SOIL COMPACTION IN THE SOUTH AFRICAN SUGAR INDUSTRY – A REVIEW

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Abstract

Soil compaction issues were featured in the recent ISSCT Agricultural Engineering Workshop held in Malelane from the 24th to the 28th of July 2000. It is therefore appropriate to review our current state of knowledge on soil compaction within the South African sugar industry.

The last comprehensive review of soil compaction within the South African sugar industry was at a SASTA workshop held in 1964. Since then, the use of mechanised infield loading and transport has developed rapidly and there has also been a significant increase in the use of tractors for other field operations such as fertilizer application and weed control. Harvesting and cane extraction during wet conditions are unavoidable at certain times of the year and past field studies have shown that compactive force due to uncontrolled infield traffic will cause most of the damage to cane stools and soils.

During the past 30 years a number of field and laboratory studies of soil compaction have been conducted by staff from the Experiment Station and continue to features prominently in the current programme of work. The paper summarises past research outcomes on the effects of compaction on cane production and soil properties, and examines management strategies for minimising yield loss.

Keywords: soil bulk density, maximum bulk density, soil compaction, sugarcane, estimating

Introduction

The importance and extent of soil compaction problems in the South African sugar industry were discussed at a SASTA symposium on soil compaction and summarised by Cleasby (1964). At that time the use of tractors for operations such as cultivation, planting, fertiliser application, weed control and cane extraction was common practice and yield depression due to compaction had become apparent. A trial conducted by BE Beater on a soil with 28% clay and 15% silt and using a tractor and 2.5 ton trailer showed a reduction of 22.7% in millable cane stalks harvested at the age of 12 months due to soil compaction (Cleasby, 1964). Soil bulk density was inc0reased from 1.30 to 1.55 ton/m^3 and porosity was reduced by 10%.

Since 1964 the size of infield vehicles has increased and haulage units up to 30 ton capacity are used to extract cane from fields. The use of these heavy vehicles has necessitated research into ways of reducing their destructive effects, leading to the development of various wheel and axle configurations, different types of tyres, and management guidelines to minimise compaction. Factors such as soil water content, texture, structure and organic matter affect the final density of soils. Taylor and Pohlen (1962) proposed a guide to benchmark the bulk density classes of uncompacted virgin soils (Table 1). From a survey of 28 soil profiles covering most of the SA sugar industry, Meyer (1985) concluded that typical wet bulk densities of uncompacted grey hydromorphic soils were >1.7 ton/m^3, for red soils between 1.3 and 1.6 ton/m^3 and for black soils between 1.2 and 1.5 ton/m^3. The main objective of this paper is to summarise soil compaction studies in the South African sugar industry since 1964 and the management guidelines developed during the last 25 years. The paper is divided into three parts: crop responses to soil compaction, physical aspects of compaction, and mechanical aspects of compaction.

Crop response

Soil compaction reduces porosity, which is an important parameter affecting root development, gas exchange rates, nutrient availability and the hydraulic properties of soils (Maud, 1960). However, it is not always detrimental and Boone (1986) gave examples of three different types of reaction from the literature, which are segments of an optimum curve. The first is where no-tillage was used resulting in no statistically significant relationships between soil compaction and yield. The second type of response is where yields are increased due to compaction (also noticed for cane in the data by Swinford, 1985). The third and most common type reported is where yields were decreased due to compaction.

Critical bulk density: In order to relate yields to soil density, critical bulk densities are required for all soil types. If these are exceeded, yields will be reduced. Data demonstrating this effect in the South African sugar industry are limited to those found in a report by Swinford (1985), from which it was determined that for a sandy loam of the Longlands form, the critical wet bulk density was 1.76 ton/m^3 (see Figure 1).

Table 1. Soil bulk density classes for uncompacted virgin soils (Taylor and Pohlen, 1962).

Class	Bulk density (ton/m^3)	Soil type
Very low	< 0.2	Peats
Low	0.2 to 0.8	Topsoils of well structured loams
Medium	0.8 to 1.3	Topsoils of most soils and well structured subsoils
High	1.3 to 1.8	Sandy, gravelly and stony subsoils
Very High	> 1.8	Extremely stony soils

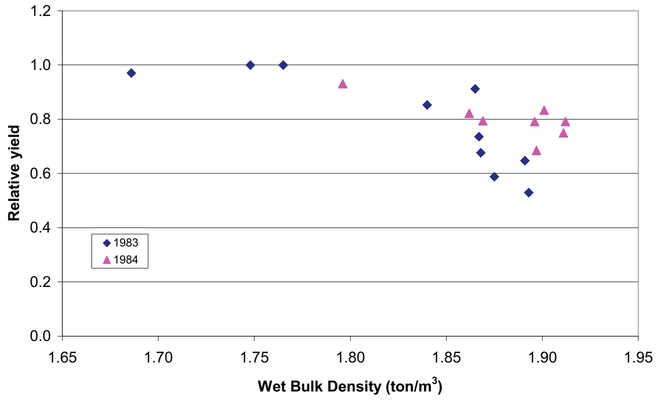

Figure 1. The effect of increasing wet bulk density on relative yield for two crops from a Longlands duplex soil (Created from data by Swinford, 1985).

Roots: Compaction densities due to vehicle tyres are highest near the soil surface and decrease with depth and distance from the tracks (Taylor, 1974). Traffic decreased the total soil volume for root growth in the interrow but not the maximum rooting depth beneath the row, when annual in-row subsoiling practice was used on annual crops (Raper *et al.*, 1994). Swinford and Boevey (1984) showed that compaction close to or on the row caused more roots to develop within the first 0.3m soil depth compared with the uncompacted treatment. The roots from the compacted soil had a larger diameter than those from the uncompacted soil, which were thin and fibrous but with a larger surface area and probably more efficient in providing the crop with water and nutrients.

Yields: The effects of infield transport on yields when harvesting sugarcane are difficult to quantify. Although changes in soil physical properties can be measured, they do not necessarily result in yield reduction (De Beer *et al.*, 1993; Swinford 1985). Donaldson (1986) found that ripping decreased soil strength in a red structured soil containing 52% clay at Komatipoort, as measured with a penetrometer, but it had no effect on yield when compared with compacted fields that were not ripped. A similar result was also found by Johnston and Wood (1971) on a non-structured red sandy clay of the Hutton form at Pongola. They showed that subsoiling reduced bulk density without increasing yield.

Moberly (1969) studied the effects of subsoiling in eleven different soils on ratoon cane and found that three showed a significant depression in yield (Glenrosa, Milkwood and Arcadia), seven gave no response and only one showed a significant yield increase (Kroonstad). However, in a recent re-evaluation four soils showed a positive response (although only one was significant) and all belonged to the grey group of soils where the second layer was an E-horizon. The negative responses were obtained mainly on soils with a high clay content.

Moberly (1972) conducted deep (up to 1000mm) tillage trials on five soil forms (Arcadia, Shortlands, Fernwood, Longlands and Milkwood). Of the 30 crops harvested, four were situated on Fernwood form soils and of these, three showed the largest responses to deep tillage, altough only one was significantly positive. The reason for the good responses obtained on the Fernwood soils where compaction problems are unlikely was thought to be nematode disturbance following inversion of the soil. Moberly concluded that the responses obtained did not warrant the high cost attached to deep tillage.

Leibbrandt (1985) studied the effects of ripping the interrow on cane yields in five commonly irrigated soils in Swaziland (Shortlands with 35 to 55% clay, Tambankulu with more than 35% clay, Arcadia with more than 50% clay, Estcourt duplex soil and Sterkspruit duplex soil). Results from nine trials showed no yield benefits due to deep ripping or chiselling the interrow after harvest. The trial on the Shortlands form soil showed a significant yield reduction when compared with the unripped treatment.

Swinford and Boevey (1984) applied various levels of compaction to a Longlands form sandy loam and found that yields were negatively affected by an increase in the level of compaction. Compaction treatments were superimposed after the plant crop was harvested and not repeated in subsequent

Table 2. Maximum bulk density, water content to obtain maximum bulk density and porosity at maximum bulk density for various parent material types (after Maud,1960).

Parent material (new name) [1]	Parent material (old name)	PMBD [2] (ton/m^3)	SWC [3] (%) at PMBD	Porosity (%) at PMBD
Tugela Schist	Tugela Schist	1.62	24.5	32.2
Granite	**Granite**	**1.84**	**13.0**	25.8
Natal group sandstone	**Table mountain sandstone**	**1.93**	**11.0**	25.8
Natal group sandstone Mist Belt	Table mountain sandstone Mist Belt	1.21	41.5	42.5
Dwyka tillite	Dwyka tillite	1.92	11.5	22.9
Pietermaritzburg shales	Lower Ecca shales	1.64	21.5	35.9
Vryheid sediments	**Middle Ecca shales**	**1.90**	**12.5**	21.8
Dolerite (red)	**Dolerite (red)**	**1.50**	**30.5**	33.9
Dolerite (black)	Dolerite (black)	1.49	28.0	35.2
Sand (light & red)	Sand (light & red)	1.95	6.5	27.2
Sand (heavey & red)	Sand (heavey & red)	1.85	16.0	31.7
Sand (grey)	Sand (grey)	1.75	10.0	33.5

1. SASEX Soil Identification and Management Working Group (1999)
2. Proctor Maximum Bulk Density (ton/m^3)
3. Soil Water Content – near field capacity and in gravimetric units

crops. Yield reduction due to compaction for the worst treatment (compaction load on both the row and interrow) was 32% in the first ratoon compared with 48% in the second ratoon (see Figure 2). The worst treatment where compaction was restricted to the interrow showed a yield reduction of 27% in the first ratoon and 35% in the second ratoon.

On a melanic soil (Mollisol), Torres *et al.* (1990) compared yield reductions following interrow compaction with stool damage caused by infield transport. In general, yields were lower where a tractor and trailer compacted the soil, compared with a grab loader. Stool damage from the grab loader resulted in a yield decrease of 7%, but interrow compaction had no effect on yield. Interrow compaction due to the tractor and trailer resulted in a yield reduction of 9%, but from stool damage there was a yield reduction of 53%. Torres *et al.* concluded that direct damage to stools was more important than compaction in affecting the yield of the following crop.

Soil physical aspects of compaction

Soil texture: Published information on the relationship between the bulk density (BD) of compacted soil and soil texture is scarce because actual clay, silt and sand content are generally not quoted. Instead the soil textural classifications are reported. Maud (1960) gave Proctor (1933) maximum bulk density (MBD) values for various parent materials commonly found in the South African sugar industry (Table 2). These values can be regarded as soil density limits for the parent materials at which root development, gaseous exchange rates, water infiltration rates and water storage are most severely affected. The water content at which these maximum densities were obtained corresponds to field water capacity (Maud, 1960; Cleasby, 1964). From data published by Maclean (1976) it was determined that the water content at which a modified Proctor MBD value was obtained corresponded to 89% (standard deviation 8.6%) of field water capacity over a wide range of textures.

Figure 3 was created from data taken from studies by Smith *et al.* (1997) conducted in the forestry industry. It shows a negative relationship between MBD (the soil was compressed with an hydraulic pressure of 1400kPa) and water content, organic carbon and clay content. A similar relationship between MBD and clay content was obtained by Henning *et al.* (1986) and the clay range for this relationship was between 5% and 28% clay but it was not linear. Henning *et al.* (1986) determined MBD by the standard Proctor method (1933) in contrast to the compression technique used by Smith *et al.* (1997). In Figure 4 the measured data from Smith *et al.* (1997) for MBD versus clay content are compared with that from a regression equation by Henning *et al.* (1986) (see equation 1 below). Although Henning *et al.* (1986) did not evaluate their equation beyond a clay content of 28%, it performed well in predicting the MBD values obtained by Smith *et al.* (1997). The only major difference occurred at a clay content of 66%, where the estimated MBD was 0.336 ton/m^3 and the measured value was 1.450 ton/m^3. It appears that equation 1 can be applied with confidence to the soils of the sugar industry with a clay content of up to 50%, and that there is a good relationship between the Proctor and 1400 kPa pressure determined MBD.

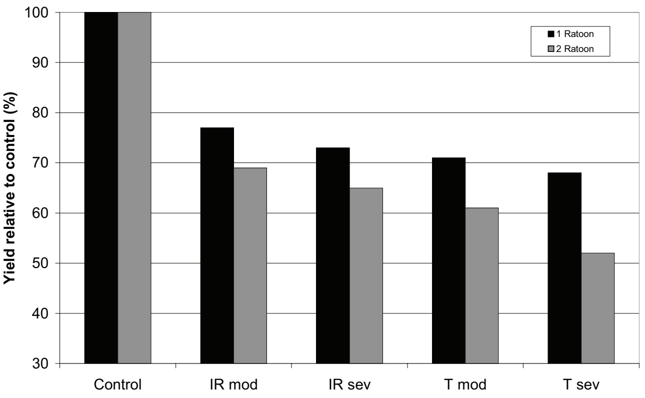

Figure 2: Yield response of the first and second ratoons relative to the compaction treatments on a Longlands form soil at La Mercy farm (after Swinford and Boevey, 1984). Treatments were: Control = no compaction, IR mod = interrow compaction load 3.7 ton, IR sev = interrow compaction load 5.7 ton, T mod = row + interrow compaction load 3.7 ton, T sev = row + interrow compaction load 5.7 ton.

Equation 1 answers the question regarding the maximum bulk density for a soil of given clay content. However, it is useful to know at what soil water content (SWC) MBD will occur in order to avoid the use of infield transport when compaction to near maximum bulk density is likely to occur. Equation 2 was developed from data by Smith *et al.*, (1997) (Figure 3) in order to relate the MBD obtained with equation 1 to SWC at which

Table 3. The relationship between maximum bulk density and other physical properties of five soils (after Smith et al., 1997). Note the parent material similarity between the data in bold in this Table and that in Table 2.

Parent Material	Soil form [1]	Clay (%)	Silt (%)	MBD [2] (ton/m^3)	SWC [3] (%)	Organic carbon (%)
Diabase	Kranskop	66	28	1.45	27.0	4.13
Dolerite	Kranskop	51	44	**1.30**	**34.0**	5.77
Granitic Gneiss	Kranskop	44	15	1.65	18.0	4.23
Ecca Sandstone	Clovelly	35	16	**1.88**	**14.0**	1.37
Granite	Hutton	26	10	**1.84**	**13.5**	1.49
Biotite Granite	Nomanci	24	17	**1.80**	**14.0**	2.36
Coarse Sandstone	Cartref	16	34	**1.94**	**10.5**	0.95
Berea Sands	Hutton	12	9	1.91	11.5	0.43

1 SASEX Soil Identification and Management Working Group (1999)
2 Maximum bulk density obtained with a hydraulic compression of 1400 kPa (Smith *et al.*, 1997)
3 Gravimetric soil water content

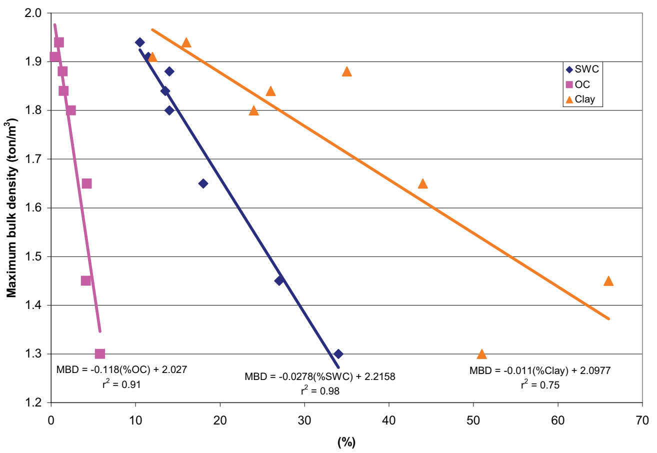

Figure 3. The relationship of maximum bulk density (after compressing the soil at 1400 kPa) with soil organic carbon (OC), soil water content (SWC) from which maximum density was obtained and clay% (created from data by Smith *et al.*, 1997).

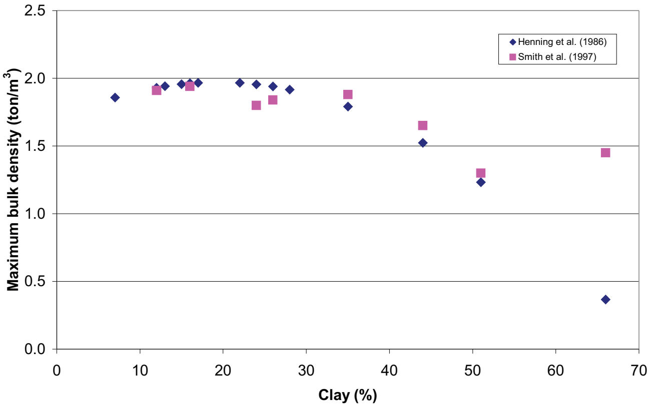

Figure 4. The comparison between Henning *et al.* (1986) estimated data and Smith *et al.* (1997) measured data on the relationship between maximum bulk density and clay content.

MBD would be reached. (See the method for assessing when is a field too wet for in field transport in Appendix 1).

$$\text{MBD} = (1692.13+28.74(\text{Clay})-0.74(\text{Clay})^2)/1000 \quad r^2 = 0.98 \tag{1}$$

$$\text{SWC}_{\text{grav}} = 78.302-35.143(\text{MBD}) \quad r^2 = 0.98 \tag{2}$$

Where

MBD = Maximum bulk density is determined with the standard Proctor (1933) method (Henning *et al.,* 1986) (ton/m^3)

SWC$_{\text{grav}}$ = Gravimetric soil water content (%) at which MBD was obtained after compressing the soil with a force of 1400 kPa (Smith *et al.,* 1997) and which was shown to be comparable to the Proctor MBD values (Figure 4)

Clay = Soil clay content (%)

These results can be applied to sugarcane as the study by Smith *et al.* (1997) was conducted on soils in the eastern region of South Africa, some of which are used for cane production. When comparing Tables 2 and 3 the similarity of the physical properties of the highlighted parent materials confirms this. More sophisticated equations have been reported by Gupta and Raper (1994) and Smith *et al.* (1997) while simpler equations were applied by Moolman (1981) for soils of the Western Cape, and Henning *et al.* (1986) for the aeolian soils in the central part of South Africa.

Moolman (1981) and Henning *et al.* (1986) also found that soil compactibility was affected by the degree to which the soil was texturally sorted. Moolman (1981) established that the grading of soils, as quantified by the coefficient of kurtosis, was the most important parameter for particle size distribution, influencing soil compactibility and explaining 82% of the variation in MBD affected by texture.

Soil water content: The degree, to which soils will compact when a force is applied is primarily dependent on the amount of water present (Cleasby 1964; Ekwue and Stone, 1995). Equation 3 is a multi-parameter linear equation with SWC, organic carbon (OC) and soil clay content as inputs. It was created from the data of Smith *et al.* (1997) to test the relative importance of these soil constituents to predict MBD. Table 4 reflects the statistical significance of each input parameter and shows that SWC accounts for most of the variation in the data, followed by OC.

$$\text{MBD} = 2.175 - 0.01913(\text{SWC}) - 0.03687(\text{OC}) + 0.000498(\text{Clay}) \quad r^2 = 0.99 \tag{3}$$

In general when trying to compact a dry soil (starting with no water), the maximum density will decrease with an increase in soil water content (SWC) until permanent wilting point (PWP) is reached (Swinford and Boevey, 1984). There-after, maximum bulk density will increase with increasing SWC (Maud, 1960; Swinford and Boevey, 1984; Henning *et al.*, 1986; Smith *et al.*, 1997). When the SWC is approximately at field capacity (FC), maximum compactibility starts to decrease quickly as the saturation point is approached (Maud, 1960; Smith *et al.*, 1997). Thus maximum resistance to soil compaction occurs when SWC is close to PWP, while the least resistance to compactibility is around FC. These two soil hydrological parameters can be estimated from clay content using equations 4 and 5, which have been developed for the South African sugar industry by Van Antwerpen *et al.* (1994).

$$\text{FC} = 54.70(\text{Clay})/(24.53+\text{Clay}) \quad r^2 = 0.91 \tag{4}$$

$$\text{PWP} = 91.94(\text{Clay})/(135.34+\text{Clay}) \quad r^2 = 0.93 \tag{5}$$

where

FC = Volumetric water % at field capacity

PWP = Volumetric water % at permanent wilting point

Figure 3 reflects the SWC at which MBD was obtained as a negative linear relationship. The work reported by Henning *et al.* (1986) suggests that the MBD obtained for a soil with only 5% clay is lower than that for a soil containing 28% clay. It is thus possible that the relationship between SWC and MBD is initially positive at low values of clay and becomes negative at higher clay contents ranging from 16% to 28%. Ekwue and Stone (1995) also reported this parabolic relationship between MBD and SWC.

Organic matter: As early as 1935 the importance of organic matter in maintaining or reducing the rate of soil degradation under sugarcane was recognized by Von Stieglitz (1935). In general, compaction causes degradation of the physical properties of soils and organic matter improves or maintains the quality of soils (Ohu *et al.*, 1985; Van Antwerpen and Meyer, 1996). However, a survey of the literature showed how few studies have quantified the effect of different organic materials on the physical properties of soils compared with other factors affecting compaction, such as texture, SWC and compactive effort.

Byproducts of sugarcane have been shown to be a valuable source of organic matter. Thompson (1965) compared retention of cane trash on the soil surface with burning of trash on a vertisol, and found a consistent but not significant lower soil bulk density for the trashing treatment. Paul (1974) evaluated the effectiveness of filter-press mud (filtercake) and concluded that soil bulk density was significantly reduced at an incorporation rate of 15.1 ton/ha with no further improvement at 30.2 ton/ha. Georges *et al.* (1985) compared the ability of bagasse and filtercake to reduce soil compaction. They concluded that bagasse was more effective than filtercake in alleviating compaction due to its lower density, greater porosity and higher water retention properties. Outside the sugar industry Ekwue and Stone (1995) studied the effects of peat and farmyard manure (FYM) on the Proctor (1933) maximum bulk density of a sandy loam and a clay soil. They also found that organic matter with the lowest density (peat) was more effective in lowering the density to which soils can be compacted, reducing their shear strength, and penetration resistance. The relative sensitivity of maximum bulk density on changes in organic matter compared with changes in clay content or soil water content, illustrates the importance of soil organic matter in controlling bulk density (see Figure 3).

Soil compaction and mechanical aspects

Traffic-induced soil compaction is a problem that has developed wherever agriculture has become highly mechanized (Taylor, 1990). The logical solution to this problem appears to be subsoiling but the complexity of alleviating soil compaction was kept in mind by Taylor (1990) when he wrote, "Even when done in a properly designed cultural system, subsoiling is treating the symptoms and intensifying the disease." However, mechanical cane operations, especially but not exclusively in irrigated areas, are bound to increase and the severity of soil compaction will therefore be aggravated. Finding a solution to this problem is therefore of the utmost importance.

Causes of compaction: Machinery such as tractors, trailers and harvesters entering fields causes soil compaction. The degree of compaction depends on a number of factors, including as soil water content, clay content, organic matter content, number of passes, axle load, and size, type, shape and inflation pressure of the tyres (Soane *et al.* 1981a & 1981b). Knowledge of the factors affecting compaction can be used to minimize the compactive effect of agricultural machinery on soils.

Maud (1960) showed that the first pass of a machine causes a much larger increase in compaction compared with subsequent passes, especially where the soil was initially loose (Soane *et al.* 1981a & 1981b). This is caused by the high porosity of the loose soil, which is significantly reduced after the first pass. The average pressure exerted by a tyre on a firm surface is about equal to the inflation pressure (Chancellor, 1977). However, Taylor *et al.* (1980) found that as the tyre width and axle loading increased, a given soil pressure occurred deeper into the profile compared with a smaller tyre with a reduced axle load, but with the same inflation pressure. They concluded that, although reducing the inflation pressure increases the soil-tyre contact area, leading to a reduction in the depth of compaction, it increases the surface area affected but not the volume of soil.

Taylor (1983) showed that a long and narrow tyre footprint in the direction of travel give better traction and less soil compaction than a contact surface with the same area but wider and shorter. Vanden Berg and Gill (1962) showed that tyres with stiff sidewalls (crossply) transmit some compaction forces directly to the ground and are less effective than the soft walled (radial) tyres in reducing the severity of soil compaction.

Alleviation of compaction: The benefits from subsoiling are shortlived compared to the complete disturbance with a mouldboard plough. Raper *et al.* (1994) reported that traffic reconsolidated soil that was initially completely disrupted to a depth of 0.5 m, into a soil condition similar to that which had never received a subsoiling treatment. In certain soils compaction may be beneficial (Swinford, 1985; Boone, 1986) and in others subsoiling may alleviate compaction, but the production potential of these may not be the same as that before compaction was introduced (Johnston and Wood, 1971; Boone 1986).

One of the attempts to reduce the effects of soil compaction was infield controlled-traffic zones (Carter, 1985). In a study to establish the minimum distance between the row and the edge of the tyre, Carter found satisfactory soil physical properties and no effect on the crop where this distance was 0.75 m. Another method of reducing soil compaction was to combine permanent infield traffic zones with a tractor or gantry having a width ranging from 6 to 12 m (Taylor, 1983).

Table 4. Statistical significance for equation 3. Note also the significant importance of the variables used (created using data taken from Smith *et al.*, 1997). There were eight observations.

Component	Coefficients	Standard Error	T Stat	P-value
Intercept	2.174598	0.0301	72.30	0.0000
X Variable 1=SWC	-0.019131	0.0034	-5.64	0.0049
X Variable 2=OC	-0.036869	0.0148	-2.49	0.0672
X Variable 3=Clay	-0.000498	0.0011	-0.44	0.6826

SWC = Gravimetric soil water content (%) OC = Organic carbon (%)

Using subsoilers to prepare for planting, Ricaud (1977) compared the yield response of fields ripped either with a regular subsoiler or a vertical mulcher. Yield increase due to subsoiling was 19.3% compared with 39.9% for vertical mulching.

Recommendations and conclusions

It is evident from the literature that damage to sugarcane stools and soil compaction are two separate issues but they can occur simultaneously. Stool damage caused by cane haulage equipment can reduce yields by as much as 50% and reduce the number of ratoons before plough-out. Large parts of the relatively flat areas of the South African sugar industry are likely to become mechanised and therefore compaction problems will become more common. In order to make provision for this growers should consider:

- Increasing the width of interrows to suit the width of infield equipment.
- Using preplanned permanent zones for infield traffic. The principles of controlled zones for traffic and the use of an infield tracks should be combined to restrict the area affected by compaction and to keep compacted zones in selected interrows.
- Not allowing transport in fields when soils are wet.
- Using transport with long tyre and track footprints in the direction of travel rather than those with the same contact area but that are wider and shorter.

Transport travelling in the interrow but next to the row is bound to cause surface root damage and compaction close to the stool, which will almost certainly have a negative effect on yield. A distance of 0.75 m between edge of the row and the wheel, as reported in the literature, will certainly be effective in avoiding stool damage and reducers the effect of soil compaction on yield, but is unlikely to be accepted by growers as a practical measure.

- A more acceptable distance between the edge of the row and the side of the wheel would be 0.40m, assuming that the width of the tyre is 0.6m.
- This means that total interrow spacing from the centre of one row to the centre of the next row must be 1.8m.
- However, this will not suit all farming systems and growers should, in conjunction with SASEX extension officers, decide on a row spacing that will best suit their infield transport.

Alleviation of soil compaction with a subsoiler is a popular technique with growers although the results from trials conducted in South Africa and Swaziland have shown no yield benefit from this practice.

- Only soils with an E-horizon in the grey soil group have shown a positive yield response to subsoiling, although limited.
- It appears that the likelihood of a positive response to subsoiling is low in soils with a high clay content.
- An alternative to subsoiling is to harvest cane on soils most susceptible to compaction during the dry months (see Table A in Appendix 1).
- The observation that subsoiling with a vertical mulcher is more efficient in alleviating compaction compared with a single tine ripper has been confirmed.

Other points of interest:

- Where soil compaction is a major problem and there is a choice of organic materials available, the principle to be applied is the use of organic materials of lowest density, as these will be more effective in reducing soil density.
- Where there is little choice of material, any type of organic material in reasonable quantities will be better than none because of the general decline of soil organic matter in cultivated soils.
- It appears that similar maximum bulk densities can be obtained when samples are either compressed with a force of 1400 kPa or compacted by the standard Proctor (1933) method.
- Future work on soil compaction in the South African sugar industry must be focused on determining the critical density of soils above which cane yields are negatively affected. Meanwhile the method for assessing the status of soil bulk density given in the Appendix 1 can be used.
- All future work on compaction must also contribute to the development of models for the estimation of soil density from factors such as soil water content, organic matter, soil texture, tyre specifications, axle load and soil stress-strain relationships.

The effects of soil density on root distribution and the hydraulic properties of soils make soil compaction models important for estimating soil changes due to various infield operations. Soil compaction models are therefore a valuable tool for inclusion into crop growth models.

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APPENDIX 1

How to assess that the field is too wet for in field transport

1. Use equations 1 and 2 to determine the maximum density of soils and the water content at which this density can be obtained:

Table A. A guide based on soil form to assess the optimal time for harvesting to minimise compactive effects (after SASEX Soil Identification and Management Working Group, 1999).

Soil group and management unit	Soil form [1]	Drainage	Soil compaction hazard	Timing of harvest operations
Brown humic	Inanda, Nomanci, Kranskop, Magwa, Lusiki, Sweetwater	Good	Low	Virtually any time of the year
Black and red structured	Shortlands, Arcadia, Rensburg, Bonheim, Inhoek, Milkwood, Mayo, Willowbrook	Moderate to poor	Moderate	Winter/spring
Red and yellow-brown	Augrabies, Bainsvlei, Hutton, Clovelly, Griffin	Good	Moderate to low	Virtually any time of the year
Grey upland	Cartref, Glenrosa	Good	Moderate	Summer
Grey bottomland	Estcourt, Klapmuts, Vilafontes, Longlands, Westleigh, Swartland, Valsrivier, Sepane, Kroonstad, Tukulu	Moderate to poor	Severe	Winter/spring
Grey deep	Fernwood, Namib, Dundee, Oakleaf	Good	Low	Summer

[1] SASEX Soil Identification and Management Working Group (1999)

$$\text{MBD} = (1692.13+28.74(\text{Clay})-0.74(\text{Clay})^2)/1000$$
$$r^2 = 0.98 \qquad (1)$$

$$\text{SWC}_{grav} = 78.302-35.143(\text{MBD})$$
$$r^2 = 0.98 \qquad (2)$$

Equation 1 can be used to estimate the maximum bulk density to which a soil with a specified clay content can be compacted. Equation 2 can be used to determine the gravimetric soil water content (SWC) at which this maximum bulk density will be obtained. The latter should be multiplied by the field bulk density (ton/m^3) in order to convert gravimetric SWC to volumetric SWC. Equation 2 should be used with caution, as no data for evaluation are available, and should not be used for soils with a clay content of less than 16%.

The simplicity of equations 1 and 2 should make them valuable for use by growers and extension officers in order to obtain an estimate of the maximum density to which these soils can be compacted thus putting densities obtained in the field into perspective.

2. Determine the current density of the soil: A number of methods are available to establish the bulk densities of soils.

a. Remove an unbroken soil core with a known volume from the profile. Dry it for 24 hours at 105°C and determine the dry mass. Divide the dry mass by the volume of the core to obtain the bulk density.

b. Use a nuclear device such as that described by Swinford and Meyer (1985), with which an immediate assessment of the bulk density can be obtained.

3. Assess the relative bulk density: Divide the soil bulk density by the maximum bulk density. The value obtained should ideally not be larger than 0.9 and in general the lower the value the better.