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# The effect of soil physical properties on growth and yield of sugarcane

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**BUREAU OF SUGAR EXPERIMENT STATIONS  
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**THE EFFECT OF SOIL PHYSICAL PROPERTIES  
ON GROWTH AND YIELD OF SUGARCANE**

by

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# 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.

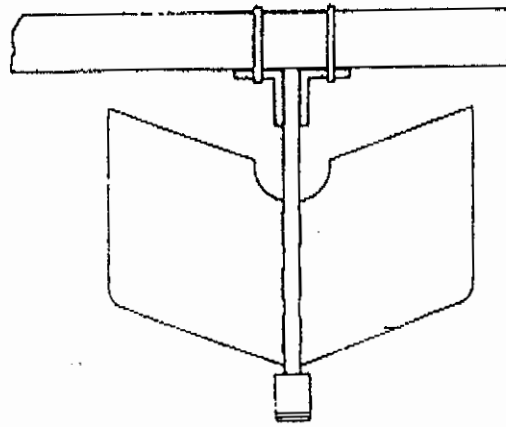
Evans (1963) reported on tillage trials conducted in various countries and concluded that there was little or no difference in yield between the various treatments compared. Changes in soil properties were not reported.

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.

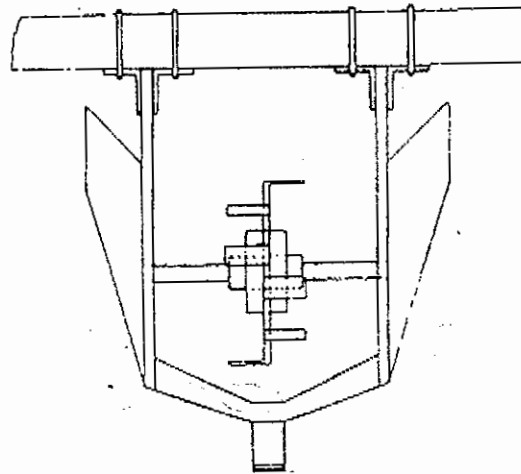
Strategic tillage has been suggested to reduce weed growth and associated tillage costs, whilst in conjunction with subsoiling to encourage deep rooting for better drought survival (Menon, 1965, Santo, 1985). Using this technique only the sowing line is disturbed, leaving the inter-row area in a more 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 deducted.

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

A) CONVENTIONAL



B) ROSSETI



C) SCARIFYING FURROWER

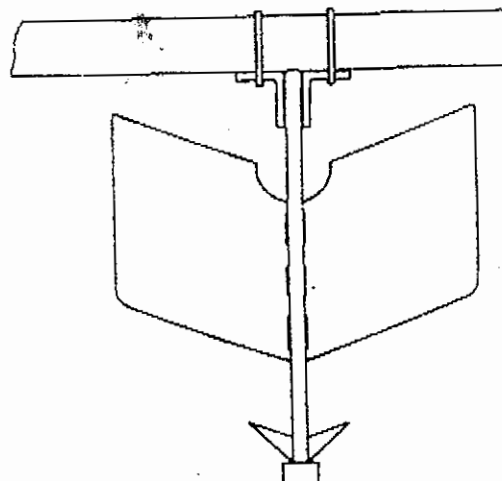


Figure 1 Opener types (from Salata *et al* 1986)



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<sup>-3</sup> 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<sup>-3</sup> in the surface and subsoil, respectively. Similar results were obtained by Srivastava (1985) at a soil density of 1.7 g cm<sup>-3</sup> 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 alluded 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  $1.75 \text{ g cm}^{-3}$  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.

## REFERENCES

- Ahmad, N and Paul, C L (1978). Effects of subsoiling on soil physical conditions and sugar cane root distribution in a Trinidad clay soil. In 'Modification of soil structure', Emerson, W W, Bond, R D and Dexter, A R eds. Wiley and Sons, Chichester, UK. p 419-429.
- Asady, G H, Smucker, A J M and Adams, M W (1985). Seedling test for the quantitative measurement of root tolerances to compacted soil. *Crop Science*, 25:802-806.

- Barnes, K K, Carleton, W M, Taylor, H M, Throckmorton, R I and Vanden Berg, G E eds. (1971). *Compaction of agricultural soils*. ASAE Monograph, ASAE, St Joseph, Michigan, 49085, USA.
- Baver, L D, Brodie, H W, Tanimoto, T and Trowse, A C Jr (1962). New approaches to the study of cane root systems. *Proc. Int. Soc. Sugar Cane Technol.*, 11:248-253.
- Bell, A F (1935). Sick soils. *Proc. Qld. Soc. Sugar Cane Technol.*, 6:9-18.
- Bell, A F (1938). Crop rotation with special reference to the principles of green manuring. *Proc. Qld. Soc. Sugar Cane Technol.*, 9:36-47.
- Braunack, M V and McPhee, J E (1991). The effect of initial soil water content and tillage implement on seedbed formation. *Soil and Tillage Res.*, 20(1):5-17.
- Brixius, W W (1977). Tires and tracks in sugarcane. *Proc. Int. Soc. Sugar Cane Technol.*, 16:1949-1961.
- Carter, M R (1990). Relative measures of soil bulk density to characterize compaction in tillage studies on fine sandy loams. *Can. J. Soil Sci.*, 70:425-433.
- Chancellor, W J (1977). Compaction of soil by agricultural equipment. *Division of Agric. Sci., Univ. California, Bull.* 1881, 53 p.
- Cleasby, T G (1964). Symposium on soil compaction. *Proc. Sth. Afr. Sugar Technol. Assn.*, 38:144-153.
- Croft, B J, Reghenzani, J R and Hurney, A P. (1984). Northern poor root syndrome of sugarcane - studies on soil transmission and the effects of various fungicidal, nutritional and agronomic treatments. *Proc. Aust. Soc. Sugar Cane Technol.*, 6:69-77.
- Davidson, L G (1956). A preliminary report of soil compaction studies of Louisiana cane soil. *Proc. Int. Soc. Sugar Cane Technol.*, 9:539-543.
- Dick, R G (1984). High flotation infield cane transporters. *Agric. Engng. Conf., Inst. Engrs., Aust. Natl. Conf. Publ. No. 84.* p 9-12.
- Dick, R G and Hurney, A P (1986). Technological change in sugarcane agriculture. *Proc. Aust. Soc. Sugar Cane Technol.*, 8:69-75.
- Eriksson, J, Hakansson, I and Danfars, B (1974). The effect of soil compaction on soil structure and crop yields. *Swedish Institute of Agric. Engng., Bull.* 354, 101 p. (Eng. transl. J. Aase, USDA-ARS.)

- Evans, H (1934). Studies on root-exudation and root-types in sugarcane. Dept. Agric. Mauritius. Sug. Res. Sta. Bull. No. 5, p 3-13.
- Evans, H (1935a). Investigations on the root-system of sugarcane varieties. Dept. Agric. Mauritius, Sug. Res. Sta. Bull. No. 6, p 3-44.
- Evans, H (1935b). The root-system of the sugar-cane. Pt I. Methods of study. Emp. J. Exp. Agric., 3:351-362.
- Evans, H (1936a). The root-system of the sugar-cane. Pt II. Some typical root-systems. Emp. J. Exp. Agric., 4:208-220.
- Evans, H (1936b). The root-system of the sugar-cane. Pt III. The early development of the root-system of sugar-cane in Mauritius. Emp. J. Exp. Agric., 4:325-331.
- Evans, H (1963). A review of recent developments and trends in sugar cane agriculture. Int. Sugar J., 65:163-166.
- Froehlich, O K (1934). Drukverteilung in baugrunde (Pressure distributions in the soil). Wien.
- Fuelling, T G and Ridge, D R (1981a). Cane transport review - soil compaction aspects. BSES Project Report, 17 p.
- Fuelling, T G and Ridge, D R (1981b). Cane transport review. BSES Project Report, 50 p.
- Gayle, G A, Skaggs, R W and Carter, C E (1987). Effects of excessive soil water conditions on sugarcane yields. Trans. ASAE, 30(4):993-997.
- Georges, J E W (1980). Effects of harvest traffic and soil water content on soil compaction and regrowth of sugar cane. Proc. Int. Soc. Sugar Cane Technol., 17:1078-1089.
- Gilmour, J M and Wood, A W (1982). BSES-CSR soil compaction trials in the Herbert Valley, 1981. Unpubl. Rept., 15 p.
- Glover, J (1967). The simultaneous growth of sugarcane roots and tops in relation to soil and climate. Sth. Afr. Sugar Technol. Assn., 41:143-159.
- Hakansson, I (1988). A method for characterizing the state of compactness of an arable soil. In 'Impact of water and external forces on soil structure', Drescher, J, Horn, R and de Boodt, M eds. Catena Suppl. 11, Catena Verlag, FRG.

- Hardy, F (1933). Root distribution of sugar-cane in different soils in Trinidad. *Tropical Agric.*, X:165-172.
- Hardy, F and Derraugh, L F (1947). The water and air relations of some Trinidad sugar-cane soils. Part I. *Trop. Agric.*, XXIV(7-9):76-87.
- Hare, C J (1960). Some observations on various soil physical properties and their bearing on yield of sugarcane on a Berbice sugar estate. *Proc. Brit. West Indies Sugar Technol.*, p 80-86.
- Hare, C J (1962). The effect of some soil physical properties on the growth of sugar cane with special reference to the availability of moisture and potassium. *Proc. Int. Soc. Sugar Cane Technol.*, 11:130-139.
- Harris, H D and Pearce, F (1990). The analysis and design of infield haulout bins for the Australian cane industry. *Agric. Engng. Conf., Inst. Engrs., Aust. Natl. Conf. Publ. No. 90/13* p 10-14.
- Hurney, A P (1975). Soil compaction studies - Mossman. BSES Project Report, 13 p.
- Irvine, J E, Richard, C A, Carter, C E and Dunckelman, J W (1984). The effect of row spacing and sub-surface drainage on sugar cane yields. *Sugar Cane No. 2*, p 3-5.
- Jain, N K and Agrawal, J P (1970). Effect of clod size in the seedbed on development and yield of sugarcane. *Soil Sci. Soc. Am. Proc.* 34:795-797.
- Kong, I (1968). Effect of soil compaction on the growth of young cane plants. *J. Chinese Agric. Chem. Soc.* 6(3,4):95-104.
- Lee, H A (1926a). Progress report on the distribution of cane roots in the soil under plantation conditions. *Hawaiian Planters Record*, 30:511-519.
- Lee, H A (1926b). The distribution of the roots of young D1135 plant cane in the soil. *Hawaiian Planters Record*, 30:267-270.
- Lee, H A (1926c). A comparison of the root weights and distribution of H109 and D1135 cane varieties. *Hawaiian Planters Record*, 30:520-523.
- Lee, H A (1926d). The distribution of the roots of sugar cane in the soil in the Hawaiian Islands. *Plant Physiology*, 1:363-378.
- Li, Song-U and Liu, Wen-cheh (1981). Pre-planting submergence as soil ecological alteration in sugar cane field. *Taiwan Sugar*, 28(3):80-84.

- Maclean, N R (1975). Long-term effects of sugar cane production on some physical and chemical properties of soils in the Goondi Mill area. *Proc. Qld. Soc. Sugar Cane Technol.*, 42:123-126.
- Maclean, N R (1976). Soil compaction studies in the Goondi Mill area. *Proc. Qld. Soc. Sugar Cane Technol.*, 43:103-109.
- Menon, R G (1965). Strip-tilling for sugar cane cultivation. *Proc. Int. Soc. Sugar Cane Technol.*, 12:531-539.
- Monteith, N H and Banath, C L (1965). The effect of soil strength of sugarcane root growth. *Tropical Agric.*, 42:293-296.
- Page, R E, Glanville, T J and Truong, P N (1986). The significance of trash retention trials in the Isis and Maryborough Mill areas. *Proc. Aust. Soc. Sugar Cane Technol.*, 8:95-101.
- Pao, T P and Hung, S L (1961). Effect of depth of underground water table on growth, yields and root system of sugar cane (NCo310). *Rept. Taiwan Sugar Expt. Sta. No. 24*, p 19-53.
- Pao, T P, Lee, Y T and Lin L Y (1961). Cane yield as affected by the frequency of cultivation with tractor on different kinds of soils. *Rept. of Taiwan Sugar Expt. Sta. No 25*, August, p 1-9.
- Prihar, S S, Verma, H N, Sandhu, K S and Singh, R (1985). Growth and yield of rainfed sugarcane in relation to mulching and surface compaction on two soils. *Ind. J. Ecol.*, 12(1):62-66.
- Primavesi, A and Primavesi, A M (1964). Factors responsible for low yields of sugar cane in old cultivated Terra Roxa Estruturada soils in Eastern Brazil. *Soil Sci. Soc. Am. Proc.*, 28(4):579-580.
- Prove, B G, Truong, P N and Evans, D (1986). Strategies for controlling caneland erosion in the wet tropical coast of Queensland. *Proc. Aust. Soc. Sugar Cane Technol.*, 8:77-84.
- Rao, R S and Narasimham, R L (1988a). Effect of soil compaction in sugarcane: Part IV. On stalk characters, cane yield and juice quality. *Int. J. Trop. Agric.*, VI:237-240.
- Rao, R S and Narasimham, R L (1988b). Effect of soil compaction in sugarcane: Part II. On root development. *Int. J. Trop. Agric.*, VI:227-231.
- Reeser, L G (1980). Tires or tracks in cane tillage. *Proc. Int. Soc. Sugar Cane Technol.*, 17:742-753.

- Rehbein, C (1979). Wheels within wheels - controlled compacting. *Cane Grower Qld. Bull.*, 42:88.
- Ricaud, R (1971). Effects of varying numbers of cultivation on sugarcane production in Louisiana. *Proc. Int. Sugar Cane Technol.*, 14:634-639.
- Roxas, M L and Villano, M (1930). Studies on the development of the sugar-cane plant in the Philippines. *The Philippine J. Sci.*, 43:367-401.
- Rudd, A V and Chardon, C W (1977). The effects of drainage on cane yields as measured by water-table heights in the Macknade Mill area. *Proc. Qld. Soc. Sugar Cane Technol.*, 44:111-117.
- Ryker, T C and Edgerton, C W (1931). Studies on sugar cane roots. Louisiana State University of Agric. Mech. Coll., Agric. Expt. Sta., Louisiana Bull. 223, 36 p.
- Salata, J C, Conde, A J and Dematte, J L I (1986). Influence of the type of furrow opener on the development of the root system and on sugarcane yield. *Proc. Int. Soc. Sugar Cane Technol.*, 18:203-212.
- Santo, L T (1985). Precision tillage experiments in unirrigated sugarcane. *Hawaiian Sugar Technol.*, 1985 Reports, p 01-04.
- Shafi, Mahommad Ch, Shah, M L, Mahmmod, T, Afghan, S and Shah, S H (1990). Cane yield and quality of sugar cane as influenced by different planting pattern. *Pakistan Sugar J.*, IV(2):3-4.
- Shiue, J J (1968). Effect of soil bulk density on the growth of sugar-cane. *Taiwan Sugar Expt. Sta. Rept.*, 44:71-72.
- Simpson, L A and Gumbs, F A (1982). Soil physical properties and sugar-cane root and shoot growth on Louisiana banks after conversion from cambered beds field layout in Trinidad, W.I. *Trop. Agric. (Trinidad)*, 59(1):38-42.
- Singh, A (1964). Soil compaction effects on the growth of sugarcane roots. *Science & Culture*, 30:606-607.
- Srivastava, A K (1985). Study on effects of soil compaction on rooting pattern of sugarcane. *J. Nuclear Agric. Biol.*, 14(2):82-83.
- Srivastava, A K (1990). Effect of pore-size on penetration of sugarcane roots. *Trop. Agric. (Trinidad)*, 67:382-383.

- Swinford, J M and Boevey, T M C (1984). The effects of soil compaction due to infield transport on ratoon cane yields and soil physical characteristics. *Proc. Sth. Afr. Sugar Technol. Assn.*, 58:198-203.
- Swinford, J M and Meyer, J H (1985). An evaluation of a nuclear density gauge for measuring infield compaction in soils of the South African sugar industry. *Proc. Sth. Afr. Sugar Technol. Assn.*, 58:218-224.
- Taylor, J H (1974). Traction, compaction, and flotation in soft soils. *Proc. Int. Soc. Sugar Cane Technol.*, 15:1114-1123.
- Taylor, J H (1983). Benefits of permanent traffic lanes in a controlled traffic crop production system. *Soil and Tillage Res.*, 3:385-395.
- Taylor, J H (1989). Controlled traffic research: An international report. *Proc. 11th Int. Congr. Agric. Engng.*, Dødd, V A and Grace, P M eds. p 1787-1794.
- Thomas, R (1928). A method of studying the roots of sugar cane. *Int. Sugar J.*, 30:298-300.
- Torres, J S, Yang, S J and Villegas, F (1990). Soil compaction and sugarcane stool damage due to semi-mechanised harvesting in the wet season. *Proc. Int. Soc. Sugar Cane Technol.*, XX Vol. 2:992-999.
- Trouse, A C Jr (1960). Cultivation. The impact of soil properties on the choice of tillage method. *Rept. Hawaiian Sugar Technologists 1960*, p 43-45.
- Trouse, A C Jr (1965). Effects of soil compression on the development of sugar-cane roots. *Proc. Int. Soc. Sugar Cane Technol.*, 12:137-152.
- Trouse, A C Jr and Humbert, R P (1959). Deep tillage in Hawaii: I Subsoiling. *Soil Sci.*, 88:150-158.
- Trouse, A C Jr and Humbert, R P (1961). Some effects of soil compaction on the development of sugar cane roots. *Soil Sci.*, 91:208-217.
- Vallance, L G (1953). Tilth - some features of its control. *Proc. Qld. Soc. Sugar Cane Technol.*, 20:123-126.
- Vallance, L G and Leverington, K C (1950). The effect of molasses and sweet sorghum residues on soil structure. *Proc. Int. Soc. Sugar Cane Technol.*, 78:209-217.
- Vallance, L G and Leverington, K C (1953). The effect of a synthetic soil conditioner (Krilium) on the aggregation of some Queensland soils. *Proc. Int. Soc. Sugar Cane Technol.*, 8:221-228.



- Venkatraman, T S and Thomas, R (1924). Simple contrivances for studying root development in agricultural crops. *Agric. J India*, 19:509-514.
- Vickers, R P, Stewart, G A and Nalder, C R (1976). An inconclusive study of the effects of wet soil machine harvesting on ratoon productivity. *Proc. Qld. Soc. Sugar Cane Technol.*, 43:57-62.
- Wiersum, L K (1957). The relationship of size and structural rigidity of pores to their penetration by roots. *Plant Soil*, 9:75-85.
- Wilson, P R (1982). The relationship between soil characteristics, water-table heights and sugar cane yields in the Macknade Mill area. In *Proc. Symp. Rural Drainage in Nth. Aust.*, DDIAE Soil and Water Studies Centre. p 55-66, Toowoomba.
- Wolters, W (1929). The root distribution of sugar cane. *Facts about Sugar*, 24:206-209.
- Wood, A W (1985). Soil degradation and management under intensive sugar cane cultivation in north Queensland. *Soil Use & Management*, 1(4):120-124.
- Wood, A W (1986). Green cane trash management in the Herbert Valley. Preliminary results and research priorities. *Proc. Aust. Soc. Sugar Cane Technol.*, 8:85-94.
- Wood, A W, Maclean, N R and Stewart, R L (1984). The effects of water levels and soil properties on sugar cane yields in the Herbert Valley. *Proc. Aust. Soc. Sugar Cane Technol.*, 6:107-114.
- Wood, R A (1965). Sugarcane root distribution. *Sth. Afr. Sugar J.*, 49:231.
- Wood, R A (1991). Ridging improves cane yields on poor quality soils. *Int. Soc. Sugar Cane Technol.*, Tech. Newsletter No: 2, Feb. 1991.
- Yang, S J (1974). Compaction studies on mechanised cane field soils. I. Influence of soil texture and moisture content on soil compaction. *Taiwan Sugar Res. Inst. Rept.*, 64:11-22.
- Yang, S J (1977). Soil physical properties and the growth of ratoon cane as influenced by mechanical harvesting. *Proc. Int. Soc. Sugar Cane Technol.*, 16:835-847.