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**A LITERATURE REVIEW OF HARVESTING
OPERATIONS AND THEIR IMPLICATION ON
SOIL COMPACTION AND YIELD IN SUGAR CANE**

by

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APPENDIX 1

Braunack, M.V. (1999a). Economic cost of soil compaction. Final report – SRDC project BS142S, BSES Internal Report, 1012.
Appendix 1, User manual for COMPACT\$

APPENDIX 2

Braunack, M.V. (1991). The effect of soil physical properties on growth and yield of sugarcane. BSES Internal Report, 528.

APPENDIX 3

Van Antwerpen, R. *eta al.*, (2000). Soil compaction in the South African sugar industry – a review. Proc. S. Afr. Sug. Technol. Ass., 74: 101-108.

1.0 INTRODUCTION

A significant effort has been applied to the investigation of soil compaction in the sugar cane industry. Most recently research performed by Dr Mike Braunack at Tully in the wet tropics of Queensland, Australia, has attempted to quantify the relationships that exist between harvesting of sugar cane, soil compaction and yield. Harvesting has the greatest impact on soil physical properties as the cane harvester and haul-out machines, the heaviest machinery used in the production of sugar cane, traffic the interspace at least two times for each implement and are required to harvest at soil moisture contents that range from field capacity to wilting point to ensure continuity of supply to their respective sugar cane mill.

A major conflict in sugar cane production is the requirement of optimum soil conditions for plant growth verses trafficability to support cultivating, planting and harvesting machines. The weight of machines (axle load) will compact soils sometimes to an extent hostile to plant root growth. Sugar cane farming in Australia can be considered row cropping. Cane is currently planted at 1.45 to 2.00 m rows, sometimes as dual or triple rows at the wider spacings. Trafficking by machinery is on the inter-row but can sometimes be near or even on the row through mismanagement.

This review will attempt to collate Australian and world information to establish an understanding of the issues involved and their impact.

2.0 BACKGROUND

In 1991 Dr Braunack completed a thorough literature review on “The Effect of Soil Physical Properties on Growth and Yield of Sugar Cane”. His review forms the background of this report and the starting point for the review of more recent works. References in this background should be referred directly to Dr Braunack’s paper in Appendix 2.

Many of the reports reviewed by Dr Braunack did not agree in their outcomes. This underlying inconsistency is a common thread that carries through to more current research. The amount of variability in nature, differing measurement techniques and the recording of only some of the parameters, particularly in older reports, make it difficult to collate results and draw any conclusions.

Overseas reports show a range of yield results from sugar cane crops that have been treated in various ways. Results range from no effect on yield to increased yields (due to weed control) to losses in yield due to soil structure degradation (Primavesi and Primavesi, 1964 (11)). Yang, 1978 (9) & Yang *et al.*, 1974 (10) in their study found no change in soil bulk density. Wood, 1985 (12) suggested that yield decline in sugar cane was partly due to soil structural degradation resulting from intensive cultivation.

The trend to larger and heavier harvesting and haul-out equipment is increasing soil structural degradation. This is accentuated when soils are wet (between field capacity and the lower plastic limit). Harvesting under these conditions increase soil bulk density, increase soil cone resistance (soil penetrometer), reduce saturated hydraulic conductivity and reduce soil porosity.

Torres and Villegas, 1992 (22) found losses up to 42% after traffic over the row associated with bulk density and saturated hydraulic conductivity increases and infiltration decreases. This was complicated by data inconsistencies and suggestions that the main cause may be due to direct stool damage by traffic (Torres *et al.*, 1990 (20)).

Increases in bulk densities reduce porosity (Hare, 1960 (35)) with greater changes in clay than silty clay. Yield decline was greater on the high density, low porosity soils than soils where density was lower and porosity higher. Observations were made from 4th to 6th ratoons.

South African research by Cleasby, 1964 (36) comparing manual and mechanical harvesting showed very little difference in shoot numbers and suggested varietal tolerance to soil compaction.

Australian work (Hurney, 1975 (37)) examining different harvesting and haul-out systems showed compaction in surface layers 0-10 cm and variable yield results due to differences in soil type and water contents. Vickers *et al.*, 1976 (38) reported no yield decline in the following ratoons if it had been harvested wet.

Significant losses have been recorded by Yang, 1977 (39) after repeated harvester passes with greater detrimental effect during periods of higher soil water content. Effects were detectable to 40 cm. Compaction under drier conditions is not as severe as under wet conditions. Higher floatation equipment will reduce soil bulk density but total axle load is the most significant issue.

Row width (1.5 m) incompatibility with current industry equipment (1.83 m) forces equipment to run hard against the row and, with driver error, traffic the entire row on occasions. Increasing row spacing to 1.85 m to match that of harvesting machinery is a logical step. This then allows a control traffic regime to be adopted.

Soil bulk density will affect cane growth at high levels but the absolute figure varies with soil texture. Rao and Narasimham, 1988b (60) found no limiting value for soil bulk density or root growth. Singh, 1964 (61) found a field bulk density of 1.75 g/cm³ restricted root growth which was reflected in poor shoot growth. An increase in soil bulk density also gave an increase in soil strength and a decrease in air-filled porosity (Swinford and Meyer, 1985, (41)). Pore continuity, rigidity and pore size distribution (Srivastava, 1990 (63)) restrict root proliferation. This occurred with sugar cane roots at pore sizes of 250 µm.

Improving soil physical condition by tillage after harvest can alleviate surface compaction and soil physical condition affecting subsequent yield. Variety, soil nutrition and the natural wetting and drying cycles of soils can mask this effect. Drying cycles cause cracking and opening of the soil and wetting cycles weaken soil strength allowing easier root penetration. Deep ripping can also be effective if soil moisture is appropriate.

Filter mud, bagasse, minimum tillage and trash blanketing have been used successfully to alleviate the effect of soil compaction (73, 74, 75, 76).

The effect on soil physical properties on sugar cane growth and yield is variable due to the influence of remedial action and climate. Attempts have been made to define the soil bulk density that limits growth and yield. This depends on soil water content used to generate the density and the soil texture. There is a need to more clearly define soil physical conditions in relation to sugar cane growth and to determine whether there is a soil physical constraint to production.

Dr Braunack identified a number of areas requiring further research:

1. A system of relative soil density should be developed that can be related to crop yield.
2. Determine the ability of sugar cane varieties to grow under high soil density/strength situations.
3. Review the impact of high floatation running gear on soil compaction.
4. Reduce sub-soil compaction by reducing equipment axle loads.
5. Investigate the impact of controlled traffic and the use of strategic tillage.
6. Study the effect of soil physical factors on soil biota.
7. The need to monitor soil physical factors in relation to plant growth over several seasons.

There is a need to more clearly define soil physical conditions and their impact on sugar cane growth.

3.0 REVIEW OF RECENT PUBLICATIONS

3.1 Soils

3.1.1 Soil water

Soil water is one of the major factors influencing soil compaction (Yang, 1980). Braunack (1993) noted that soil water content at the time of impact is critical to the extent of soil compaction (Chancellor 1977). When soil moisture falls between field capacity and the lower plastic limit soil compaction can be created when supporting machinery loads used in sugar cane production.

Braunack (1995) noted the higher the soil moisture content the greater is the potential for compaction. Movement of machinery, particularly harvesting, should be done under drier conditions to reduce the impact on soil physical properties Yang, (1977) in Braunack and Peatey (1999).

3.1.2 Soil texture

Soil texture is considered the other major variable in soil compaction. As the percentage of sand, silt and clay in a soil change so does the soils texture. Different soil textures will have the capacity to hold different amounts of soil water and will react differently under load. A soils texture also has a bearing on its capacity to maintain its structure and Conway *et al.* (1996) stated that it directly affects, water, air, nutrient movement and root growth.

3.1.3 Soil organic matter

Soil organic matter has a lesser effect on the physical attributes of compaction although Meyer and Van Antwerpen (1996) noted that increasing soil organic matter is an effective way to reduce the effect of compaction and maintain lower bulk density. Organic matter plays a vital role in providing food for soil fauna that can slowly repair the damage of compaction.

4.0 SOIL QUALITY INDICATORS

These indicators are methods of estimating how hostile the soil is for root growth, the health of soils and their potential to repair.

There are four soil physical properties commonly measured:

- bulk density
- soil cone resistance
- saturated hydraulic conductivity
- pore space.

It is also important to consider three other factors

- compaction depth
- organic matter
- soil fauna.

Torres *et al.* (1990) noted in Yang (1996) that the measurement of soil physical properties showed bulk density and soil cone resistance increased and soil porosity and water intake rate decreased as soils became more compacted. These four main characteristics are linked.

4.1 Bulk density

Bulk density is the dry weight of soil per volume. The standard measure is grams per cubic centimetre (g/cm^3). Bulk densities range depending on soil type and the level of compaction. Yang (1980) described natural bulk densities usually greater than 1.45g/cm^3 and can reach 1.6 g/cm^3 in Taiwanese soils. Braunack and Peatey (1999) noted soil bulk density increased as soil water content increased at the time of impact (Yang 1974).

Eastwood *et al.* (1997) reported that in Guyana with hand harvesting and the use of a Bell 120 loader, when soil bulk density exceeded 1.45 g/cm^3 in the 0-30 cm, there was a distinct yield decline.

Braunack and Peatey (1999) also found repeated traffic over the row brings bulk densities towards an equilibrium with little change occurring with subsequent traffic. The largest change occurs with the first trafficking. This was quantified by Braunack and McGarry (2001) measuring 80% of the final compaction in the wheel tracks occurring in the first pass.

A relationship for the resistance to root penetration was given by Torres and Rodriguez (1995) that at any given bulk density the mechanical resistance for root penetration is inversely related to moisture content.

Results by McGarry (1998) showed that conventional plough-out in Bundaberg and Tully was not effective in reducing bulk densities in the inter-rows. Inter-rows are better left hard to cater for wet weather harvest. This was also the least cost option.

Pinto and Bellinaso (2000) of Brazil refer to a threshold value of 1.30 g/cm^3 for bulk density in comparing 2 types of haul-out driven both on and off the cane row.

Van Antwerpen (2001) noted organic matter with the lowest bulk density is more efficient at lowering soil bulk density. Farmyard manure was reported to give better results than filter press. There was a 13.5% and 5.0% reduction in bulk density respectively.

4.2 Soil cone resistance

Soil cone resistance is a measure of the pressure required to push a rod through the soil. For any particular soil, values will vary as soil moisture changes. This is measured in mega Pascals (MPa).

Braunack and Peatey (1999) noted that root growth was suggested to be greatly restricted at cone resistance values greater than 2 MPa (Greacen, 1969). Values greater than 3 MPa are considered to effectively stop cane root penetration (Braunack, pers. com. 2002).

Typical results from a yellow podsolic in Bundaberg McGarry *et al.* (1997) showed soil cone resistance in the entire profile of the inter-row to be over 2 MPa and the cane row reaching 2 MPa resistance at 380mm depth.

4.3 Saturated hydraulic conductivity

Saturated hydraulic conductivity is the rate water moves through a saturated core of soil. It is usually measured in millimetres per minute or hour (mm/min) (mm/hr) and requires connectivity of pore spaces for effective water movement.

McGarry *et al.* (1997) researching in Bundaberg on a yellow podsollic showed four soil physical characteristics in the row that indicated suitable conditions for cane growth. The interspace was completely different. At 200mm depth there was 85% more soil pores less than 3mm and 58% more pores at less than 1mm in the cane row than in the inter-row.

Braunack and Peatey (1999) noted that saturated hydraulic conductivity decreases after traffic as soil cone resistance increased. Although saturated hydraulic conductivity was significantly decreased at the 15-20 cm depth, pore connectivity was maintained at one site. This was a function of traffic impacting when soil water content was below the plastic limit.

4.4 Pore space

Pore space is a measure of air spaces in the soil. These pores must be connected through the soil to allow air and water movement. As a load is applied to a soil air is compressed and expelled causing an increase in bulk density and associated changes. Braunack and Peatey (1999) noted from Torres and Villegas (1992) that air-filled porosity falling below 10% indicates aeration may be a limiting factor in crop growth.

Heisler and Kaiser (1995) stated a reduction in soil porosity is mainly a loss in pores greater than 50µm that are inhabited by soil mesofauna. Typical are the Collembola whose population were measured in different crops with varying trafficking regimes in Germany. A drop in population was attributed to a loss of habitat, caused by machinery traffic, and where resulting pore sizes were too small causing damage to the waxy coating of the Collembola. The modified environment was also linked to a reduction in available food.

4.5 Compaction depth

Compaction depth is a measure of the depth in centimetres (cm) or millimetres (mm) from the soil surface to a significant change in or pre-described value for bulk density or soil cone resistance reading.

Braunack and Crees (1998) found in a haul-out trial a traffic pan at 320 mm formed under dual road tyres and no evidence of a pan was found under super-singles. Traffic pans affect root growth by reducing depth and consequently volume of soil available for plant exploitation

It must be remembered that compaction is not always related to depth as Braunack and Hurney (2000) found traffic over the row caused direct damage to the stool and nodal buds. Buds closer to the soil surface are likely to suffer more damage. Braunack (1998c) found there was less soil compaction in wider row spacing compared to the narrower rows.

Braunack and Ainslie (2001) observed soil resistance in the Mackay green cane trash blanket trials of less than 2 MPa from 0-200 mm and greater than 2 MPa from 200 mm. This reflected the depth of tillage before planting this crop cycle.

Yang (1980) found the influence of compaction reaches 30-40 cm and a plough pan was noted at 30-45 cm in Taiwanese soils. It was also noted that this was being effectively managed by deep ripping to 35 cm.

4.6 Soil organic matter

Meyer and Van Antwerpen (1996) recorded soil aggregate stability based on soil crumb measurements indicating that trash treatments are more stable than burnt treatments in all soil crumb sizes.

Bell *et al.* (2001) found an increase in total and labile C concentrations in soils under green cane trash blanket and the presence of surface cover from the trash blanket itself greatly increases water infiltration caused by surface crusting on Bundaberg soils.

4.7 Soil fauna activity

Heisler and Kaiser (1995) stated a reduction in soil porosity is mainly a loss in pores greater than 50 µm, which are inhabited by soil mesofauna. Typical are the Collembola whose population were measured in different crops with varying trafficking regimes.

Braunack *et al.* (2001) recognised that earthworms can be considered an indicator of soil health. They undertake tillage for free, create pathways for water, air and root access and incorporate organic materials that aid in increasing soil stability. They also noted that cultivation reduces numbers of *Metarizium*, *Adelina* and the mycorrhizal fungus VAM. A trash blanket and zero till are the best way of maintaining these beneficial organisms.

5.0 ORGANISM EFFECTS

5.1 Soil biota

Braunack (1993) found the maintenance of good vegetation cover reduces the depth of ruts and will reduce soil damage.

Braunack *et al.* (2001) noted a concern that strategic tillage may inadvertently build up cane diseases. A study by Croft and Saunders (1996) found disease incidence does not increase by planting back into the old row as compared to planting into the inter-row. Observation of insect numbers revealed low population numbers.

McGarry (1998) found structural stability improves with incorporation of organic matter by soil fauna and increases in soil fauna activity. Reduced soil disturbance will promote this increase. Conventional tillage has been shown to decrease worm numbers and they did not recover after one crop cycle (Rohrig *et al.*, 1998 in McGarry, 1998).

Chapman *et al.* (2001) in Mackay found a 70% increase in worm numbers measured in green cane trash blanket uncultivated and suggested this as the main reason for superior performance over burnt cane plots.

5.2 Roots

Braunack and Peatey (1999) noted that the majority of sugar cane roots occur in the top 60 cm (Moore, 1987) and that cane root growth is suggested to be greatly restricted at cone resistance values greater than 2 MPa (Greacen, 1969).

Braunack and Hurney (1998) indicated that traffic over the row increases soil compaction and the difficulty for plant roots to access moisture and nutrients.

5.3 Stool damage

Braunack and Peatey (1999) noted the cause of crop loss in ratoons may be direct physical damage to stools and buds (Swinford and Boevey, 1984). Trials in Tully and Ingham under dry conditions show little to no response to harvesting traffic (Braunack *et al.* 1993).

Braunack and Hurney (2000) reported that traffic over the row is expected to cause direct damage to the stool and hence nodal buds. Buds closer to the soil surface are likely to suffer more damage. Deeper buds are then forced to germinate and will be slower because of higher soil compaction at depth. Wetter soils are worse as compaction penetrates deeper into the soil. The effect of damage is cumulative (Yang 1977) and not always immediately seen. Trends of lower yields become evident in older ratoons.

5.4 Trash

Braunack and Ainslie (2001) in Mackay reported that soil bulk density, saturated hydraulic conductivity, aggregate stability and soil cone resistance were all measured on three soil management treatments to find which gave the most suitable conditions for plant growth in the row. Treatments were cultivated burnt cane (CC-BC), cultivated green cane trash blanket (CC-GCTB) and zero tillage green cane trash blanket (ZT-GCTB). Bulk densities in the cane row were lowest under ZT-GCTB.

Wood 1991 found greater bulk densities in GCTB but his measurements were taken in the inter-row.

Braunack and Ainslie (2001) also reported saturated hydraulic conductivity increased under ZT-GCTB probably due to increased aggregate stability and micropore continuity. Results show less impact on soil indicators in the row under ZT-GCTB than CC-BC and CC-GCTB.

Chapman *et al.* (2001) showed that the best yield response was under GCTB with no cultivation. Experimental and farmer experience found no advantage in raking trash from the stool. It was noted that heavy wet soils can be a problem where drainage is poor. Water conservation is another benefit with the trial yielding an extra 16t/ha cane equivalent to 2 ML of irrigation.

Bell *et al.* (2001) reported an increase in total and labile C concentrations in soils under green cane trash blanket management. The presence of surface cover from the trash blanket itself increased water infiltration 3-fold by reducing surface crusting on Bundaberg soils. Advantages can be negated by low hydraulic conductivity of subsurface layers caused by compaction during harvest.

5.5 Varieties

Braunack (1994) reported on a Tully trial where there appeared to be varietal difference in the response to trafficking the rows of Q117 and Q138.

Jackson (1996) had 26 genotypes measured after a dry harvest and conditions that simulate wet harvesting. This was achieved by spray irrigation of 50-60 mm and driving a tractor and haul-out on top of all stools. A waterlogging treatment also commenced. Large differences were recorded in early stalk numbers and final yields were depressed by 30% due to the wet harvest and waterlogged treatments. At harvest there was large variation due to genotype, however, very little genotype x treatment interaction in yield. The relative genotype performance was consistent under both optimum and wet harvesting.

Editorial (2001) noted that variety selection is important. Varieties with suitable characteristics such as moderate tonnage, high sucrose, tillering and ratooning capabilities are preferred for chopper harvesting.

6.0 MACHINERY CHARACTERISTICS

Editorial (2001) also noted that the future of sugar cane harvesting and other aspects of cane production undoubtedly lie in increased mechanisation. It is increasing difficult to find labour for hand harvesting therefore the percentage of machine harvesting will increase.

Braunack (1995) noted a concern of the increasing size of harvesters and haul-outs, and therefore increasing weight. A definite trend was also identified by Ridge (2002).

Van Antwerpen (2001) proposed that the increased mechanisation in the sugar industry is largely responsible for the reduced number of ratoons.

6.1 Weight (axle load)

Conway and Porter (1996) reported on soil deformation plus stress measurements taken during cane harvesting. A soil stress transducer was used to measure soil pressure when harvester and haul-outs pass over the row where it was placed. Soil deformation was measured by the point grid method. The soil stress transducer showed pressure by a wheeled harvester to be 70 kPa normal vertical stress and 90 kPa shear stress probably due to traction of the driven wheel. Soil deformation was measured with soils compacting to 80% of their original volume. This is an increase of 25% in their bulk density.

Braunack and Peatey (1999) cited Hakansson and Petelkau (1994) reporting that reduced axle loadings will reduce soil compaction at depth.

Braunack and McGarry (2001) reported that reduce axle loads are preferred. Most soils can withstand loads of about 6 t/axle when dry. Lower axle loads are better.

Torres and Rodriguez (1995) in Columbia found increasing axle loads can increase deep compaction irrespective of contact pressures. Recommend axle loads should be under 10 t, and surface contact pressure must be under 100 kPa.

Norris *et al.* (2000b) stated that ground pressure can be minimised by reducing equipment weight or increasing the contact area (foot print) of the equipment. High floatation systems typically operate in Australia with tyre pressures less than 2.5 bar, however maximum axle loads can still exceed 10 T/axle. In comparison The Brazilian cropping system is based on 1.1m row spacings. They are promoting low axle loadings of a maximum of 7 t/axle and low pressure Trelle-bourg tyres (Neves, pers com, 2000 in Norris et al., 2000b).

6.2 Repeated passes

Conway and Porter (1996) noted that each row has a minimum of 4 passes, that is 2 passes by the harvester and 2 passes by an infield haul-out.

Braunack and McGarry (2001) reported 80% of compaction in the wheel tracks occurs in first pass.

Braunack (1993) showed there was very little change in soil conditions between the 5th and 10th passes compared with that between the 1st and 5th passes. Depth of ruts increased as the number of passes or turns increased. Rut depth was approximately twice that after 8 passes or turns compared to 1 pass or turn. Ruts formed on a turn were approximately twice the depth of those formed by travelling straight.

Braunack and Peatey (1999) showed that repeated traffic over the row brings bulk densities towards an equilibrium with little change occurring with subsequent traffic. The largest change occurs with the first trafficking.

Braunack and Crees (1998) measured an increase in the number of passes resulted in increases of the soil cone resistance with dual tyres. Greatest change was in the 0-300 mm depth. Super singles also increased soil cone resistance but not to the same magnitude.

6.3 Track width

Braunack and Crees (1998) reported that in a Burdekin trial super single tyres (2.17 m track width) are further away from the row than dual tyres (2.37 m track width). Running gear was causing compaction and vertical sides to the row profile.

Norris *et al.* (2000b) calculated that 63% of the area would be tracked with 1.5 m cane rows and 1.83 m track width. With driver error compaction may even approach 90%. Matching track widths to inter-row spaces can mean a 2 row harvester tracking a 3 m span, ie 2 x 1.5 m rows, as being practiced in the Burdekin.

6.4 Mis-match track and row width

Braunack and Peatey (1999) promoted a mis-match of row spacing – 1.5 m row and 1.8 m equipment. It is suggested that to prevent soil physical degradation in the row that all traffic should be restricted to the inter-row. Harvesting under drier conditions will reduce the effect of traffic on soil physical properties.

Braunack and Crees (1998) also observed a mismatch in crop row spacing and haul-out track width results in tyres running close to the row and producing vertical sides to the row profile.

Braunack (1998a) noted some degradation of soil condition in the row was caused by mismatched harvesting equipment (elevator too short) causing haul-outs to creep onto rows to fill can bins evenly.

In Columbia, Torres *et al.* (1990) has also observed that none of the tracks of infield gear matched rows of 1.5 m causing severe direct damage of cane stool.

6.5 Tyre pressure

Braunack and Crees (1998) found that lower tyre pressures will give lower soil cone resistance readings and may also provide improved mobility under wet conditions.

As a rule of thumb, ground pressures can be estimated by tyre width (W) and ground contact pressure (P). P can be taken as the tyre inflation pressure.

Example: a tyre with ground pressure 700 kPa has half this pressure at a depth that is equal to the width (530 mm) of the tyre. Therefore soil pressure from this load will be 350 kPa at 530 mm depth.

In Guyana, Eastwood *et al.* (1997) recorded radial tyres at 54 kPa (0.5 bar) on a Bell 120 loader causing transient compaction that did not affect yield when driven over the stool.

Torres *et al.* (1990) in Colombian research using four types of haul-out and a Cameco grab loader, measured surface pressures caused by haul-out equipment ranged from 76-456 kPa. The highest measured in a conventional wagon and lower pressures on high floatation tyres. A Steiger tractor pulling 2 self-tipping wagons of 7 ton capacity caused the least damage to the first ratoon. Soil compaction and stool damage can be minimised by avoiding harvest in extremely wet periods and adjusting row spacings.

In another study Torres and Rodriguez (1995) measuring compaction under tracks noted the average surface pressure of 14-28 kPa. Pressure distribution under a trash blanket follows an irregular pattern, reaching a peak value toward the rear of the track centre and creating pressure values 2-3 times greater than expected. They also suggest reducing the contact pressure of tyres to less than 200 kPa, preferably less than 100 kPa.

Pinto and Bellinaso (2000) compare conventional truck tyres (110 psi) and infield transporters (30 psi). All infield transport caused soil compaction with a container trailer in the inter-row reducing yield by 2.1% and a truck 11.5% compared to the control. Infield trailers with low pressure high flotation tyres reduced losses by 9.4%.

Case Corporation (2001) states the Austoft AHX1800 harvester has an axle load of 6.7 t and ground pressure of 100 kPa.

Behravan (2001) in Iran noted that steel tracks are causing less adverse effect than rubber wheels in harvesting and haul-out operations.

6.6 Chopper harvesters

Editorial (2001) reported that chopper harvesters are useful as they handle upright and horizontal cane, green and burnt, and at high yields but are a significant investment. Higher levels of extraneous matter, cane loss and sugar loss due to the number of cuts

and further deterioration compared to manual and whole stick methods was the trend for the future as labour is becoming increasingly difficult to find.

6.7 Stick harvesters

Editorial (2001) reported that mechanical cutters that base cut cane will probably be phased out due to a shortage in manual labour availability who are needed to windrow and strip cane. These machines have some limitations as they cannot generally cut cane exceeding 10% lean and topping mechanically is a challenge.

Meyer (1999) compared bundle type harvester and chopper harvesters resulting in approximately 22 t/hour and 37 t/hour respectively. Low outputs are not unexpected considering the range of machines, crop characteristics, field conditions and operators.

6.8 Mechanical loading

Editorial (2001) researched mechanical loading and found it is cost effective (compared to hand loading) and can reduce time to milling considerably resulting in improved cane quality. The disadvantages are the possibility of including stones, soil and thrash with cane and uprooting stools. It can also double ash content compared to manual loading.

Eastwood *et al.* (1997) found no distinct difference between manual and a Bell 120 machine loader.

Torres *et al.* (1990) found the grab loader damaged the stool least of all the loading and haul-out equipment.

7.0 YIELD

Braunack and Hurney (1998) looking at trials in Tully found no statistical difference when yields were reduced with traffic over the row compared to traffic in the row. Braunack (2000) reported that Tully and Bundaberg reduced tillage trial results indicate yield is not being compromised by reducing the number of tillage operations. McGarry (1998) reported that the Bundaberg experiment showed stool plough-out did not perform significantly better in cane yields, CCS and tS/ha than other treatments, conventional, stool spray-out, but was only better than plough-out replant in yield. Braunack *et al.* (1999) results showed that there are potential savings that can have an immediate impact on current expenditure. These come from reduced costs of production, reduced wear and tear on machinery and time saving in land preparation.

Braunack and Hurney (2000) recorded yield losses varied from 1% to 20% when comparing row traffic with inter-row traffic where tyre imprints were noticeable on the surface. Soil conditions that were considered suitable for harvesting resulted in degraded soils and yield loss, especially when trafficked over the stool. The general trend for yield was that traffic over the row reduced yield compared to traffic near the row and traffic in the inter-row. Soil conditions in the row became more degraded with time reflecting in lower yields. Braunack (2001) determined that given the level of yields it is thought that an extra ratoon could have been successfully grown at both sites thereby increasing the length of crop cycle by one year at Tully and two years at Ingham.

Braunack (1998c) has stated that moving from 1.5 m rows to 1.8 m rows (30 cm duals) has resulted in an increased yield of up to 25%.

Chapman *et al.* (2001) measured an increase in cane yield of 16 T/ha in green cane trash blanket at Mackay. This increase was attributed to reduced compaction and increased soil fauna activity enabling greater moisture penetration and retention.

Eastwood *et al.* (1997) quoted that work at Copersucar (Anon 1997) also found a 15% yield response when traffic is removed from stool. When researching the effects of using a mechanical loader over several years they found there was no significant adverse effect on ratoon yields even though the loader over wet soils increased soil cone resistance in the top 300 mm. Resistance dissipated under shrinking and swelling by next harvest even when the loader had run over the stool.

Torres *et al.* (1990) measured yield losses where there was an average of 21% difference in cane yield compared to an area of no traffic. The Cameco tractor and wagons caused the greatest decline in stalk population and yield (33%).

Pinto and Bellinaso (2000) measured yield in first ratoon was down 2.1% when tractor-drawn containers on high floatation tyres were driven in the inter-row and down 6.7% when trucks are driven in the inter-row. Losses of 5.9% and 11.5% respectively were found when trafficking the row.

Yang (1980) reported as high as 40% yield reduction measured in soils with severe compaction. Yang *et al.* (1978) also found 13% increase in yield by working soils rather than performing no tillage operation after harvest.

Bell (2002) reported on a compaction trial at Bundaberg in 2000 where Q124 was autumn planted into compacted and uncompacted treatments. Yield in compacted plots were depressed 20%. This was attributed to a relic compaction layer from the old inter-row not being completely erased and hydraulic conductivity being greatly reduced possibly causing short term waterlogging during crop establishment.

Meyer and Van Antwerpen, (1996) found that thirteen 40 ha blocks fallowing with green manure gave an average yield increase of 40% in plant and 25% in first and second ratoon compared to thirteen non-fallowed blocks. The increase was attributed to prolific rooting aided by improved soil physical properties, particularly air filled porosity increasing from 11.9% to 16.1%. Hydraulic conductivity and soil cone resistance were also significantly improved.

8.0 MANAGEMENT

8.1 Burning

Pinto and Bellinaso (2000) mentioned legislation to phase out burning in Brazil is one of the main driving forces to change. All land with less than a 12% slope will be harvested green by 2005 and all land with a slope greater than 12% will be harvested green by 2012.

8.2 Traffic on stool

Braunack (1995) noted haul-outs on the top or side of the cane row in commercial harvesting.

Braunack and Hurney (1998) described a situation where traffic over the row appeared to cause soil to be more massive in structure (fewer cracks and holes).

Pinto and Bellinaso (2000) in Brazil noticed that although all traffic should occur in the inter-row, it was observed that heavy traffic occurs on the row as well.

Norris *et al.* (2000b) commented that the Columbian industry is looking at adopting row spacings of 1.7 – 1.75 m to better match the wheel tracks of machines to avoid stool damage.

8.3 Row width

Braunack (1994) in Tully showed soil physical properties in the row are less favourable in 1.5 m rows than 1.8 m rows but there was no significant difference in yields that ranged from –26% to +18%. Braunack and Ainslie (2001) noted that all sites compacted due to 1.5 m row and 1.8 m machinery. Braunack and Crees (1998) discussed matching crop row spacing and machine widths. This has been suggested to reduce the effect of infield traffic on the stool (Braunack, 1997). Braunack (1998a) reported that the Australian sugar industry is having a gradual move towards 1.8 m dual rows at 0.5 m apart. Braunack (1998c) noted that there was less soil compaction in the wider rows compared to the narrower rows.

Norris *et al.* (2000b) reported the Columbian industry adopting row spacings of 1.7 – 1.75 m to better match the wheel tracks of machines.

8.4 Controlled traffic

Norris *et al.* (2000b) noted Louisiana cane growers use narrow tyres on 1.83 m rows compacting 21% and with error 32% of the field. This is a controlled traffic practice that deliberately sets out to compact the inter-row for wet weather trafficability. Norris *et al.* (2000b) suggested an alternative is to use 2.1 m beds and high density planting techniques to compact 18% of area or 23% with the error of a guidance system.

Braunack (1998a) reported controlled traffic increased wet weather trafficability. Braunack and Peatey (1999) also noted that controlled traffic will manage compaction and soil physical degradation.

8.5 Strategies to reduce compaction

Braunack and Hurney (2000) noted that the solution to the current soil compaction problems and their effects are 1.8 m rows and controlled traffic. Braunack (1994) reported that soil compaction can be reduced by:

- the use of high flotation tyres,
- harvesting under drier conditions.

Braunack (1998c) also suggested the best strategy is not only to harvest under dry conditions but also reduce the number of passes.

Torres *et al.* (1990) recognised the effects of compaction mainly at 25-30 cm during a wet harvest that should be able to be fixed using conventional cultural practices.

Pinto and Bellinaso (2000) concluded that to minimise the effects of soil compaction the infield transport equipment should be designed to fit the sugar cane inter-row and must be equipped with high floatation tyres or tracks (rubber or steel).

8.6 Strategic tillage

Braunack (2000) describes strategic tillage as disturbing the row and leaving the inter-row. The reduced tillage trial at Tully and Bundaberg show results indicating that yield is not being compromised by reducing the number of tillage operations.

Braunack *et al.* (2001) show there was no yield penalty in planting back into the same row. The effect of strategic tillage on soil borne organisms was less damaging than conventional practices. Braunack *et al.* (2001) commented there was concern that strategic tillage would allow a build up of cane pests and diseases. This had been investigated and was found not to be the case.

McGarry (1998) reported that ploughing out the row only is the most efficient way to plant cane. Conventional methods use twice the amount of fuel and one third more tractor hours.

8.7 Guidance system

Braunack (1998a) put forward the concept of the need for guidance systems in cane. Braunack (1998c) recognised the benefits in reducing the spread of soil compaction and that it depends on accurately traversing the same area each time. Suitable guidance systems for planting and harvesting will assist in reducing the spread of traffic zones into the plant growth area.

Norris *et al.* (2000b) noted that a guidance system has a significant role to play.

9.0 ECONOMICS

Meyer (1997) reported that the South African sugar industry has been searching for a viable mechanical cane harvesting aid or a fully mechanised harvesting system. A review of manual, semi-mechanised, whole stalk, and chopper harvesting systems outlines issues to be considered when selecting a harvesting system. Numerous advantages and disadvantages are presented ranging from labour availability and cost, field layout and machine performance to cane yield, cane losses, transport system and management related issues.

Braunack (1999a) showed that the economic loss to the Queensland sugar industry has been estimated as ranging between \$54 to \$164 million at a yield reduction of 5 and 15% (\$145 to \$431/ha).

Braunack (1999a) calculated that every 1% loss of productivity to soil compaction was worth in the order of \$10 million to the Australian sugar industry. A conservative average of 10% would therefore relate to a \$100 million potential loss to the industry in Queensland.

10.0 MODELLING

Braunack (1996) reported a collaborative research project with Dr Inge Hakanssen, Swedish Agricultural University. The research model is being developed to estimate yield loss due to compaction. Braunack (1999a) described how Hakanssen (1990) developed the concept of degree of compactness which is the dry bulk density of a

soil as a percentage of the maximum bulk density of the same soil after a standard compression test.

Braunack (1999a) developed a computer model, “COMPACT\$”, that uses a soil compactness value to predict yield loss. The Scandinavian compaction model has been modified for the Australian sugar industry. The model uses a crop response curve based on the degree of soil compactness derived from current and historical trials. The model enables different scenarios to be examined with respect to potential yield loss. This will aid in making informed management decisions to minimise the effect of soil compaction and reduce potential yield losses.

The user manual for soil compaction model “COMPACT\$” is attached as Appendix 1.

Conway and Porter (1995) reported that the FLAC program (Fast Lagrangian Analysis of Continua) is suited to modelling agricultural traffic processes and can provide valuable information on soil behaviour. Simulations of a tyre passing over a cane block with soil in both a soft and firm state closely matched model results to field measurements.

Bentley (2000) has developed a technique resulting in a “Compaction Index” (CI) that will give quantitative comparison of potential compaction effects.

Parameters used to calculate the index are:

- gross vehicle mass (Tons)
- average ground pressure or axle loadings (Bar)
- average tyre pressures (Bar)

1bar = 100kPa

The compaction index formula is:

$$CI = GMV \times GP \times TP$$

This gives a relative index that allows for the comparison of machinery on easily obtainable information.

Meyer (1998) developed a model in South Africa to estimate the performance and cost of sugar cane chopper harvesters and associated infield transports. The purpose of the model is as a tool for assessing the viability of introducing a fully mechanised harvesting system under different agronomic and management situations.

11.0 DISCUSSION

Compaction has a major impact on reducing the potential yield of sugar cane crops. The greatest cause of compaction is trafficking of cane blocks by machinery under

wet conditions. Highest levels of compaction occur when soil moisture is high, soils are of fine texture and heavy loads are applied to the stool in the cane row.

The Australian sugar industry is highly mechanised and applies greatest loads to the soil during harvesting. This needs to be managed to maximise yield. Least compaction has been observed when harvesting manually. A change to harvesting with any component of manual handling would not be practical as labour could not be found, efficiencies would drop and costs would make this system unviable. The only other fully mechanical system available is the whole stick harvesting system, which is

reported to be showing the same compaction as chopper harvesting systems. The grab loader still traffics the stool and loaded haul-out equipment is similar in weight to those carrying billets, as sugar industries across the world try to reach optimum field efficiencies. If harvesting groups decide to change to this type of harvesting there would be difficulties at the mill trying to cope with cane presented in whole stick and billet form.

All industries overseas are increasing in their percentage of cane harvested with chopper harvesters.

Maximising yield in a chopper harvester system is the challenge faced. Accepting that harvesting and haul-out equipment have to traffic cane blocks, the least impact on cane yield will occur by minimising the area trafficked.

Staying within Queensland Transport Department limits, the least compacted area will be achieved with a 2.1 m wheel spacing requiring high density planting, a guidance system and narrow tyres running in dedicated inter-rows. The least cost system is 1.83 m wheel spacing with wide single or dual rows using controlled traffic, permanent beds, a guidance system and narrow tyres. An alternative to this would be to design a system on 1.83 m that aims to reduce compaction by keeping axle loads less than 6-7 t/axle and tyre pressures under 100 kPa.

A number of other beneficial practices should be considered when planning future farming practices:

- Trash blanketing. This may not be suitable on wet soils or in cold areas early in the season. Consider laser levelling and raking the trash off the stool.
- Reduced tillage, strategic tillage and zero tillage. Cultivate the soil as little as possible.
- Reduce traffic in cane blocks to as little as possible.
- Avoid trafficking the soil when it is wet. Lower soil moisture will result in lower levels of compaction.
- Include fallow cover crops in the rotation.
- Plough pans from previous crop cycles must be ruptured to allow root penetration.
- Varieties. Good agronomic characteristics, suitable for your soil type and local conditions, resistant or tolerant to pests and diseases should be selected to give the greatest yield possible.

When planning future harvesting and haul-out practices it is highly recommended to utilise Dr Braunack's model COMPACT\$ to compare harvesting and haul-out options in relation to their compaction, yield loss and the impact that has on total farm income.

12.0 FURTHER READING

In 1991 Dr Braunack completed a thorough literature review on "The Effect of Soil Physical Properties on Growth and Yield of Sugar Cane".

Soil compaction in the South African sugar industry – a review by Van Antwerpen *et al.* (2000). This paper summarises past research outcomes on the effects of compaction on cane production and soil properties, and examines management strategies for minimising yield loss. This review is attached as Appendix 3.

13.0 REFERENCES

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APPENDIX 1

Braunack, M.V. (1999a). Economic cost of soil compaction. Final report – SRDC project BS142S, BSES Internal Report, 1012.
Appendix 1, User manual for COMPACT\$

APPENDIX 2

Braunack, M.V. (1991). The effect of soil physical properties on growth and yield of sugarcane. BSES Internal Report, 528.

APPENDIX 3

Van Antwerpen, R. et al., (2000). Soil compaction in the South African sugar industry – a review. *Proc. S. Afr. Sug. Technol. Ass.*, 74: 101-108.

APPENDIX 1

USER MANUAL FOR COMPACT\$

A model to calculate yield loss due to soil compaction when harvesting sugarcane

INTRODUCTION

The model to estimate yield losses due to harvesting sugarcane has been adapted from a Swedish model developed by Arvidsson and Håkansson (1991). The Scandinavian model was developed from the results of a large number of field trials conducted over many years investigating soil compaction in annual crops.

The model has been adapted for conditions applying to the Australian sugar industry, and validated using data from trials conducted to quantify the effect of harvesting traffic on sugarcane response (Braunack, 1994; Braunack & Håkansson, 1997).

Yield losses are calculated using simple input parameters which are generally available at the grower level. The output from the model estimates the following: (1) yield loss (as a %) in the following crop due to topsoil compaction; and (2) yield loss due to subsoil compaction.

Model input

The model has been set-up in an Excel spreadsheet (Table 1) and runs in Excel 97.

Input data are as follows:

At the top of the spreadsheet basic information is entered.

- Crop value in \$ per hectare, usually the \$ value of cane per hectare (Row 2).
- This could be based on the average yield for the block or farm, and before or after costs have been deducted, for example \$2,400.00, based on 80 tonne cane @ \$30.00 per tonne.
- Area harvested in hectares (Row 1).
- This could be the area of a particular block or the area of a farm.
- Clay content of the soil (Row 2).
- Estimated from a field texture determination.
- Specific information about operations and equipment is entered in rows 3 to 20 of the spreadsheet, as follows:

- Row 3: Can be used to distinguish between harvesting and haulout operations, by entering specific data for the harvester in the first column and the haulout in the second column.
- Row 4: The number of operations is entered, usually two for the harvester since it travels over each inter-row twice, the number of haulout passes varies, but usually there is a minimum of two passes.
- Row 5: Crop row spacing (in metres) is entered here depending on the row spacing in the block. See Attachment 1.
- Row 6, 7: Soil moisture classes of the topsoil and subsoil are entered using a subjective scale of 1 (very dry) to 5 (very wet). This is the soil moisture in the block at the time of harvesting. This is explained in Attachment 2.
- Row 8: Extra driving is the turning at the end of the rows. This should be 1, since no turning occurs in the cropped area, it all occurs on the headland.
- Row 9, 10: Weight (kg) loaded and unloaded of the front axle of a harvester or haulout or tractor.
- Row 11, 12: Weight (kg) loaded and unloaded for the rear axle of harvester or haulout or tractor.
- Row 13, 14: Weight (kg) loaded and unloaded of trailed bin, or the mean values for multiple axles of trailed bins or trucks or articulated units.
- Row 15-17: Tyre inflation pressure for the corresponding axles given in rows 10, 12 and 14 or track ground pressure for tracked units.
- Row 18: Number of rear axles - 1 for single axle units, 2 for dual axle units and 3 for tri-axle units.
- Row 19, 20: An estimate of the proportion of the area where traffic occurs over the row (line 19) and near-the-row (line 20). Yield losses are greater when traffic occurs over the row compared with traffic in the inter-row. See Attachment 3.

TABLE 1

CALCULATION OF YIELD LOSSES CAUSED BY COMPACTION		Hectares:					
		Crop value/ha:		Clay, %:		Alternative:	
Operation							Sum
1	Number of operations						
2	Working width						
3	Soil moisture class, topsoil						
4	Soil moisture class, subsoil						
5	Extra driving						
6	Weight first axle, loaded						
7	Weight first axle, no load						
8	Weight second axle, loaded						
9	Weight second axle, no load						
10	Weight rear axle(s) loaded						
11	Weight rear axle(s), no load						
12	Inflation pressure, first						
13	Inflation pressure, second						
14	Inflation pressure, rear						
15	Number of rear axles						
16	Driven in-row, %						
17	Driven near-row, %						
18	Driven between-rows, %						
19	Topsoil, ton/ha						
20	First axle	0.00	0.00	0.00	0.00	0.00	0.00
21	Second axle	0.00	0.00	0.00	0.00	0.00	0.00
22	Rear axle(s)	0.00	0.00	0.00	0.00	0.00	0.00
23	In-row	0.00	0.00	0.00	0.00	0.00	0.00
24	Near-row	0.00	0.00	0.00	0.00	0.00	0.00
25	Between rows	0.00	0.00	0.00	0.00	0.00	0.00
26	Total	0.00	0.00	0.00	0.00	0.00	0.00
27	Topsoil, yield loss (%)						
28	First axle	0.00	0.00	0.00	0.00	0.00	0.00
29	Second axle	0.00	0.00	0.00	0.00	0.00	0.00
30	Rear axle(s)	0.00	0.00	0.00	0.00	0.00	0.00
31	In-row	0.00	0.00	0.00	0.00	0.00	0.00
32	Near-row	0.00	0.00	0.00	0.00	0.00	0.00
33	Between rows	0.00	0.00	0.00	0.00	0.00	0.00
34	Total	0.00	0.00	0.00	0.00	0.00	0.00
35	Subsoil, 20-40 cm, ton/ha						
36	First axle	0.00	0.00	0.00	0.00	0.00	0.00
37	Second axle	0.00	0.00	0.00	0.00	0.00	0.00
38	Rear axle(s)	0.00	0.00	0.00	0.00	0.00	0.00
39	Total vehicle	0.00	0.00	0.00	0.00	0.00	0.00
40	Subsoil, 20-40 cm, yield loss						
41	First axle	0.00	0.00	0.00	0.00	0.00	0.00
42	Second axle	0.00	0.00	0.00	0.00	0.00	0.00
43	Rear axle(s)	0.00	0.00	0.00	0.00	0.00	0.00
44	Total vehicle	0.00	0.00	0.00	0.00	0.00	0.00
45	Subsoil, >40 cm, ton/ha						
46	First axle	0.00	0.00	0.00	0.00	0.00	0.00
47	Second axle	0.00	0.00	0.00	0.00	0.00	0.00
48	Rear axle(s)	0.00	0.00	0.00	0.00	0.00	0.00
49	Total vehicle	0.00	0.00	0.00	0.00	0.00	0.00
50	>40 cm, per mile yearly loss						
51	First axle	0.00	0.00	0.00	0.00	0.00	0.00
52	Second axle	0.00	0.00	0.00	0.00	0.00	0.00
53	Rear axle(s)	0.00	0.00	0.00	0.00	0.00	0.00
54	Total vehicle	0.00	0.00	0.00	0.00	0.00	0.00
55	Total cost, Aust. \$						
56	In-row	0.00	0.00	0.00	0.00	0.00	0.00
57	Near row	0.00	0.00	0.00	0.00	0.00	0.00
58	Between rows	0.00	0.00	0.00	0.00	0.00	0.00
59	20-40 cm	0.00	0.00	0.00	0.00	0.00	0.00
60	<40 cm in 50 years	0.00	0.00	0.00	0.00	0.00	0.00
61	Total	0.00	0.00	0.00	0.00	0.00	0.00

Model output

Model output occurs in rows 23 to 64.

The first output is an estimate of traffic intensity for the topsoil (ton km/ha) for the operation and an estimate of traffic in the row, near-the-row and in the inter-row, with the total traffic intensity given in row 29.

The estimated yield loss (%) in the topsoil due to soil compaction is given in row 37.

These same outputs are provided for estimated yield loss to subsoil compaction in rows 47 and 57. Losses estimated for deeper layers (> 40cm) are considered to be a permanent loss to productivity.

The estimated economic loss for the harvesting equipment used, under the soil conditions defined for a particular operation or circumstance, is given in row 64 as \$ over the area nominated. The \$ value per hectare is calculated by dividing this \$ value by the area nominated.

The model provides an estimate of traffic intensity for the given equipment inputs and an estimate of yield loss (%) for the following crop due to soil compaction in the soil surface and in the subsoil due to that traffic under the conditions stipulated. The model also provides an estimated economic value (\$) of that loss, depending on the price input of the product. This estimate can be for a specific block or can apply to the whole farm depending on the area input.

Model computations

1) Yield loss in the following crop due to topsoil compaction at harvest

Yield losses due to topsoil compaction will depend on where the harvesting traffic occurs relative to the row. Traffic over-the-row will result in greater losses than traffic near-the-row and the least loss will occur when traffic is in the inter-row. Therefore position of traffic is divided into three categories, traffic in-row, near-row and between-rows. Yield loss is assumed to be a function of traffic intensity (ton-km, the weight of vehicle times the distance travelled in the field), corrected for soil moisture and tyre inflation (or track ground pressure) pressure. Traffic intensity is calculated as follows:

$$\text{Corrected Ton-km} = (\text{uncorrected ton km}) (\log (\text{tyre pressure}) - 1.2) (\text{soil moisture} \times 0.2675 - 0.056), \quad (1)$$

The yield loss is calculated separately for traffic in-row, near-row and between-rows. Yield loss is linearly correlated with traffic intensity. This is done in steps, because at high traffic intensities the yield loss due to additional traffic is less. This is because the largest change occurs with the first pass of traffic and less change occurs with each additional pass.

2) Yield loss due to subsoil compaction

Yield loss due to subsoil compaction is also based on traffic intensity, and correlated to the number of ton-km. Because subsoil compaction persists through time, no distinction is made between the in-row and between-row areas. The subsoil is also divided into two layers: 20 to 40 cm and > 40 cm.

Losses for the 20 to 40 cm layer are considered over a 10 year period; the figure given in the spreadsheet (Row 47) is the total loss for that period as a percentage of one year's yield. Only axle loads greater than 4 tonnes are considered to influence this layer, so a correction of 4 tonnes is made when calculating the traffic intensity (ton km):

$$\text{Corrected ton-km} = (\text{uncorrected ton-km})(\log(\text{tyre pressure}) - 0.53)((\text{soil moisture} - 2) \times 0.326) \quad (2)$$

and yield loss is calculated as,

$$\text{Yield loss (\%)} = \text{corrected ton-km}/40 \quad (3)$$

Yield losses for the layer > 40 cm are considered permanent and are given as a permanent loss to productivity. This is due to expense and effort required to remove deep subsoil compaction. The economic cost of this loss is calculated over a 50 yr period.

Yield loss is assumed proportional to the corrected traffic intensity, but only axle loads greater than 6 tonnes are considered in calculating the traffic intensity:

$$\text{Corrected ton km} = (\text{uncorrected ton-km})(\log(\text{tyre pressure}) - 0.27)((\text{soil moisture} - 2) \times 0.272) \quad (4)$$

with yield loss being calculated as,

$$\text{Yield loss (per mille)} = \text{corrected ton-km}/40 \quad (5)$$

An example of the Compaction Model output is set out in Attachment 4.

Database

A second sheet has been included containing a database of haulout equipment commonly used throughout the industry. Data can be copied into the calculation sheet to generate output for various situations. The data can be manipulated to generate specific equipment used by individual growers, if this information is not readily available from the grower or contractor.

References

- Arvidson, J. and Håkansson, I. 1991. A model for estimating crop yield losses caused by soil compaction. *Soil & Tillage Res.*, 20:319-332.
- Braunack, M.V. 1994. Tillage and traffic for sustainable sugarcane production. Proc. 13th ISTRO Conference, Aalborg, Denmark, Vol.2, p.769-775.
- Braunack, M.V. and Håkansson, I. 1997. The response of sugarcane to harvesting traffic. Proc. 14th ISTRO Conference, Putawy, Poland. Vol. 2A, p.95-98.

Attachment 1

Working width metric equivalents of imperial row spacings.

Metric	Imperial
1.5 m	4'11"
1.65 m	5'5"
1.8 m	5'11"
1.83 m	6'0"
2.0 m	6'6"
2.2 m	7'2"

This table can be used to estimate the working width in metres if the distance is provided in imperial measurement.

Attachment 2

Subjective soil moisture scale for use in COMPACT\$.

Class 1 – Very Dry

Soil is very dry and hard both at the surface and at depth. No wheel ruts are formed except in recently tilled, loose soil.

Example: Harvest after a long dry period. Too dry for tillage operations.

Class 2 – Dry

Soil is dry and firm. No wheel ruts are formed except in recently cultivated, loose soil or when using wheels with extremely high ground pressure. In previously trafficked areas, tyre lugs make little or no imprint.

Example: Harvesting after 2-3 weeks dry weather. Minimum soil moisture for tillage.

Class 3 – Intermediate

Soil is drained and further drying of the surface by evaporation has occurred. Tyre lugs imprint to the full depth of lugs, but usually no imprint of the tyre is made, unless the soil has been recently loosened and is soft. The optimal soil moisture for most tillage operations (just below the lower plastic limit of the soil).

Example: The most common soil moisture encountered at harvest.

Class 4 – Moist

Soil is not completely drained. Wheel ruts (5-10 cm deep) formed by nearly all vehicles. Traffickability is reduced for heavy vehicles with conventional wheels. Wheel slip occurs.

Example: Wettest condition for harvest with conventional wheels. Some wet spots (hollows) may have moisture class of 4.5.

Class 5 – Wet

Soil is very wet, with surface ponding occurring. Generally the upper limit for vehicular field traffic. Deep ruts are formed (10-20 cm) even by vehicles with low ground pressure. Vehicles bog if not equipped with low-ground-pressure tyres. Large amount of wheel slip.

Example: Deep rut formation due to harvest traffic.

Attachment 3

Row Spacing (m)	Total length (m/ha)	Length (m) trafficked at various percentages												
		0	5	10	15	20	30	40	50	60	70	80	90	100
1.5	6667	0	333	667	1000	1333	2000	2667	3334	4000	4667	5334	6000	6667
1.65	6061	0	303	606	909	1212	1818	2424	3031	3637	4243	4849	5455	6061
1.8	5555	0	278	556	833	1111	1667	2222	2778	3333	3889	4444	5000	5555
1.85	5465	0	273	547	820	1093	1640	2186	2733	3279	3826	4372	4919	5465
2	5000	0	250	500	750	1000	1500	2000	2500	3000	3500	4000	4500	5000
2.2	4545	0	227	455	682	909	1364	1818	2273	2727	3182	3636	4091	4545

This table can be used to estimate the percent driven in each position by estimating the length of row per hectare driven over or alongside by field observation.

For example, if there is no visual evidence of traffic over the row (in-row) 0 is assigned for driven in-row, 50 is assigned for driven near-row %. The amount for driven between-rows % is automatically entered.

Attachment 4**An example of the compaction model output**

This example illustrates the results of a simulation using data from the attached database. The haulout unit is a 12 t Carta bin articulated with a John Deere 7710 Tractor. The simulation consists of three (3) passes of the fully laden haulout under moist soil conditions (Class 4) in the surface and slightly wetter soil conditions (Class 4.2) in the subsoil. Row spacing is 1.5 m and it has been designated that 10% of the traffic occurred over the row with 45% of the traffic occurring near-the-row and 45% in the middle of the interspace.

As a result, the model predicts potential yield losses for the next ratoon crop to be 13.2% due to compaction in the surface soil, 4.4% due to compaction in the upper subsoil and 1.4% due to compaction in the lower subsoil.

Therefore, the potential economic cost due to this soil compaction, as a result of harvesting under moist soil conditions, is \$597.00 per hectare.

CALCULATION OF YIELD LOSSES CAUSED BY COMPACTION				Features: 20			
Operation		Crop value/ha: 2,400 Clay, %:		20 Alternative:			
		Cata 12t Dual Conveyor Flevstar with John Deere 7710 Articulated (Self Propelled)		Sum			
Number of operations	1	2					
Working width	1.5	1.5					
Soil moisture class, topsoil	4	4					
Soil moisture class, subsoil	4.2	4.2					
Extra driving	1.1	1.1					
Weight first axle, loaded	0	0					
Weight first axle, no load	0	0					
Weight second axle, loaded	8590	8590					
Weight second axle, no load	7850	7850					
Weight rear axle(s) loaded	14060	14060					
Weight rear axle(s) no load	6190	6190					
Inflation pressure, first	0	0					
Inflation pressure, second	178	178					
Inflation pressure, rear	267	267					
Number of rear axles	2	2					
Driven in-row, %	10	10					
Driven rear-row, %	45	45					
Driven between-rows, %	45	100	45	100	100	100	
Topsail, ton/ha							
First axle	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Second axle	82.82	0.00	125.24	0.00	0.00	0.00	187.86
Rear axle(s)	30.54	0.00	161.09	0.00	0.00	0.00	271.63
In-row	15.32	0.00	30.63	0.00	0.00	0.00	45.95
Rear-row	68.92	0.00	137.85	0.00	0.00	0.00	206.77
Between rows	68.92	0.00	137.85	0.00	0.00	0.00	206.77
Total	153.18	0.00	306.33	0.00	0.00	0.00	459.49
Topsail, yield loss (%)							
First axle	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Second axle	1.60	0.00	3.41	0.00	0.00	0.00	5.41
Rear axle(s)	2.81	0.00	5.21	0.00	0.00	0.00	7.82
In-row	2.20	0.00	4.40	0.00	0.00	0.00	6.59
Rear-row	1.53	0.00	3.07	0.00	0.00	0.00	4.60
Between rows	0.60	0.00	1.08	0.00	0.00	0.00	2.03
Total	4.41	0.00	8.82	0.00	0.00	0.00	13.23
Subsoil, 20-40 cm, ton/ha							
First axle	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Second axle	36.07	0.00	78.13	0.00	0.00	0.00	114.20
Rear axle(s)	21.20	0.00	42.40	0.00	0.00	0.00	63.80
Total vehicle	57.27	0.00	118.53	0.00	0.00	0.00	177.80
Subsoil, 20-40 cm, yield loss							
First axle	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Second axle	0.95	0.00	1.90	0.00	0.00	0.00	2.85
Rear axle(s)	0.53	0.00	1.06	0.00	0.00	0.00	1.59
Total vehicle	1.48	0.00	2.96	0.00	0.00	0.00	4.44
Subsoil, >40 cm, ton/ha							
First axle	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Second axle	13.24	0.00	36.48	0.00	0.00	0.00	49.00
Rear axle(s)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total vehicle	13.24	0.00	36.48	0.00	0.00	0.00	57.72
>40 cm, per mille yearly loss							
First axle	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Second axle	0.48	0.00	0.96	0.00	0.00	0.00	1.44
Rear axle(s)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total vehicle	0.48	0.00	0.96	0.00	0.00	0.00	1.44
Total cost, Aust. \$							
In-row	1055.18	0.00	2110.36	0.00	0.00	0.00	3165.55
Rear-row	738.25	0.00	1472.50	0.00	0.00	0.00	2208.74
Between rows	345.42	0.00	690.83	0.00	0.00	0.00	976.25
20-40 cm	711.18	0.00	1422.37	0.00	0.00	0.00	2133.55
<40 cm in 50 years	1154.46	0.00	2308.93	0.00	0.00	0.00	3463.39
Total	3982.60	0.00	7964.99	0.00	0.00	0.00	11947.49

THE EFFECT OF SOIL PHYSICAL PROPERTIES ON GROWTH AND YIELD OF SUGARCANE

M V Braunack, BSES, Tully

ABSTRACT

The literature reporting the effect of soil physical properties on sugarcane growth and yield has been reviewed and areas for further investigation are suggested. There is conflicting evidence in relation to the number of cultivations and cane yield, with little or no effect in plant cane but a significant interaction with the ratoon crop. The effect of soil compaction on cane growth has also been variable, with little or no effect in some instances and dramatic decreases in others. Overall as bulk density increased, the yield of cane decreased. The compaction effect depends on the soil water content at the time of impact.

A major concern in the sugar industry is the trend to larger and heavier equipment and the effect this will have on the soil resource. To reduce the effect of compaction it was suggested that harvesters and haulout equipment be fitted with load sharing, high flotation running gear. When compared with equipment on conventional running gear, again the effect on soil compaction has been variable.

It is difficult to isolate any one soil property influencing cane growth and yield.

Green cane harvesting with trash blanketing has been introduced to reduce costs and it is hoped to improve soil structure. However, few studies have examined the effect on soil properties. Soil water and temperature are modified by the trash blanket and soil structure has been observed to improve after three years. Long term studies are required to substantiate these trends and resolve problems with insects and pathogens.

It is concluded that soil properties do influence cane growth and yield, but further work is required to resolve the inconsistent results of previous workers.

It is suggested that the effect of compaction on cane growth be investigated under controlled conditions. Also, a system of controlled traffic should be investigated to determine the effect of field traffic on cane production and to manage compaction for benefit.

Long term studies need to be undertaken to determine the effect of different management strategies on soil properties and sustainability of production.

This should enable management strategies to be developed which minimise soil degradation and maintain productivity.

INTRODUCTION

There is a vast literature on the topic of soil physical properties and their effect on crop growth and yield (Barnes *et al* 1971, Eriksson *et al* 1974, Chancellor, 1977). However, very little pertains to the effect on sugarcane. This may reflect on the fact that new varieties and fertiliser applications tend to mask soil physical constraints on cane growth, and it is only with the move to larger machinery that soil constraints may be limiting cane yields. Also, soil related problems may have only recently been perceived as such, especially after the response to soil fumigation under trial conditions (Croft *et al* 1984).

In agriculture there is always a conflict between the soil conditions required for plant growth and those to support machinery. For plant growth the soil should be in a loose friable condition, with adequate aeration and water. To support machinery, soil should be sufficiently strong to support the machine without undue adverse consequences for subsequent plant growth.

It is inevitable that changes in soil physical properties will occur when an area is cultivated or trafficked during the production of a crop. The question remains as to what level of change is beneficial and what level of damage is detrimental to crop growth. The objective of management should be to maximise and maintain 'good' soil condition whilst minimising detrimental conditions.

Tillage is one means whereby soil properties may be rapidly altered. However, if tillage is undertaken at an inappropriate time, greater damage may be caused than it was trying to alleviate. For example, smearing may interrupt pore continuity, compaction may occur and cloddy conditions may be generated which are not suitable as seedbeds. Also, subsequent traffic over loose cultivated soil may recompact it to a higher level and a greater depth than before tillage. Hence a vicious cycle of tillage-traffic-tillage-traffic soon develops. The trend to larger and consequently heavier and higher axle load machinery for increased efficiency just accelerates the situation. An engineering solution has been to spread the load over a larger area using dual wheels or wider tracks, so soil physical properties are also affected over a larger area and to a greater depth (Eriksson *et al* 1974). There is an urgent need to improve management (and soil conditions in particular) to enable a downsizing of machinery to reduce the adverse effect on soil physical properties. As soil conditions are improved the need for heavy duty tillage operations will be reduced. By restricting all field traffic to specific areas, soil conditions between the tracks may be improved/optimised for plant growth. Such a management strategy is termed controlled traffic (Taylor, 1983; 1989).

There is no single soil factor which can be said to singly affect plant growth and subsequent yield. The interaction between environmental and soil factors is more important in determining growth and final yield than any single property in isolation.

Soil physical factors which will influence soil properties and plant growth include - soil aeration, soil water, soil temperature, soil strength and compaction. These in turn are affected through changes in porosity, pore continuity, aggregate stability and bulk density.

This paper reviews the literature on the effect of soil physical properties on the growth and yield of sugarcane. The effect of cultural practice on seedbed preparation, number of tillage passes and deep tillage on cane growth is discussed. The effect of soil compaction on cane growth is examined, as are techniques for minimising such effects. A section deals with root growth, root distribution and the effect of compaction on sugarcane roots. Finally a section deals with strategies for improving soil physical conditions for cane growth. It is hoped to be able to provide an insight into the problems involved and some guide as to which warrant further investigation with respect to the problem of yield decline.

CULTIVATION/CULTURAL PRACTICES FOR CANE PRODUCTION

Tillage is usually undertaken to improve soil conditions for crop establishment and growth and for weed control. To achieve good yields there needs to be good crop establishment in the first instance. Subsequent to that, good management of the ratoon sequence is required to maintain yield throughout the crop cycle.

The seedbed for sugarcane does not need to be as fine as for small seeded crops due to the way it is propagated (Trowse, 1960). Hence the time and energy invested in seedbed formation should be less due to the reduced number of tillage operations. However, little work has been undertaken in defining seedbed conditions for sugarcane as a plant crop. Jain and Agrawal (1970) determined that a seedbed consisting of 3.2 to 6.4 mm aggregates resulted in greater germination and increased root growth compared with a finer seedbed. The overall effect was to increase plant height, number of tillers and number of millable canes and cane yield. They also determined that deviation to a coarser seedbed was not as detrimental as deviation to a finer seedbed. The reason for this was a reduction in pore space in the finer seedbed compared with that in the coarser seedbeds.

Care needs to be exercised in land preparation for irrigation or for drainage control in a rainfed situation, or even changing cultural management from one system to another. Such change usually requires the grading or levelling of an area and subsequent relocation of topsoil and exposure of subsoil. Little work has been undertaken for sugarcane in this area. Simpson and Gumbs (1982) found that, at the end of a wet season, root growth and stalk height of sugarcane was found to be higher where topsoil thickness had increased due to grading. These differences were maintained into the dry season. The differences were attributed to lower bulk density, higher soil porosity and lower soil strength on the high side of the field compared with the low side where subsoil had been exposed. This would indicate that some amelioration would need to be undertaken to improve cane growth in these areas.

Historically, cane production has involved intensive cultivation with potential degradation of the soil resource. This, however, depends on the soil type and soil conditions at the time of tillage. Wood (1985) suggested that yield decline was due in part to soil structural degradation, caused by intensive cultivation. Significant differences were found

in the top 7 cm of the soil with higher bulk density and lower porosity in the cultivated soil compared with the uncultivated soil. Differences were attributed to compaction induced by harvesters and haulout traffic.

There is conflicting evidence as to the effect of the number of cultivations on cane yield. In these studies no soil physical properties were measured, so there is no indication as to whether there was a soil constraint to cane yield. Ricaud (1971) found little or no difference in cane yield with an increasing number of cultivations for a plant cane crop. With a ratoon crop, an increasing number of cultivations were required to produce normal yields. This was, however, dependent on the level of grass infestation (Ricaud, 1971).

On two contrasting soil types, a sandy loam and a heavy clay, Pao *et al* (1961) found that 4-5 cultivations resulted in a slight increase in cane yield. The difference was only significant on the heavy clay soil. Again no soil factors were measured so the effect of soil physical properties due to cultivation on cane yield is unknown.

Visual observations by Primavesi and Primavesi (1964) of old cane land and new cane land suggest that continued cultivation of old land leads to soil structural degradation and reduced yields. Soil texture, fertiliser practice and extractable nutrients were similar on both areas. No consideration was given to biological factors.

Evans (1963) reported on tillage trials conducted in various countries and concluded that there was little or no difference in yield between the various treatments compared. Changes in soil properties were not reported.

Deep tillage appears to be ineffective due to the fact that cane roots do not dry the soil sufficiently below 30 cm to induce shattering (Trowse and Humbert, 1959). If deep tillage or subsoiling is undertaken when the soil is too wet, puddling occurs and poor cane growth results. The direction of passes also affects the degree of soil disturbance, with increased disturbance resulting from passes at 45 and 90° to the original pass (Trowse and Humbert, 1959). The results are presented as observations rather than as physical measurements, so there is no real indication as to how deep tillage and subsoiling affected soil physical properties and cane growth.

Strategic tillage has been suggested to reduce weed growth and associated tillage costs, whilst in conjunction with subsoiling to encourage deep rooting for better drought survival (Menon, 1965, Santo, 1985). Using this technique only the sowing line is disturbed, leaving the inter-row area in a more compact condition and less favourable for weed growth and lateral spread of cane roots. Menon (1965) found, however, no significant difference between strip-tillage and conventional tillage for both root distribution and final cane yield. Again no soil physical attributes were measured so no definite cause for the lack of treatment effect can be deduced.

Salata *et al* (1986) found that the opener type (Figure 1) affected soil strength and root growth of sugarcane in sandy soils. A scarifying furrow opener resulted in 25% less soil strength below the furrow compared with a Roseti and conventional furrow opener. As

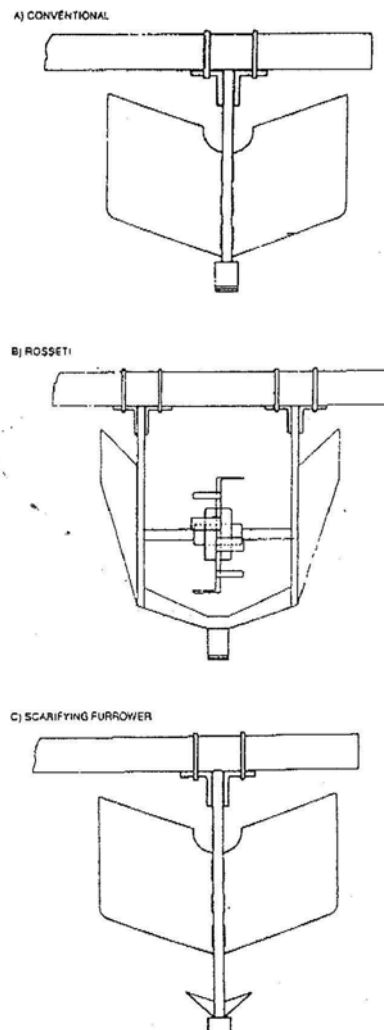


Figure 1 Opener types (from Salata *et al* 1986)

a consequence, a greater root proliferation occurred which translated to an increase in cane yield. No data were provided for water distribution profiles which may have affected root distribution and final yield. No definite conclusion can be drawn with respect to root growth and cane yield in relation to soil parameters since only soil strength was assessed.

COMPACTION IN CANE SOILS

Compaction is defined as a decrease in volume of an element of soil; associated with this process is an increase in bulk density. There is a vast literature and many reviews on soil compaction and its effect on plant growth and yield. It is not the purpose of this article to review that literature, but to restrict the discussion specifically to that pertaining to sugarcane.

The culture of sugarcane is rather unique in that after planting in rows, the crop is maintained and persists through several ratoons. This provides a form of pseudo-controlled traffic, but equipment wheel spacings are not common (Torres, *et al* 1990). This leads to potential damage to the plant itself, and soil compaction over the whole interrow due to up and down trafficking during fertilisation and harvesting. Because sugarcane tends to be grown in the tropics both with and without irrigation, there is a high probability that harvest will occur under wet soil conditions which will enhance soil compaction. This may affect subsequent root growth and hence crop yield.

Shallow compaction may be removed by cultivation. However, as machinery increases in size and axle weight the compaction effect occurs deeper in the profile (Eriksson, *et al* 1974). This may be reduced by deep ripping at an appropriate soil water content. Not all compaction results from mechanical operations. Some compaction occurs from naturally occurring processes, such as shrink-swell behaviour, and some soils have naturally genetic compact layers or are hard setting.

Also, sugarcane tends to be grown as a monoculture and this contributes to soil structural degradation with continued cultivation of the same area.

The change from hand harvesting to mechanical harvesting of cane has increased the possibility of creating adverse soil conditions through soil compaction. Growers have expressed concern about compaction and the adverse effect it may have on plant growth and yield. This is of increasing importance with fluctuations in the price for the product and increasing costs of production.

It is difficult to compare production systems throughout all sugar growing areas since some countries use manual harvesting and mechanised haulout while others use mechanised harvesting and haulout. Each system will have a different impact on the soil at the time of harvest.

Notwithstanding the above, there is general concern throughout the sugar industry worldwide as to the effect of mechanisation on the long term productivity of the crop.

Compaction affects the amount and continuity of pore space available for water, air and root movement. Soil strength tends to increase which also influences root growth. Changes in soil surface properties may lead to surface crust formation, reduced water infiltration, increased runoff and hence erosion (Prove, *et al* 1986). All these factors combine to affect subsequent plant growth and yield. This may be of special significance with respect to sugarcane in that the crop goes through several ratoon phases before being replanted.

The majority of studies of compaction on cane soils have concentrated on the identification of bulk density which limits root growth. The main emphasis has been the effect of field traffic in causing compaction under wet harvest conditions. These wet conditions do not occur every year, so the problem appears to be a transient one. There is a need to more clearly define 'wet' conditions. It is suggested that an appropriate range of water content would be that occurring between the lower plastic limit (PL) and that at which maximum bulk density occurs. Also, it is important to know the time the soil remains within this range as this corresponds with maximum compactibility of the soil and operations should be avoided during this period. However, no long term studies have been undertaken to determine the cumulative effect of compaction/traffic on crop performance.

LABORATORY STUDIES ON COMPACTION

To reduce the variability associated with field studies, several workers have examined the effect of soil compaction on plant growth and yield under laboratory conditions.

Yang (1974) and Shiue (1968) found that compaction of sugarcane soils, as assessed by dry bulk density, increased as applied load increased and as soil water content increased. The level of compaction at any level of applied load was dependent on soil texture, with fine textured soils compacting more than coarse textured soils. A similar observation was made by Kong (1968). Bulk densities of 1.5 to 1.7 g cm⁻³ were detrimental for root growth in these soils (Shiue, 1968; Kong, 1968).

In a field study artificially compacting soil to various bulk densities, Rao and Narasimham (1988a) found that cane yield was limited by a density of 1.5 and 1.6 g cm⁻³ in the surface and subsoil, respectively. Similar results were obtained by Srivastava (1985) at a soil density of 1.7 g cm⁻³ for a clay loam soil. Prihar *et al* (1985) also determined that surface compaction reduced yield. However, no values for soil density were quoted.

Not all compaction is detrimental as is evidenced by the use of press-wheels to improve sett-soil contact in loose seedbeds (Rehbein, 1979). However, with increasing size and weight of machinery, soil compaction may be a serious problem if harvesting or cultural operations are conducted under inappropriate soil moisture conditions.

Several studies have been undertaken to examine the effect of soil compaction on cane growth (Davidson, 1956; Hare, 1960; Cleasby, 1964); the effect of mechanised harvesting and haulout on soil compaction (Hurney, 1975; Vickers *et al.*, 1976; Yang, 1977; Georges, 1980; Fuelling and Ridge, 1981a; Gilmour and Wood, 1982; Swinford and Boevey, 1984; Swinford and Meyer, 1985; Torres *et al.*, 1990); and the effect of long term cane production on cane soil properties (Maclean, 1975; 1976).

Davidson (1956) compared cultivated and virgin soils to determine the effect of compaction on bulk density. For subsoils, the virgin areas were lower in bulk density compared with the cultivated areas for both soil types studied. As an ameliorative measure a subsoiling operation was undertaken. There was no effect of subsoiling on subsequent yield (Davidson, 1956). Also, water stability of soil aggregates was greater for the virgin soil compared with the cultivated soil.

Hare (1960) found that compaction in the field increased bulk density and reduced porosity and this was dependent on soil type, with greater changes on clay soils compared with silty clays. Yield declined more on the high density, low porosity soils than on soils where density was lower and porosity higher. This was observed for the 4th to 6th ratoon in the British West Indies (Hare, 1960; 1962).

A similar situation has been observed in South Africa (Cleasby, 1964), where an increasing number of mechanical harvests compared with manual harvesting has resulted in a decline in yield. Also, there was very little difference in the number of shoots between compaction treatments for one variety, which suggests that certain varieties may be able to tolerate a level of compaction with only a small deleterious affect on yield. These measurements, however, were taken before cane maturity.

MECHANISED HARVEST AND HAULOUT

Trials were established on the wet tropical coast of north Queensland to examine the effect of different harvesting and haulout systems on subsequent yield (Hurney, 1975). The main effect was confined to the top 10 cm of the soil for all systems. Results tended to be variable between sites, but this reflects the difference in soil water content at the time of impact. In contrast to other studies, there were no differences in cane yield between systems although there were marked differences in soil properties. Cultivation tended to overcome the compactive effect, but no consideration was given to subsequent traffic and possible re-compaction. Unfortunately the study was only a short term one and no cumulative effect was assessed.

The effect of a wet harvest was examined by comparing the yield of the following ratoon with harvest conditions in the previous year. There was little or no yield decline in the following ratoon if it had been harvested wet in the previous year (Vickers *et al.* 1976). This tends to support the results above, but it is unknown whether a critical soil water content at harvest exists before a yield decline occurs.

Yang (1977), however, found a significant yield loss of a ratoon crop with an increasing number of harvester passes, which increased soil strength and reduced porosity. The effect was much greater at higher soil water contents than at low soil water contents. The compaction effect was detectable to a depth of 40 cm which is considerably deeper than in the study by Hurney (1975). Different soil types probably account for the different response to vehicular traffic. Also, different machines were used in each study, which may account for the difference.

A common observation is that compaction under dry soil water conditions is not as severe as that under wet conditions (Hurney, 1975, Yang, 1977). As a result of mechanical harvesting soil compaction was detected at shallower depths compared with manual harvest (Georges, 1980). Also, trafficking at increasing soil water content caused a significant increase in density. Changes in soil physical properties affected the early growth of cane, but these differences were less evident at maturity. Root distribution was not affected, however, which contrasts with results of other workers.

Trials conducted by Gilmour and Wood (1982) indicated very little difference in soil bulk density, strength and porosity between conventional and high flotation haulout equipment. No soil water content at the time of impact is given, which would indicate whether or not the soil was in a condition susceptible for compaction to occur. Also, there was no difference in yield between treatments which tends to support the findings by Hurney (1975) and Vickers *et al* (1976).

Swinford and Boevey (1984) and Swinford and Meyer (1985) found that moderate and severe compaction caused an increase in bulk density and soil strength and a decrease in air filled porosity. Compaction over the row had a greater effect than compaction of the inter-row, it was presumed due to direct damage to the stool. Soil water content at the time of impact was 8 and 14%, ie it was in the range (8%) where it was not susceptible to compaction in one instance, but susceptible in the other instance. Cane yield was markedly reduced by both compaction treatments, which contrasts with previous results where little or no effect on yield was detected.

Torres *et al* (1990) also compared the effect of row and inter-row compaction under wet harvest conditions on soil properties and subsequent ratoon yield. Passage of machinery resulted in an increase in bulk density and soil strength. Correspondingly porosity and infiltration rate decreased. Root distribution was unaffected. However, direct damage to the stool by equipment was thought to be the largest cause of yield decline.

MINIMISING COMPACTION EFFECTS

To improve traction and reduce compaction dual wheels, tracks and flotation tyres have been used at various times (Taylor, 1974). There have been studies to determine whether tyres or tracks are most suited for operations undertaken in sugar production, based on performance and operating costs (Brixius, 1977, Reeser, 1980).

Fuelling and Ridge (1981b) recommend that equipment be fitted with high flotation and load sharing running gear to allow harvest to continue under wet conditions and reduce compaction and subsequent cultivation requirements. A similar recommendation was also made by Dick (1984). Recently, Harris and Pearce (1990) presented a design for a large capacity, high flotation haulout bin that would be compatible for cane harvesting areas throughout Australia. No assessment of a reduction in soil compaction compared with conventional equipment was made.

In general as the weight of machinery has increased, to maintain a constant ground pressure wider tyres, dual wheels or wider tracks have been utilised. However, this has resulted in an increased area of soil being compacted to a growth retarding level. Also, it is the total axle load and not surface pressure which causes compaction problems with depth in the profile (Froehlich, 1934). Contact pressure under tracks is lower than that under wheels, but the distribution is uneven due to load redistribution and presence of rollers (Brixius, 1977). This may play a significant role in soil compaction.

The best way to minimise compaction problems is to traffic an area at the appropriate soil water content ie under dry conditions. However, this is not always possible in the tropics when rainfall during the cane harvest creates adverse soil conditions. To avoid deterioration of the cane, especially if burnt, it should be harvested within a certain period of time. Hence, harvest under wet conditions is perhaps more prevalent than it should be.

To prevent stool damage by machinery an increase in row spacing is necessary (Torres *et al* 1990). It has been shown, however, that yield tends to decrease with an increase in row spacing (Shafi *et al* 1990). Other workers have determined that there was no significant difference in t ha⁻¹ sugar with different row spacings (Irvine *et al* 1984). There may be some yield compensation with ratoons as possibly more shoots will develop in the wider inter-row areas. An increase in row spacing would also facilitate the adoption of a controlled traffic system whereby compaction could be managed for benefit.

CANE ROOT GROWTH

Studies of sugarcane roots were undertaken in order to develop strategies for cultivation, irrigation and fertiliser placement. These were to ensure roots were not damaged during cultivation and to ensure maximum water and fertiliser use efficiency. Interest in sugarcane roots and the development of techniques for the study of the morphology, distribution and the effect of soil properties on sugarcane root growth dates back to the 1920's and has continued since that time (Venkatraman and Thomas, 1924; Lee, 1926a,b,c,d; Thomas, 1928; Wolters, 1929; Roxas and Villano, 1930; Hardy, 1933; Evans, 1934, 1935a,b, 1936a,b; Trowse and Humbert, 1961; Baver *et al* 1962; Singh, 1964; Wood, 1965; Trowse, 1965; Monteith and Banath, 1965; Glover, 1967; Ahmad and Paul, 1978; Rao and Narasimham, 1986; Srivastava, 1990).

ROOT TYPE

Briefly, three types of roots have been identified for sugarcane. These consist of sett roots which initiate from root primordia around the node of the sett after planting, shoot roots which initiate from the base of newly germinated shoots and replace the sett roots as the plant develops and deep roots which, although are individual, gradually inter-twine and give the appearance of ropes and hence the name of rope roots. These are illustrated and more fully discussed by Evans (1934).

Techniques for examining root systems are provided by Venkatraman and Thomas (1924), Evans (1935a,b), Glover (1967) and Ahmad and Paul (1978).

DISTRIBUTION OF ROOTS

Many studies have been carried out on the distribution of the roots of sugarcane worldwide, but few have been undertaken in Australia. These studies were instigated to determine the best method and position for fertiliser placement and cultivation, as stated earlier.

A common observation with many cane varieties and on many soil types is that 50-70% of cane roots occur within the top 20 cm of the profile (Lee, 1926d; Wolters, 1929; Ryker and Edgerton, 1931; Hardy, 1933; Evans, 1935a; Wood, 1965). Lateral spread of roots into the interrow is largely confined to the 10 cm depth (Hardy, 1933). Also, there is a difference in distribution between planting in furrows and on hills, with a greater proportion of roots at depth when planted on hills (Lee, 1926d; Wood, 1991).

Most early studies were qualitative in nature, in that they were based on profile observations in pits. (Venkatraman and Thomas, 1924; Wolters, 1929; Roxas and Villano, 1930; Evans, 1935a,b). A gradual move was made into quantitative studies which involved sieving various layers of soil and weighing the roots so separated and determining the percentage of roots in each layer (Lee, 1926d; Wolters, 1929). Another technique used in quantitative studies was the extraction of soil cores and washing the roots from defined depths (Hardy, 1933; Ahmad and Paul, 1978). The major concern with these studies is adequate replication to enable an evaluation of root distribution in the profile.

SOIL PHYSICAL PROPERTIES AND ROOTS

Plant roots require an adequate water supply, good aeration and relatively loose material for proliferation through the profile. Soil compaction reduces soil water availability, reduces aeration and increases soil strength largely through decreasing soil porosity and increased bulk density. Thus it is difficult to isolate any one of these factors in the study of soil properties on root growth. It is the interaction between these properties rather than any one taken in isolation which determines root growth and hence crop yield. Field

operations under wet conditions may smear the soil, thus reducing pore continuity which will also affect root growth through the profile. There has been some inference that poor root growth will be reflected in poor shoot growth and a reduced yield (Wolters, 1929; Glover, 1967).

The effect of compaction on root growth has been examined in the past by placing cores of varying density into pots of loose soil of the same type and observing whether or not cane roots penetrated the cores (Trowse and Humbert, 1961; Trowse, 1965; Juang and Uehara, 1971). The pots were kept well watered. This technique is questionable in that roots will tend to grow preferentially in loose rather than compact soil. This is evident in these experiments in that the soil surrounding the cores became root bound with very few roots penetrating the cores even at the lowest density. Thus little idea is gained as to the soil bulk density limiting growth as was the intention of the experiment. However, it was observed that root growth was restricted by increasing soil bulk density and that the so called 'critical' bulk density varied with soil texture (Trowse and Humbert, 1961; Trowse, 1965; Juang and Uehara, 1971). Unfortunately it appears that there is no 'critical' bulk density that applies to all soil types, so this property cannot be used as an indicator for potential plant response. Rao and Narasimham (1988) also found that root growth was restricted as the level of soil compaction increased. No limiting value of soil bulk density was aluded to. A larger number of roots were found to develop in the surface soil as the compaction level increased. Singh (1964) determined that a field bulk density of 1.75 g cm^{-3} restricted root growth which was reflected in poor shoot growth. It is interesting to note that chemically there was little difference between productive and unproductive areas of the field. Also, in a laboratory experiment Singh (1964) found that cane root growth was reduced as bulk density increased, a similar result to that determined by many other workers. Monteith and Banath (1965) also determined that root growth decreased with increasing bulk density and soil strength, and that density was dependent on soil texture.

Root proliferation also depends on pore continuity and rigidity and pore size distribution. Wiersum (1957) demonstrated that roots failed to penetrate rigid pores smaller in diameter than the root. In a laboratory study, Srivastava (1990) has shown that sugarcane roots are restricted by a pore size of $250 \mu\text{m}$. Since aeration and water supply was not limiting, it was concluded that rigid pores of this size may limit root proliferation. This may also vary with genotype and be affected by soil temperature, aeration and water content.

SOIL WATER AND CANE GROWTH

Studies by Hardy and Derraugh (1947) indicate that during the wet season air-filled porosity falls below 10% for relatively long periods of time on clay soils. They suggest that cane roots would suffer 'physiological drought' during this time which may affect crop growth. However, they also emphasise the importance of cracks in aeration and profile water replenishment under the conditions of the study. In contrast sandy soils experienced air filled porosities of less than 10% for shorter periods of time compared with the clay soil.

Water table depth has been shown to significantly affect cane yield in pot trials (Pao and Hung, 1961; Juang and Uehara, 1971) and in the field (Rudd and Chardon, 1977; Wilson, 1982; Wood *et al* 1984). The yield of cane was significantly reduced when the water table was at 50 cm compared with 150 cm. Rudd and Chardon, (1977) and Wilson (1982) found that as the number of days that the water table was 50 cm or less from the soil surface increased, the yield of cane decreased. The implication of this is the requirement for drainage works to reduce the height of the water table and the duration of water logging. Irvine *et al* (1984), however, found that the yield of a plant crop and a first ratoon crop was not affected by drainage, but for the second ratoon crop the yield on the undrained plots was depressed by 30% compared with the drained plots.

Gayle *et al* (1987) developed a model to relate relative yield to a stress-day-index, which was defined as excess water above the 45 cm depth. This model also indicated that as the stress-day-index increased the relative yield of cane decreased. The model was developed as an aid in assessing various drainage parameters and the effect of drainage on yield. The model, however, has only been tested on a limited amount of data, so it would need further calibration before extrapolation to other areas could be made.

IMPROVING SOIL PHYSICAL CONDITIONS

Tillage/cultivation is a rapid way of altering soil physical conditions. However, care needs to be exercised to ensure that tillage is undertaken at an appropriate soil water content (Braunack and McPhee, 1991). No studies of this interaction have been undertaken with respect to sugarcane. Tillage also tends to alleviate surface compaction caused by harvest under moderate-wet to wet conditions, and this is perhaps why little evidence is available for the effect of soil physical condition on subsequent yield. Crop nutrition and new varieties are probably masking soil physical effects to some extent also.

To improve water holding capacity and root proliferation through the profile, deep ripping or subsoiling has been used (Trowse and Humbert, 1959; Ahmad and Paul, 1978). Again soil water content at the time of the operation is important. Also, the effect is relatively short lived as subsequent field traffic recompacts the loosened material (Trowse and Humbert, 1959).

Historically, agricultural systems have been based on crop rotation in order to maintain good soil physical condition. This method was suggested as being beneficial for cane soils in the 30's and again in the 80's (Bell, 1935, 1938; Li and Liu, 1981). However, the length of the cane crop cycle and the short period of time between crops tends to preclude crop rotation with cane. Also, many cane growing areas are land locked and there have been no economically viable alternative crops to grow.

To improve the physical structure of cane surface soils additives have been used with varying success. Various workers have measured wet aggregate stability of soil aggregates after the addition and incubation of molasses and sorghum residues (Vallance and Leverington, 1950) and of synthetic soil conditioners (Vallance and Leverington,

1953a, b). The effect, however, was relatively short lived with subsequent working and puddling reducing wet aggregate stability of the soils studied. No studies were undertaken to examine the effectiveness or longevity under field conditions. It should be noted that artificial soil conditioners only stabilise the soil structure that is present at the time of application, and do not create a well aggregated structure, so it is possible to stabilise a poorly structured soil condition.

Recently minimum tillage and trash blanketing have been adopted to largely reduce costs of cane production. It is believed that these techniques will increase the level of organic matter in the surface soil and reduce soil compaction (Wood, 1985). However, few studies have measured soil physical properties to determine whether changes had occurred (Dick and Hurney, 1986; Wood, 1986). Wood (1986) determined that the bulk density and porosity was similar for burnt trash, trash incorporated and trash blanket treatments during the plant crop. However, after the first ratoon the trash blanket treatment had a higher bulk density and lower porosity compared with the other two treatments. This was due to the non-cultivation of this treatment, whereas the other two were cultivated. Page *et al* (1986) found that soil water content in the top 30 cm was higher under a trash blanket compared with the burnt cane treatment. Also, after three years aggregate stability had increased slightly, but only for the 5 to 2 and < 0.125 mm sizes.

Further studies are required to monitor soil physical properties under the different systems of management to determine whether detrimental or beneficial changes are occurring.

CONCLUSIONS

Sugarcane growth and yield is affected by soil physical properties, but the results tend to be inconsistent. The response seems to be determined by the climatic conditions during and after a particular treatment. The effect of soil physical properties on cane growth and yield tends to be transient, due to the influence of remedial action and climate.

Attempts have been made to define soil bulk density that limits growth and hence yield. However, this depends on the soil water content used to generate the density and the texture of the soil. Results have been difficult to relate to yield. A system of relative density as developed by Hakansson (1988) and Carter (1990) would be more appropriate and could be related to crop yield. This technique involves relating the soil bulk density to a maximum or standard compaction state for that soil type. Many workers have found that as soil bulk density increases that cane yield decreased. However, yield measurement was often not made at maturity or the trials were conducted in pots.

There is a need to determine the ability of cane varieties to grow under high soil density/strength situations. The technique developed by Asady *et al* (1985) would be an appropriate way of screening varieties for the ability of roots to penetrate compact soils. This would enable varieties to be selected which would grow under adverse soil conditions or to be grown after wet harvest conditions. It is speculated that soil compaction may also affect the ratooning ability of cane. Soil temperature and water

relations may also be altered which would affect the subsequent growth of cane. These factors would influence the growth of cane after a 'wet' harvest.

To reduce the impact of soil compaction, high flotation running gear has been used. Results have been variable with no differences being detected when conventional running gear was used in some cases. Also, yields have not declined as expected after a wet harvest. With the use of wider tyres, the area impacted increases, as does the possibility of directly damaging the stool.

There is a clear need to investigate the use of a controlled traffic system for cane production. This will enable the separation of the traffic areas and the plant growth areas. This should result in provision of optimum conditions for traction and plant growth, thereby minimising the adverse effect of a wet harvest.

There is an obvious need to study the effect of soil physical factors in relation to the soil biota, both beneficial and detrimental organisms, and their effect on yield.

Most studies examined in this article were of short duration. Notwithstanding the cost of long term trials, it would be of benefit to monitor soil physical factors in relation to plant growth over several seasons at the one site. This would be facilitated if reference sites were already in existence in an area. Unique opportunities exist where new areas are brought into production, since parameters can be measured in a pristine state and changes with time can be monitored. Changes can also be compared with those on adjacent areas of the same soil type which have been under cane production for an extended period of time. This may allow an assessment of management strategies to reduce unfavourable changes in soil properties. The new areas brought into cane production can range from old pasture to cleared woodland and may also include old headlands on current areas under cane production. Thus there is the possibility that the new areas may in fact be in poorer condition than degraded old land, since the best areas for agricultural production were developed first. The suitability of such sites for monitoring changes would need to be established in the first instance.

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