Measurements and Mapping of Soil Compaction for a Mechanized Centre Pivot Irrigation System

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Abstract

The objective was to investigate the influence of centre pivot wheels on compaction of soils in the vicinity of the tracks, its spatial variability and soil compaction prospects for mechanical harvesting operations at Ubombo Sugar estate. Two centre pivots were selected for purposes of the study, SMB manually harvested and EEL09 being mechanically harvested. Measurements were taken using an automated P5 Hand Penetrometer on sampled points and a handheld Juno SB GPS was used to capture positions of each data point. Statistical analysis was performed on compaction values using SPSS, soil compaction maps produced using ArcGIS software and penetration trends using HPen32 software and geospatial interpolation technique. Significantly higher soil compaction values at 0 to 15 cm depth ($p<0.01$) were associated with EEL09 centre pivot with an average of 3210 kPa compared to those of SMB at average of 1389 kPa. A parallel trend was observed at depth of 0 to 30 cm where significant differences in soil compaction between EEL09 (average of 4987 kPa) and SMB (average of 2209 kPa) centre pivots were recorded. Soil compaction mapping indicates that there is a general decline in soil compaction as one move away from the wheel tracks for both centre pivots. These observations are in agreement with the results obtained in a study conducted in a cracking clay soil where cone index measurements indicated that there was no lateral spread of compaction in the traffic lanes in a controlled traffic system. The trend on both pivots also indicates that compaction is spatially variable owing to the heterogeneity of soils within a centre pivot and the differences in harvesting systems. Higher compaction values were obtained for the mechanically harvested centre pivot (EEL09) and an increase in compaction for SMB was due to machinery traversing in-field when collecting manually harvested sugarcane. The current trend of soil compaction among the fields will generally affect soil infiltration, water storage capacity, irrigation systems performance and subsequent reduction in sugarcane yields.

Keywords: Centre pivot, compaction, harvesting, manual, mechanical, soil, sugarcane.

Introduction

Soil compaction is a serious concern for a majority of agricultural soils at global scale due to the evolution of conventional farming methods into mechanized operations. An increase in the frequency and type of machinery used for farm operations has led to the consolidation of soils in the field. Soil compaction research has revealed to have significant reduction in crop yields due to increased runoff and soil structure deterioration, hence water and soil quality degradation. In Pennsylvania in particular, a 10 percent yield reduction in wheat has been reported due to soil compaction problems[1]. Compaction is therefore considered to be an issue that will likely to affect crop production and be of supreme importance in the subsequent years. Notwithstanding the problems associated with soil compaction, 47% of the sugarcane fields at Ubombo Sugar estate are now irrigated by mechanized centre pivot systems subsequent to innovations to convert poorly performing fields of furrow and dragline sprinkler systems and the number is set to rise as a result of the impetus for strategic future developments of the estate[2]. In addition, a majority of these fields are increasingly being mechanically harvested by chopper harvesters owing to the demand of biomass for cogeneration and high throughput capacity of the factory consequent to the expansion project. However, no efforts have been made to study and mitigate the effects of mechanizing these field operations to avoid land degradation and yield losses on sugarcane.

The consolidation of agricultural soils affects crop production by creating poor environment for root growth, reduction of water infiltration and increased runoff, hence soil erosion. Soil compaction caused by the passage of vehicles results in important economic and ecological consequences, such as poor crop productivity due to problems of crop establishment and root growth and excessive soil erosion due to reduced water infiltrability[3]. Wheel traffic from heavy machinery can compress soils to varying degrees throughout the plant root zone, often causing increased mechanical strength and decreased air and water permeability[4]. This condition can impede root elongation and significantly reduce crop growth and yield. The detrimental effects of soil compaction on crop performance have been reported to reduce crop growth potential, which included water infiltration, plant available water capacity, oxygen supply and de-nitrification[5]. Compacted soil layers affect crops directly as plant roots encounter high physical resistance and indirectly by causing poor soil aeration, lowering the access of plants to soil water and increasing water logging[6]. In addition, an increase in the compactness of soil result in decreased root size, higher concentration of roots in the upper soil, lower rooting depth and a greater distance between the nearest roots[7]. Plant nutrient uptake and effectiveness of fertilization are also reduced by soil compaction. A similar study conducted in 2002 where Cone Index (CI) data was used to explain corn yield variation within a field, it was found that the mean CI throughout the top 76.2 cm soil profile was appropriate to explain yield variation[8]. It was also concluded that the maximum CI values at or above 1.4 MPa resulted in below average yields for 89% of the readings exceeding this limit. Another study conducted in 2006 to investigate the influence of soil compaction on sunflower production showed that plant height and leaf area were reduced by compaction due to deteriorated soil conditions for root growth[9]. The root biomass was lowered by 16 to 33% in compacted soil compared to non-compacted one. The study concluded that soil compaction was a major cause of the reduction of biomass accumulation in the plant root and the grain yield per plant.

In a mechanized centre pivot irrigation system, the centre pivot is repeatedly and continually driven on predetermined wheel tracks. Efforts have been previously made to improve traction along centre pivot wheel tracks through gravelling, use of dual drive wheels, installation of furrow busters, star tracks and back boom sprinklers. This prolonged movement on the predetermined tracks leads to the development of wheel ruts as a result of the repeated trafficking of the tower wheels over wet or moist soil[10]. Information of the lateral effect of centre pivot wheels on compaction of soil in the vicinity of the tracks is limited. Assessing and understanding the lateral effect of centre pivot wheels on soil penetration resistance is a crucial step towards appropriate application of the centre pivot irrigation technology within the estate. In addition, assessing the effect of mechanizing harvesting operations remains salient to make radical decisions towards soil management. Therefore, this study investigated the effect of centre pivot wheels on compaction of soil in the vicinity of the wheels, its spatial variability within the field and soil compaction prospects for mechanical harvesting operations to generate soil compaction maps which will form basis for sustainable management of soils to improve irrigation system performance and sugarcane yields in the estate.

Material and Methods

Experimental site: The experimental field work was performed at the end of the 2013/14 cropping season on two fields under centre pivot irrigation systems harvested manually and mechanically at Ubombo Sugar estate in the Lubombo region of Swaziland[11]. The fields were located at Sangwaluma and Lukhalweni Sections ($26^0$45'80"S, $31^0$56'26''E and $26^0$45'26''S, $31^0$53'53''E) with 70.4 and 49.1 ha respectively. The crop was primarily sugarcane and soils were generally characterized as sandy loam. Field measurements were carried out immediately after mechanical and manual harvesting for each of the centre pivots.

Sampling and soil compaction measurements: Stratified random sampling technique was used for soil compaction data collection by randomly selecting three wheel tracks from the total number of tracks as determined by centre pivot size. Soil Penetration Resistance (PR) was used as an indicator of soil compaction[12]. Measurements of soil compaction were taken using an automated P5 Hand Penetrometer from the sampled points when the soil was sufficiently brought to field capacity by soaking a column of water over all measurement points over night for pivots SMB and EEL09 (figure-1). The measurements were taken by gradually pushing a soil cone into the soil to measure the penetration resistance of the soil and pressure readings for each corresponding depth were stored in the data logger. The soil cone usually mimics a growing plant root as it penetrates the soil during elongation. A handheld Juno SB GPS was used to capture positions of each measurement point to enable generation of raster files for the production of soil compaction maps using geospatial interpolation tool for ArcGIS software ESRI Inc, 2010. Measurements were started on both sides of each track at a distance of 50 cm from the centre of the wheel track spreading out laterally by an incremental distance of 50 cm for 2 m and then by an incremental distance of 1 m up to 3 m to coincide with traffic lanes produced by chopper harvesters for the mechanically harvested centre pivot area. As a result, a total of 5 data points on each side of the track were acquired to make 10 measurements per wheel track and procedures were replicated on all four quadrants of the centre pivot irrigation system (figure-2). Data was downloaded from the data logger of the P5 Penetrometer and exported into Microsoft Excel for miscellaneous analysis. Graphs of penetration resistances were produced from the measurements for each data point using HPen32 software to study soil compaction for each specific site (figure-7 to 10). Interpolation technique was employed for purposes of predicting soil compaction trend for positions that lacked sampled points within the plots to enable superimposition of soil compaction trend (raster) for each centre pivot[13].

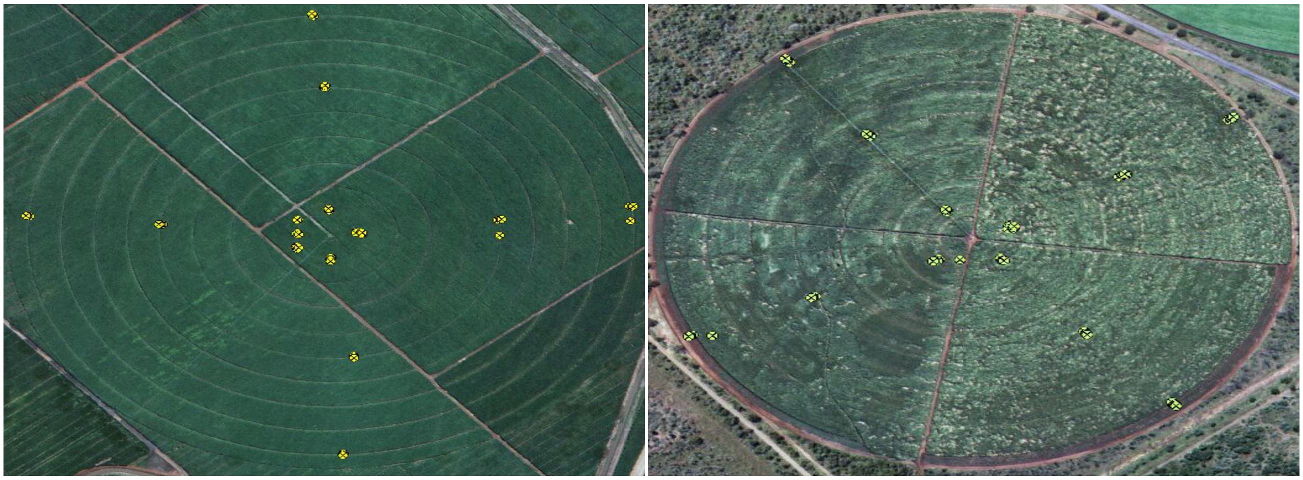
Results and Discussion

Soil compaction analysis and mapping: Statistical analysis was performed to compare soil compaction values using one-way analysis of variance (ANOVA) from the Statistical Package of Social Sciences (SPSS) program, version 20 IBM Inc, 2011. Analysis was performed for soil depths 0 to 15 cm, 0 to 30 cm and 0 to 60 cm. For the depth of 0 to 15 cm, significantly higher soil compaction values ($p<0.01$) were associated with EEL09 centre pivot with an average of 3210 kPa compared to those of SMB at average of 1389 kPa (Table-1). A parallel trend was observed at depth of 0 to 30 cm where significant difference in soil compaction between EEL09 (average of 4987 kPa) and SMB (average of 2209 kPa) centre pivots were recorded. At 0 to 60 cm depth, average value for EEL09 was 5321 kPa and 3412 kPa for SMB centre pivot although measurements were limited by soil depth for EEL09. This was attributed to the fact that EEL09 was mechanically harvested by chopper hence high compaction values as opposed to SMB where compaction values were relatively lower. The higher values at SMB were induced by machinery removing cut cane particularly in the A and B quadrants of the pivot where the soils are relatively heavy and the fact that the portion was relatively wet during harvesting (figure-6). Geographical Information System (GIS) maps of soil compaction were developed using ArcGIS program ESRI Inc, 2010 for EEL09 and SMB centre pivots (figure-5 to 6). It is evident that high soil compaction values were obtained for EE09 as opposed to SMB and the limiting factor among others being shallow soils of 50 to 60cm for EEL09. The trend in both pivots indicates that compaction is spatially variable owing to the heterogeneity of soils within the centre pivots and the differences in the machinery used for harvesting the two centre pivots (Figure-5 to 6). It also imperative to be cognisant that actual penetration resistances towards root elongation and water absorption in the fields are generally higher than the values obtained owing to the normal irrigation practice of applying 25 mm per cycle which is lower than field capacities of the two centre pivots.

Soil compaction around pivot wheels: Soil compaction values for measurements obtained at the vicinity of the wheel tracks were converted into raster files using geospatial interpolation technique to generate soil compaction trend around the centre pivot wheel tracks of EEL09 and SMB centre pivots (Figure-3 and 4). The mapping indicates that there is a general decline in soil compaction as one move away from the track. The high compaction at a specific site towards the last data point of the mid track of EEL09 was a result of traffic lanes produced by chopper between the cane rows as trend highlighted a reduction in compaction away from the wheel track (Figure-3, 7 and 8). The trend generated for SMB track indicates that compaction was higher near the centre of the track and decreased laterally away from the wheel track (Figure-4 and 9). These observations are in agreement with the results obtained in a study conducted in a cracking clay soil where cone index measurements indicated that there was no lateral spread of compaction in the traffic lanes in a controlled traffic system[14]. Results of a study in a loamy soil due to traffic stated that the geometry of the severely compacted areas under wheel tracks was bulb-shaped and the area could be approximated by a half-ellipse[15]. Integration and consolidation of these findings indicate that regardless of soil type, traffic has no lateral effect on compaction of surrounding soils.

Soil compaction under mechanical harvesting: Figures – 3, 7 and 10 presents the influence of mechanical harvesting operations on soil compaction. The general compaction of the soil is significantly lower than compaction values obtained after mechanical harvesting by chopper and additionally by machinery collecting cane infield for the manually harvested centre pivot. For the same track at EEL09, there was a huge difference between compaction values obtained in portions not tempered by chopper at 3 m. Figure-7 indicates that the first two readings were very high in terms of compaction particularly because the chopper wheel had passed in that portion as opposed to the three other readings which were significantly lower. Evidence is shown in the raster displaying the trend of compaction around the tracks where one portion of the maps shows very high compaction values as it has been tempered by the chopper wheel (Figure-3). Figure-10 also proves to have high compaction for SMB pivot that the rest of the field as it has been measured on field sections traversed by machinery collecting cut cane. A major predisposing factor could have been the clayey soil type harvested at relatively wet conditions. However, it is imperative to note that compaction from this kind of machinery is still lower than that of chopper as shown in figure-7 and 10.

Figure–1
Measurement of soil compaction using P5 Hand Penetrometer after soaking soil near field capacity at each data point in the centre pivots

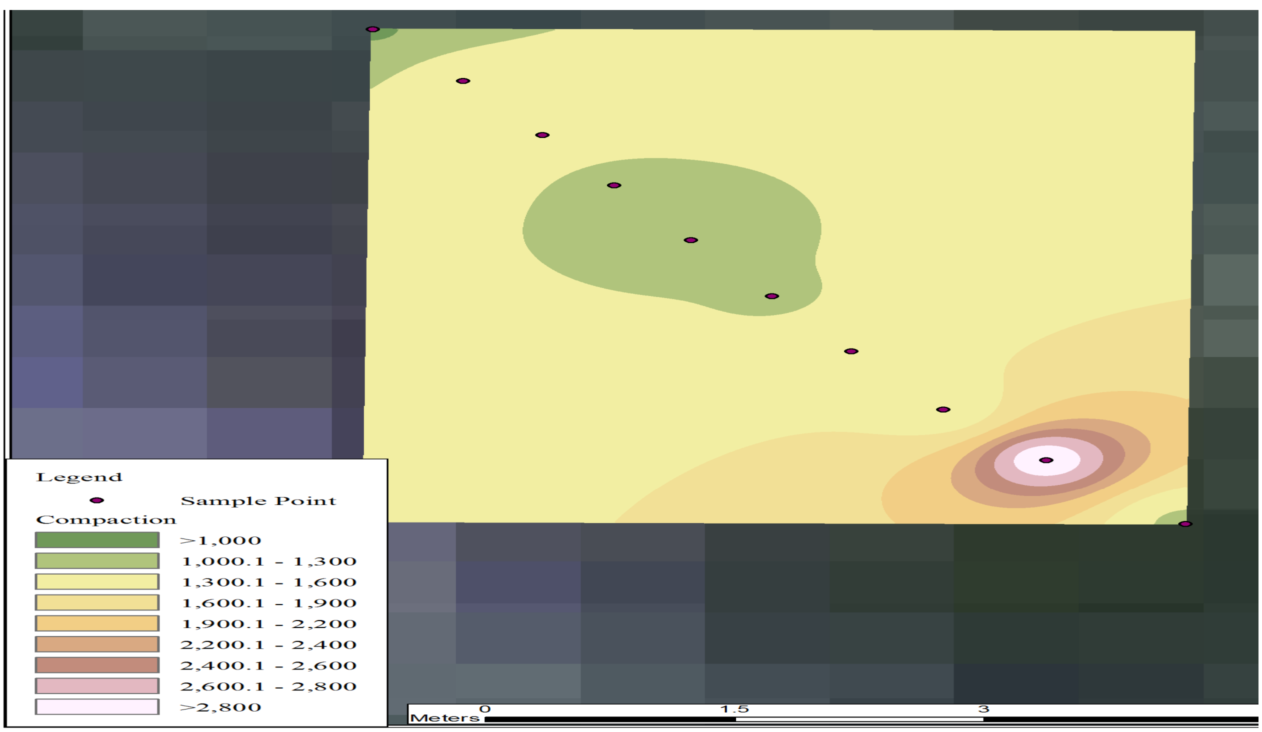


Figure–2
Measurement points superimposed on the aerial images of SMB and EEL09 centre pivots

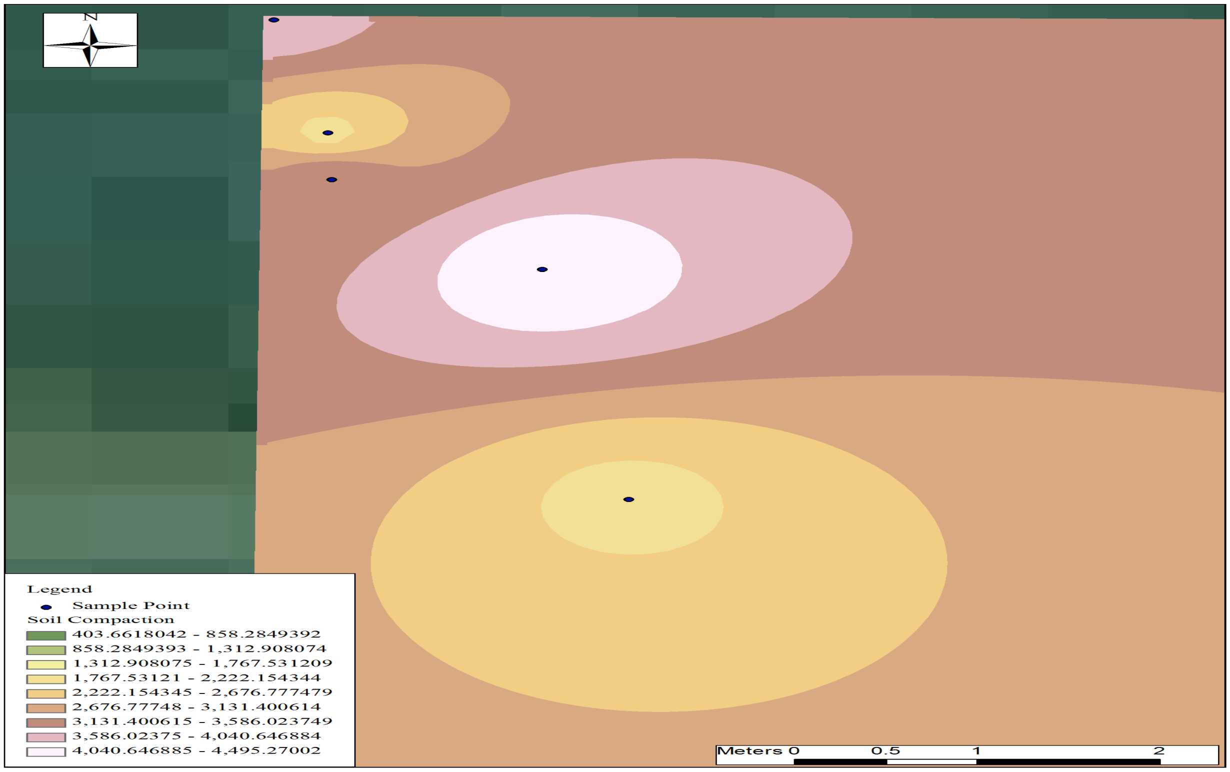
Table–1
Average soil compaction (kPa) for all wheel tracks of SMB and EEL09 centre pivots

Test centre pivot	Area (ha)	Soil depth (cm)	First track	Mid track	Last track
			2500*	2500*	2500*
SMB	70.4	0-15	2149	1720	298
		0-30	1251	1007	4369
		0-60	3279	2644	4313
EEL09	49.1	0-15	3678	2971	2981
		0-30	4601	4822	5538
		0-60	5223	5410	5330

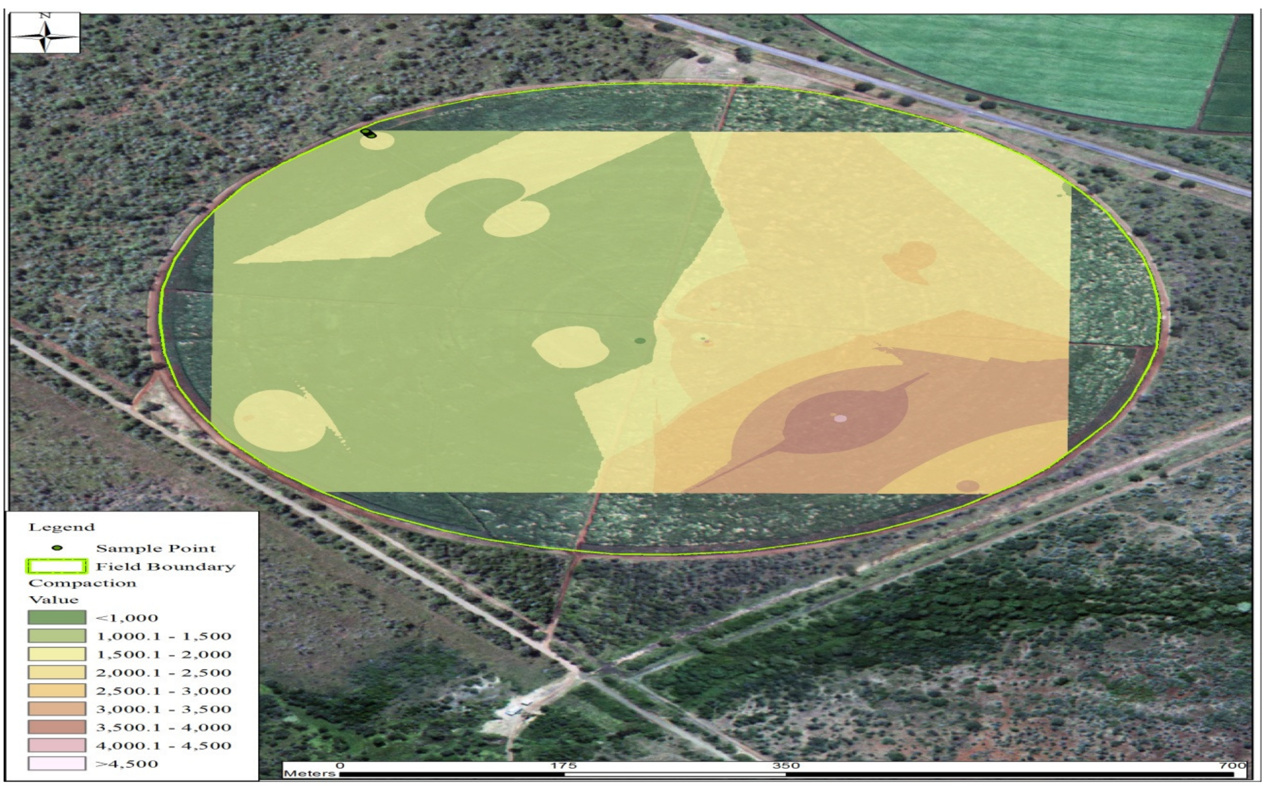
*Maximum penetration resistance ideal for sugarcane root growth



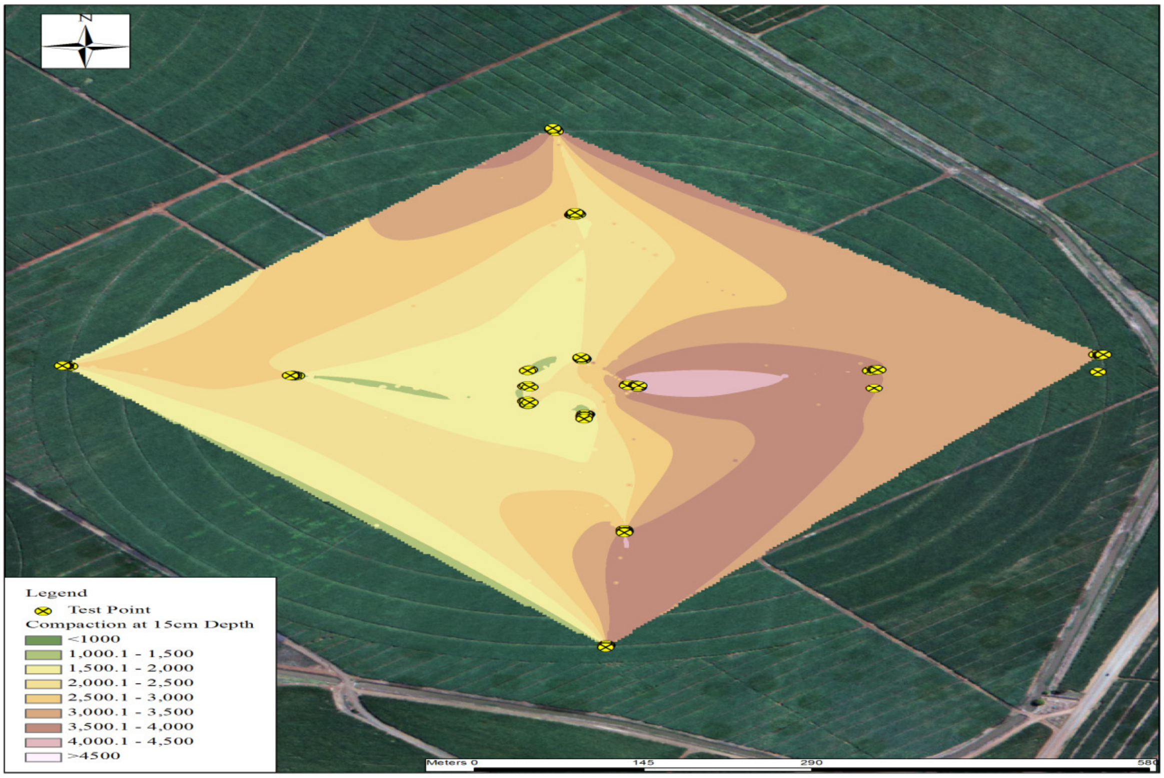
Figure–3
Soil compaction trend in the vicinity of the mid track of EEL09 centre pivot at 15 cm depth



Figure–4
Soil compaction trend in the vicinity of the first track of SMB centre pivot at 15 cm depth



Figure–5
General soil compaction trends interpolated from data points for the entire EEL09 centre pivot at 30 cm depth



Figure–6
General soil compaction trends interpolated from data points for the entire SMB centre pivot at 30 cm depth

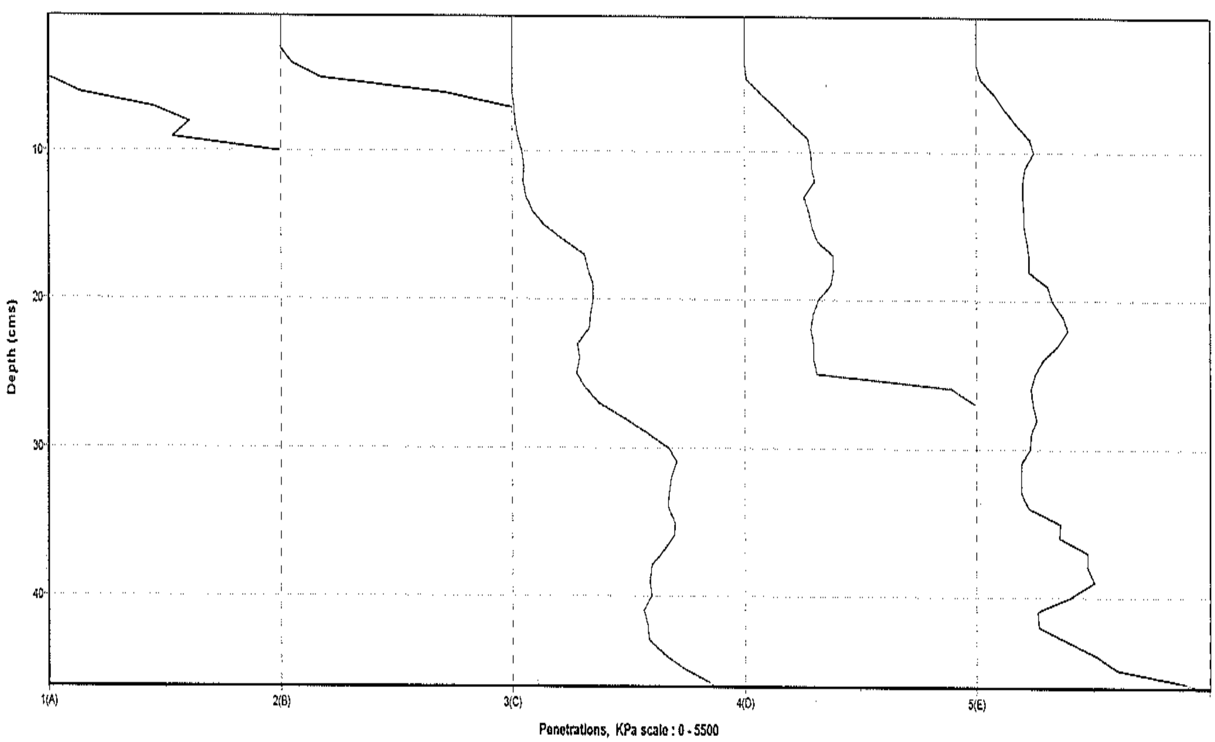


Figure-7
Soil penetrations for EEL09 with portion where chopper wheel has passed during harvesting

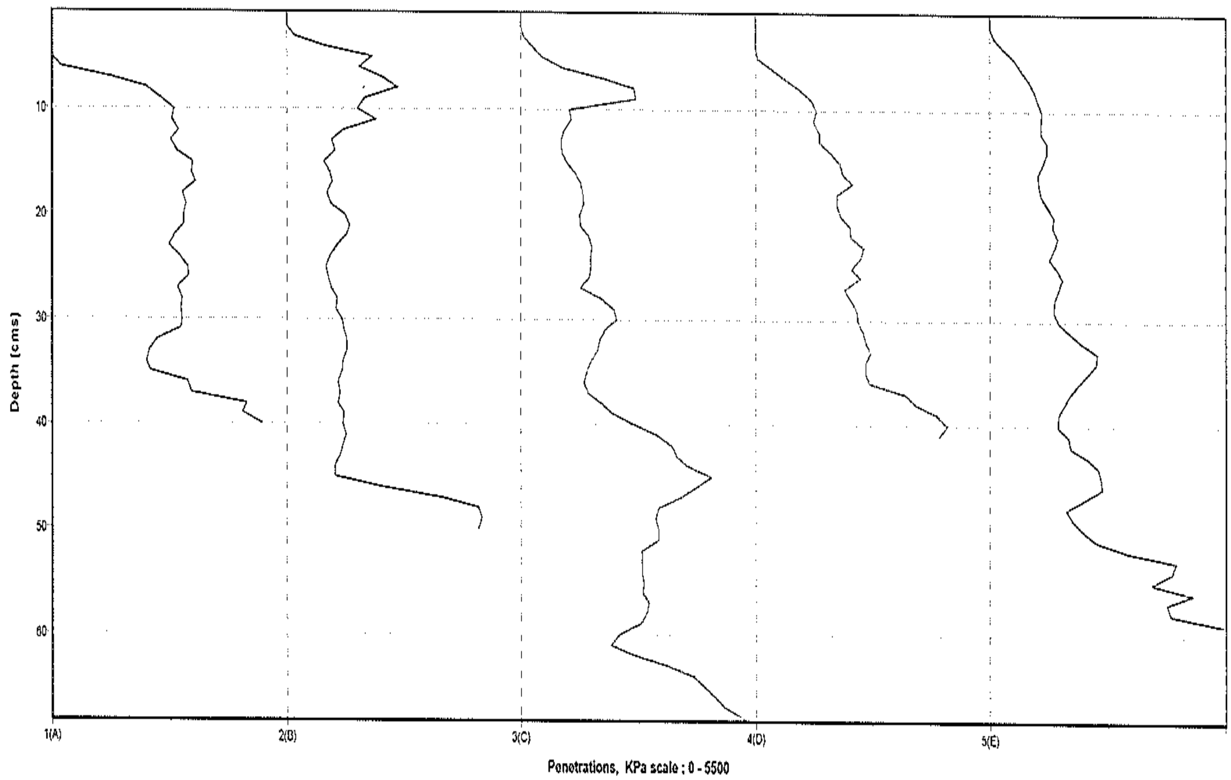


Figure -8
Soil penetrations for EEL09 indication high compaction in the top 10 cm away from the wheel track

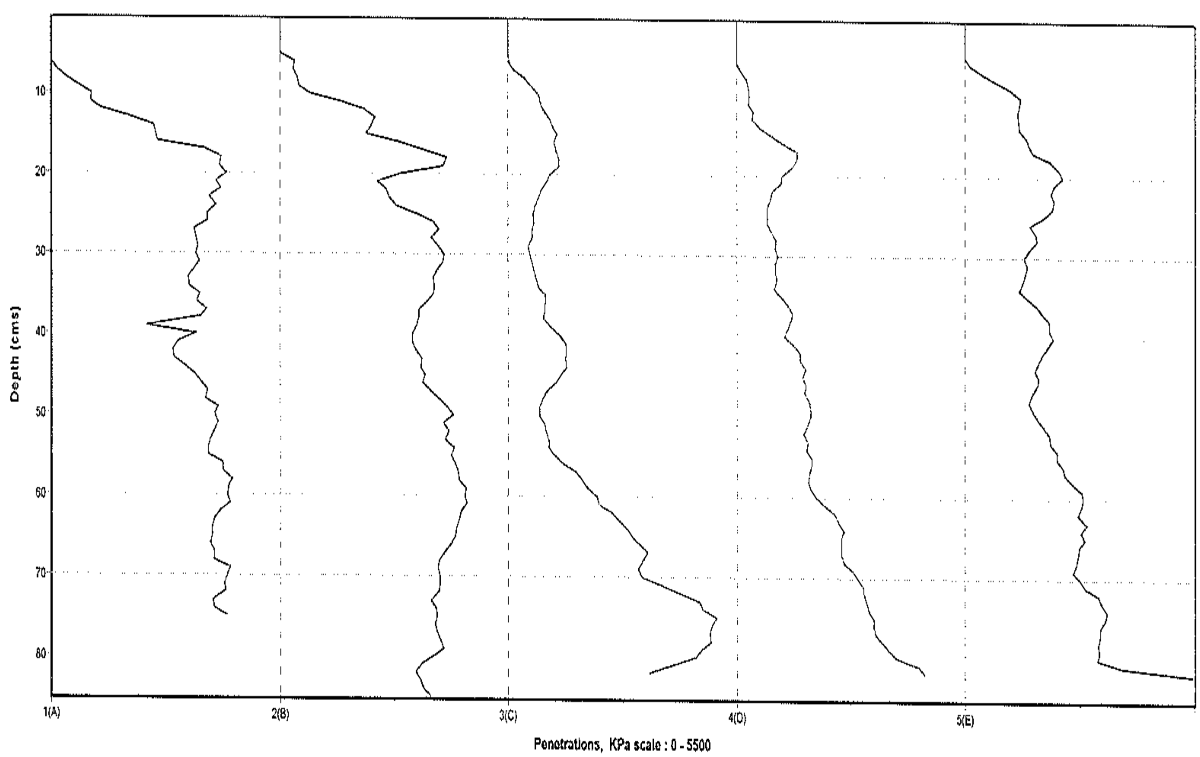


Figure-9
Soil penetrations for SMB showing compaction away from the centre of the wheel track

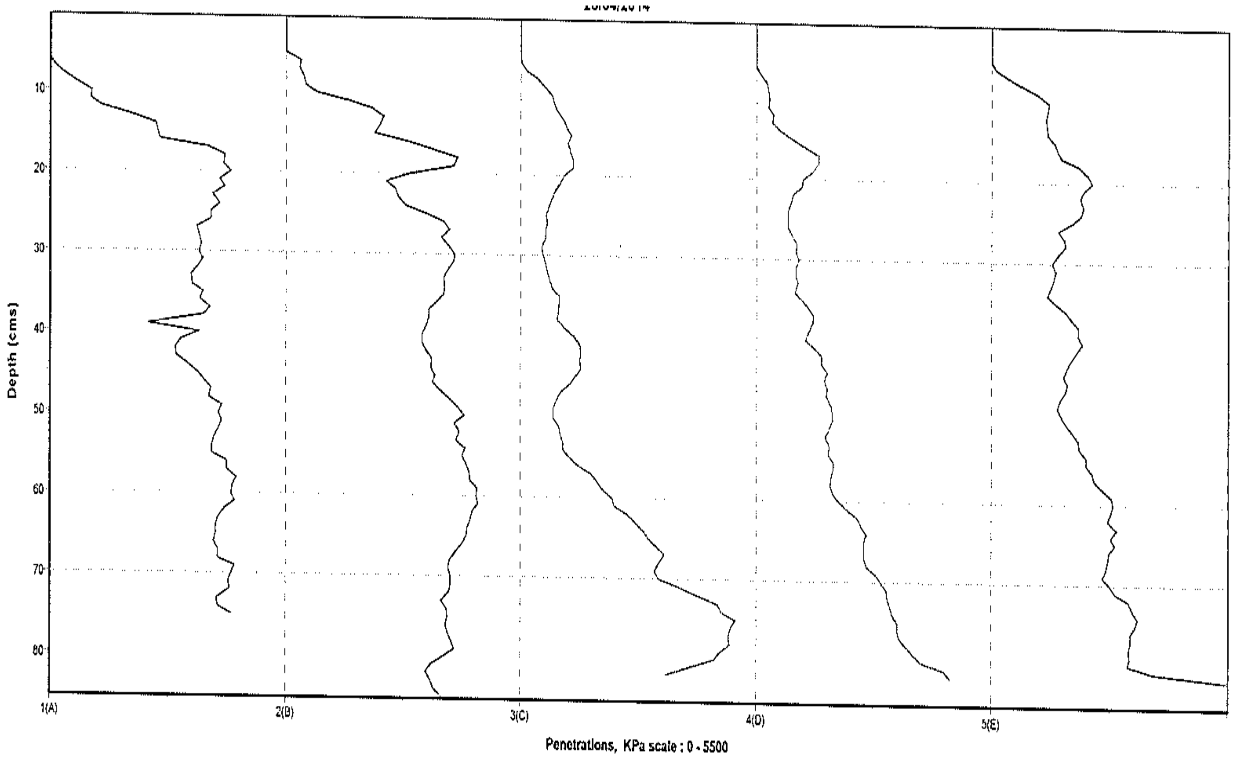


Figure-10
Soil penetrations for SMB showing compaction by machinery removing cut cane

Conclusion

There is no lateral effect of centre pivot wheels on compaction of soils in the vicinity of the tracks. Soil compaction is generally aggravated by mechanical harvesting and timing of operations as compaction values were higher for EEL09 which is chopper harvested. A remarkable increase in soil compaction for SMB centre pivot was also observed due to machinery traversing when collecting manually harvested sugarcane and the moist soil conditions during harvesting particularly the portions covered by heavy soils with high moisture retention. Actual penetration resistances towards root elongation are higher than the values obtained as fields are not irrigated to field capacity. The current trend of soil compaction among the fields will generally affect soil infiltration, water storage capacity, irrigation systems performance and subsequent reduction in sugarcane yields.

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