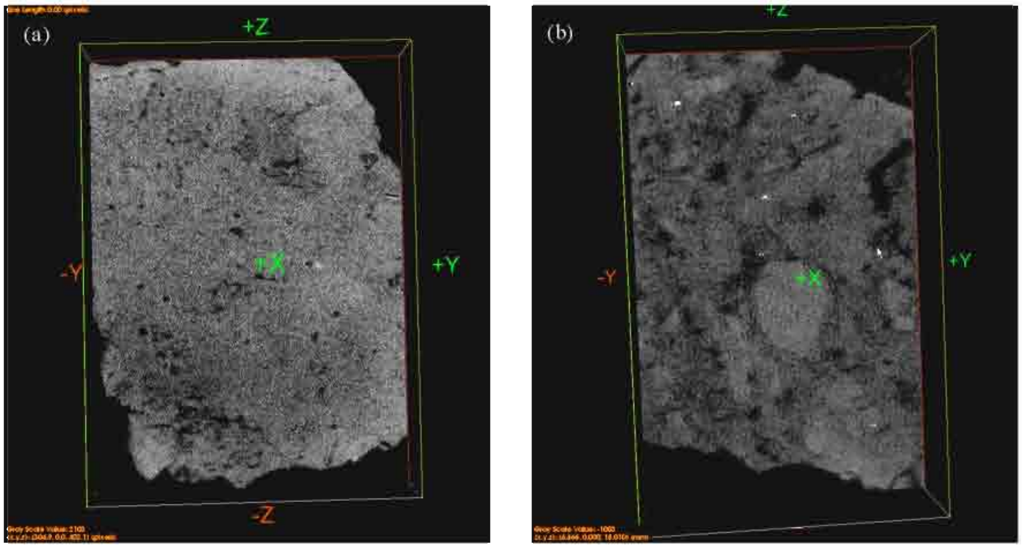

Fig. 5: Tomographic images of soil (a) before subsoiling and (b) after subsoiling

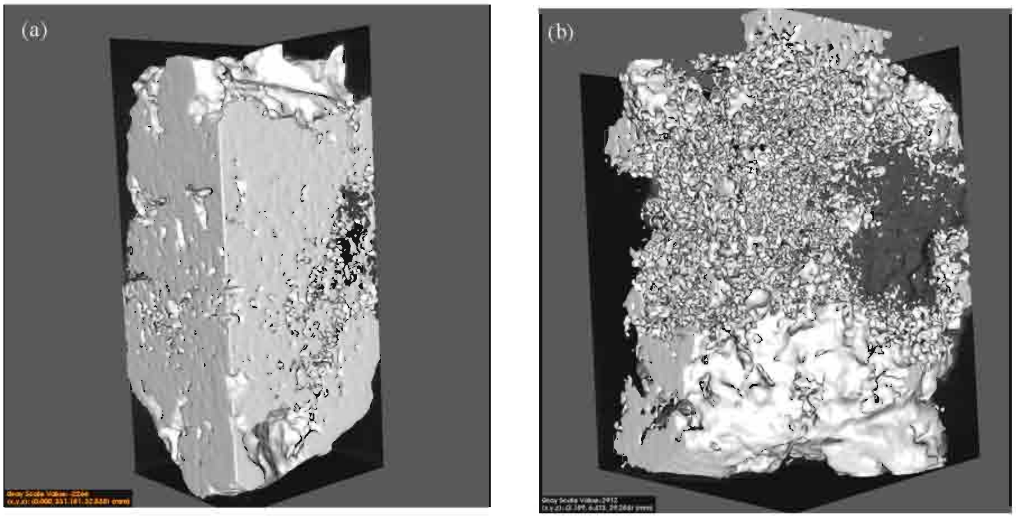

Fig. 6: CT-scan images created with more than 1800 Hounsfild Value, (a) after harvesting and (b) after subsoiling

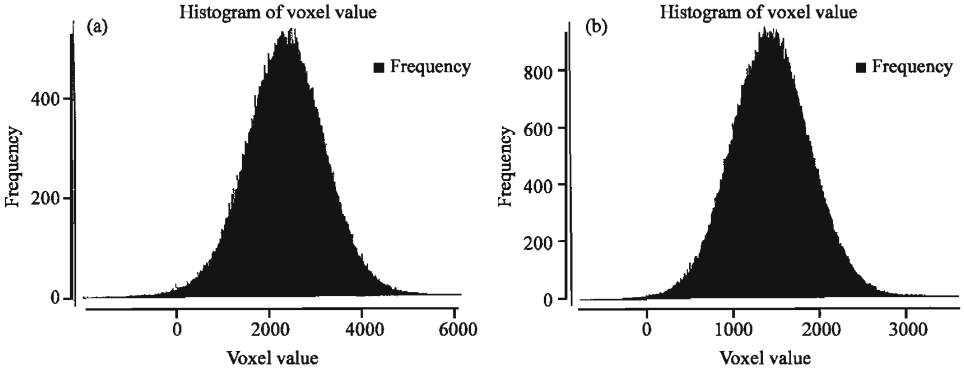

Fig. 7: Density distribution histogram for (a) before subsoiling and (b) after subsoiling

the soil compacted and porosity decreases. The macropores in the surface layer (0-25 cm), however, are collapsed, possibly due to traffic. CT is a very useful tool for collecting data on porosity or bulk density. Similar results have been reported by other researchers (i.e., Olsen and Borresen, 1997).

General discussion: The main aim of this study was to evaluate the application of new method of cultivation in which compaction could be minimized in sugarcane production. From proctor test, it was clear that if enough moisture content is available, all soil textures of these region are susceptible to compaction. The results also indicated that during harvesting period which is a wet period (rainy season) the moisture content of the soil between 13.1 and 18.5%. These moisture content make the soils compactable when traffic harvesting load is applied. In the field, as it was clear from the results, harvesting traffic compacted the soil layers between 0 to 60 cm depth. The maximum compaction happened in the first 20 cm depth of the soil and there was no compaction beyond 60 cm depth.

The results also showed that subsoiling the soil using a double shank subsoiler was loosening this compacted layer (0-60 cm). Most of soil physical parameters were restored to values similar or close to the initial values, measured before the traffic of the infield machines. Normal ratooning practices, carried out by the sugarcane company, including a single passage of a double shank subsoiler and a furrower, were enough to restore soil physical properties. The same results were reported by Torres and Pantoja (2005) for similar conditions.

The CT-scan could easily detect the differences between the loosen and compacted soil. Generally, the CT-scan results also indicated that compaction can be treated by subsoiling and soil physical properties can be improved by such operations. Since 1997 this type of managing soil compaction has been used in the field and high amount of sugarcane yield (more than 100 t ha^{-1} mill-able cane) point outs that it is a successful operation.

CONCLUSIONS

Matching infield machinery tracks to fit inter-row spacing is required to reduce direct tool damage and to limit soil compaction.

Based on the results of this study, the following conclusions are drawn:

- Proctor test results indicated that
    - The optimum moisture content was correlated to the soil particle size.
    - The soil compactness is dependent on the soil particle size.
- The results of the field experiment showed that the harvesting traffic can result in negatively changes in soil conditions, but subsoiling can treat the soil compaction and improve soil physical properties.
- CT-Scan results confirm that subsoiling may result in improving the soil conditions and this should be used to treat compaction.
- It is suggested that lighter weight of harvesting halouts be used to reduce soil compaction.

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