EFFECT OF SURFACE APPLIED PRESSURE BY VEHICLES FITTED WITH PNEUMATIC TYRES ON PROPERTIES OF A VIRGIN SOIL

VAN ANTWERPEN R[1], LYNE PWL[1], MEYER E[2] and BROUWERS M[3]

[1]*South African Sugarcane Research Institute, Private Bag X02, Mount Edgecombe, 4300, South Africa*
rianto.van.antwerpen@sugar.org.za, *peter.lyne@sugar.org.za*
[2]*eddie.meyer@iuncapped.co.za*
[3]*CIRAD, c/o SASRI, Private Bag X02, Mount Edgecombe, 4300, South Africa*
marinus.brouwers@cirad.fr

Abstract

Soil compaction is often studied by comparing virgin sites to commercial fields with a long-term cultivation history. The establishment of a new research farm in a virgin area of the Mpumalanga province in South Africa provided an opportunity to induce compaction to quantify the buffer capacity of a virgin soil against degradation of its soil physical properties.

The soil of the trial site is a shallow (±0.4 m) Cambisol with uniform texture (±44% clay), and 3.8% organic matter in the A-horizon, overlying weathered basalt. Row spacings were 1.5 m and 1.8 m, and only haulage vehicles with matching wheel spacings were allowed in the field. Compaction treatments, starting after harvest of the plant crop in 2003, consisted of pressure applied with commercial 30 ton capacity loaded haulage vehicles fitted with either radial tyres or high flotation tyres. After harvest the soil was kept dry in one part of the field and watered elsewhere to create differential water contents at the time of treatment application.

Results showed reduced water infiltration rates, increased soil bulk density, increased penetration resistance and reduced root distribution in all the compaction treatments. The treatments with a higher water content were more susceptible to degradation.

It is concluded that even a virgin soil in good physical condition will be degraded over the period of a few years to the physical threshold limits. The buffer capacity of this soil against compaction (and therefore of most other soils) degraded over a period of only three years. Permanent traffic lanes should therefore be considered essential in most agricultural systems to protect the productive areas of fields. Proper spacing of interrows and the use of low pressure high flotation tyres on all axles should be considered as additional measures to achieve this goal.

Keywords: compaction, bulk density, penetration resistance, water infiltration, sugarcane, yield

Introduction

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

Factors such as soil water content, texture, structure and organic matter affect the final density of soils (Smith *et al*., 1997). Taylor and Pohlen (1962) proposed a guide to benchmark the bulk density classes of uncompacted virgin soils (Table 1). Georges *et al*. (1985) found that tyre dimension and inflation pressure had no significant effect on soil compaction in a dry soil with swell and shrink properties. They also found that, regardless of the soil water content at the time of compaction, it had no effect on cane yield or quality. However, Wood (1965) reported restricted root growth caused by impeded drainage that was the result of soil compaction. The objective of this paper is to quantify degradation of a virgin soil caused by two infield management systems at two soil water content levels relative to no wheel traffic.

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

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

Materials and Methods

A field trial was established in 2002 on the then newly acquired South African Sugarcane Research Institute (SASRI) research farm near Komatipoort (latitude 25°33'10"S, longitude 31°57'17"E, elevation 166 m) in the north-eastern corner of South Africa. In preparation for trial work the natural vegetation (grass, lowveld shrubs and trees) was removed using a bulldozer. The site was planted to sugarcane (lodging-resistant variety N32) in July 2002 at row spacings of 1.5 m and 1.8 m (a tramline arrangement of 1.2 m interrow space followed by 0.6 m between closely spaced cane rows) and the first compaction treatments were applied after the plant crop was harvested in July 2003. The compaction treatments were repeated after harvest in 2004 and 2005.

The soil

The soil was a Hutton/Glenrosa (Soil Classification Working Group, 1991) or Cambisol (FAO, 1998) with 4.4% organic matter and between 30 and 34% clay in the top 100 mm layer, with no significant differences between the trial plots (see Table 2). The depth of the A and B horizons ranged from 300 to 700 mm, whereafter there was an abrupt change to weathered basalt.

Fertiliser

Soil samples representing one hectare each were collected for analysis in July 2001 from the trial site after the bush was cleared (Table 2). Because of the pristine condition of the soil no fertiliser other than N was applied to the plant crop. The fertiliser recommendations made by the SASRI Fertiliser Advisory Service (FAS) for the plant crop and three ratoons are given in Table 3.

Irrigation

The Canesim crop model (radiation use efficiency version as described by Singels and Bezuidenhout, 2002) was used to schedule irrigation. However, due to drought in 2004 and 2005, water was applied when available. For this reason the 2004-2005 and 2005-2006 season crops received 157 and 247 mm less water, respectively, compared to the 2003-2004 crop (Table 3).

Table 2. Soil analysis before any cane was planted at the trial site (29 July 2001).

Field no.	pH water	#pH buffer	*N min	+NH_3 (%)	P (kg/ha)	K (kg/ha)	Ca (kg/ha)	Mg (kg/ha)	OM (%)	Clay (%)
7A	6.11	7.30	2	0	24	538	7 277	2 463	3.6	45.0
7B	6.05	7.23	2	0	25	457	6 825	2 486	3.8	46.2
8A	6.39	7.51	2	1	>181	850	7 481	2 283	3.8	47.6
8B	6.67	7.55	2	1	>181	1 318	8 769	2 373	4.0	38.0

#The pH above which N losses will be greater than the lowest threshold of 5% (Schumann, 2000).
*Nitrogen mineralisation category (Meyer *et al.*, 1983)
+Estimated N loss (as NH_3) at the current soil pH (Schumann, 2000).

Table 3. Fertiliser required and applied based on full cycle advice, and irrigation applied and rainfall received.

Season	Crop	N (kg/ha)	P (kg/ha)	K (kg/ha)	Fertiliser applied (kg/ha)	Rain (mm)	Irrigation (mm)
2002-2003	Plant	120	0	0	260 kg urea	–	–
2003-2004	Ratoon 1	160	20	150	750 kg 5:1:5 (46)	818	548
2004-2005	Ratoon 2	160	20	150	750 kg 5:1:5 (46)	458	751
2005-2006	Ratoon 3	160	20	150	750 kg 5:1:5 (46)	780	339

Truck and axle loads

The haulage vehicle used to simulate the extraction of sugarcane was a 30 ton Mercedes Powerliner rigid truck without the four-axle drawbar trailer. The truck had three axles. The steering axle was fitted with single tyres and the rear tandem axle was fitted with dual radial tyres or single high flotation tyres (Table 4). To apply the compaction treatments the vehicle moved steadily in 2nd gear at an average speed of 5 km/h. The pressure in the high flotation tyres was approximately 20 and 50% lower for the front and back tyres, respectively, compared with the pressure in the radial tyres. Axle load was obtained by weighing the vehicles sequentially axle by axle. The mass of the vehicles was expressed per axle and also per contact area for the various axles (Table 5).

Table 4: Specifications of the tyres used.

Tyres	Front pressure (kPa)	Rear pressure (kPa)	Rear tyre print width (mm)
Radial	800	700	260 + 260
High flotation	650	350	590

Table 5. Summary of the axle load (ton/axle) and the estimated pressure per wheel (kg/cm^2) of a laden truck.

Axle	Radial tyres		High flotation tyres	
	2003	2004	2003	2004
	Ton/axle		Ton/axle	
First	7.26	7.62	7.38	7.70
Second	9.04	10.38	8.60	10.30
Third	7.62	9.14	7.52	9.10
	kPa		kPa	
First	527	553	535	559
Second	164	188	122	145
Third	138	166	106	128

Field layout and treatments

The trial site was flat, with a slope of 1% in a north-eastern direction. All vehicle-applied treatments could not be randomised due to the size of the vehicle and the space required for turning. The centre portion of the field was irrigated (30 mm) three days before the compaction treatments were applied to create zones with different levels of water content (dry on either end of the field and wet in the centre). Each treatment was replicated four times.

Truck applied treatments were (i) no soil compaction (control), and (ii) compaction created with fully loaded commercial trucks fitted with conventional radial tyres and later with high flotation tyres. In 2003 the compaction treatments were applied for the first time and the effect of the applied treatments measured 12 months later (Table 6). This procedure was followed throughout the duration of the trial. The compaction treatments were applied for the third and last time in 2005 and the effect measured in 2006. In 2003 compaction was applied only when the soil water content was near permanent wilting point. In 2004 and 2005 soil compaction was applied at two levels of soil water content, near permanent wilting point and near field water capacity. In the fields with 1.5 m row spacing, the tyres missed the cane row marginally on either side of the truck, with one cane row under the truck. In fields with a tramline row arrangement (1.2 m interrow space and 0.6 m spaced cane rows on a bed raised 100 mm above the interrow area; Figure 1) the treatment-applying vehicle traveled in the centre of the interrow without the risk of damaging the stools. Changes in soil properties due to compaction were quantified through bulk density, penetration resistance and water infiltration rates.

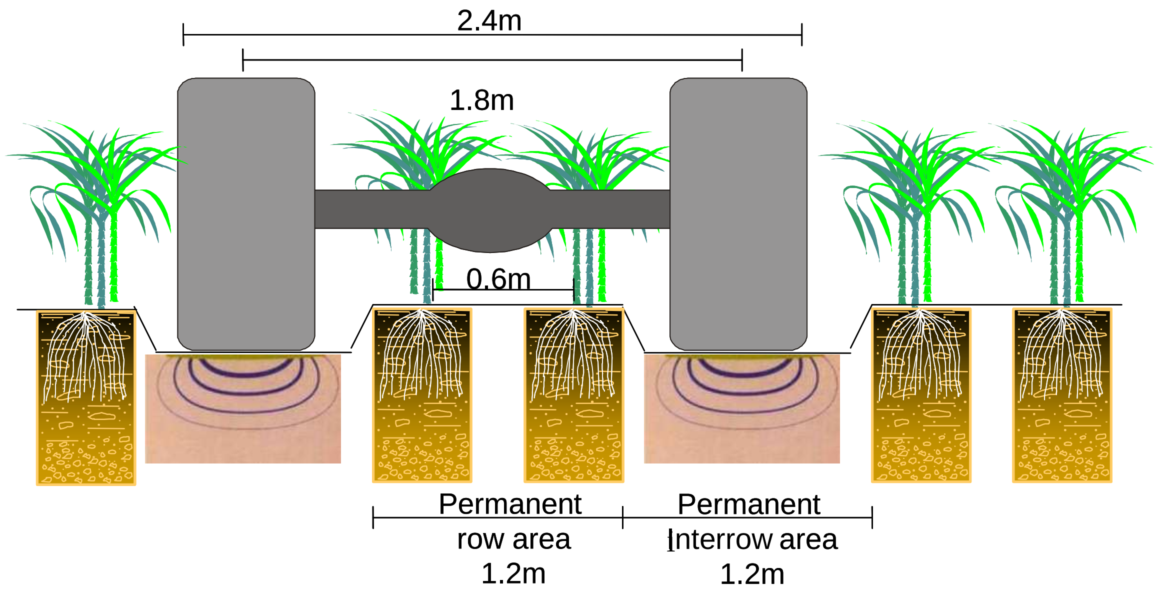

Figure 1. The 1.2 m interrow spacing combined with a 0.6 m row spacing arrangement that should be suitable for most farms.

Table 6. Timeline of treatments applied and measurements recorded.

Year	2001	2002	2003	2004	2005	2006
Measurement before treatment	Initial soil properties of the site	Soil properties per plot	Soil properties before compaction	Soil properties after first compaction	Soil properties after second compaction	Soil properties after third compaction
Treatment	Bush clearing	Cane planting	First compaction	Second compaction	Third compaction	–

Measurements

Soil bulk density and volumetric soil water content was determined using a nuclear surface moisture density gauge (Troxler 3430) at depths of 50, 150 and 300 mm. Volumetric water retention at field capacity and permanent wilting point were estimated from clay content (van Antwerpen *et al*., 1994) as 30.4 and 16.6% respectively. Clay content was determined using the hydrometer method (Day, 1965). Soil resistance to penetration by a steel rod fitted with a 12.5 mm wide cone tip (129 mm^2 surface area) was determined using a computer-controlled penetrometer at a penetration depth rate of 1 080 mm/minute. Resistance was recorded at 5 mm intervals to a maximum soil depth of 500 mm on three cane rows (one cane row on either side of the truck and one below), and two interrows (the area of wheel travel) in triplicate. Water infiltration rates were determined using the double ring infiltrometer as described by Bouwer (1986). A 20 mm falling head (change in the level of the water surface in the ring) was used for timing before the infiltrometer was topped up to the full point. These measurements were made in the interrow area only.

Statistical analysis

The penetrometer data for depths of 100 and 150 mm (which had the highest resistance values) were averaged and log transformed before being analysed with restricted maximum likelihood analysis (REML; Genstat, 2006). Significant differences between each level of the main effects (i.e. year, water, tyre) and their interactions were established by the Wald’s test for fixed effects in REML. The Sidak allpairwise multiple comparison test and the t-test were used to quantify significant differences. The dry soil bulk density data were not transformed, and significant differences between each level of the main effects (i.e. year, tyre) and their interactions were established by the Wald’s test for fixed effects in REML. The least significant difference (LSD) allpairwise multiple comparison test was used to quantify these significant differences (at 5% level). Yield data were log transformed before REML analysis. Significant differences between each level of the main effects (i.e. year, water, tyre) and their interactions were established by the Wald’s test for fixed effects in REML. The Sidak allpairwise multiple comparison test and the t-test were used to quantify significant differences.

Results and Discussion

Applied pressure

In 2003 the gross weights of the trucks applying compaction were 23.92 and 23.50 tons fitted with radial tyres and high flotation tyres, respectively. In 2004 the gross mass values were 27.14 and 27.10 tons, respectively. Due to the heavier load in 2004 the downward pressure was higher compared with 2003, but similar between vehicles within any year. In 2003 the truck fitted with radial tyres was 420 kg heavier than when it was fitted with high flotation tyres. In 2004 the difference was only 40 kg in favour of the truck fitted with radial tyres. However, within the assumptions made of the contact area for the various wheels (radials back 260 x 260 mm x 2 for dual wheels; high flotation back 590 x 590 mm; all front wheels 260 x 250 mm) the pressure per unit area was substantially lower (24%) for the high flotation tyres compared to the radial tyres. Pressure from the front wheels (1st axle) was comparable between the high flotation and radial tyres (Table 5). This is an indication that the benefit from using high flotation tyres was nullified by the high pressure front tyres. The high pressure was necessary because of the loading on the front axle, and it was not possible to fit larger front tyres to reduce the pressure.

Bulk density

Results from 2003 showed an increase in bulk density with depth even before any compaction treatment was applied (Figure 2A and C). This confirms that the soil was not disturbed to significant depths before crop establishment, and fits the medium (topsoil) and high (subsoils, i.e. 300 mm depth) classes for virgin soils given by Taylor and Pohlen (1962) in Table 1. The mean soil density (across all treatments, depths, row spacings and soil water contents) was shown to increase by significant increments with each compactive effort from 2003 to 2006. However, more detailed analysis revealed that, after the first compaction treatment was applied in 2003 (measured in 2004), the increase in bulk density for both tyre types (radial and high flotation) and water regimes (wet and dry), and nearly all depths, was not significant and only became significant relative to the virgin condition (2003) after the second compaction treatments were applied. Compaction applied for the second time (2004, but measured in 2005; Table 6) on the 'wet' area (after the first irrigation) resulted in dramatic increases in bulk density (Figure 2B, 14% increase; 2D, 11% increase). Applying compaction for the third time (2005) did not lead to a further significant increase in bulk density. The most likely reason is that the bulk densities obtained in 2004 were already similar to the maximum Proctor densities (Proctor, 1933) of 1 450 and 1 467 kg/m^3 for the topsoil (0-150 mm) and subsoil (>150 mm) layers, respectively. Bulk density changes in the control treatment were not significantly different over time or depth (data not shown).

Row spacing had a significant effect on bulk density, with the 1.5 m row spacing showing the lower density (Table 7). This was expected because the outside walls of the wheels fitted to the truck were within 100 mm of the stools in an area with potentially more roots, which act as a shock absorbent. The big question was, how had the crop responded to this 'root damage' treatment? There was no apparent effect on yield, as will be discussed in the section on yield response.

Table 7. Effect of row spacing on interrow soil bulk density.

Row spacing (m)	Bulk density (tons/m^3)
1.5	1.196
1.8	1.237
Standard error of difference	0.011

Penetration resistance

Penetration resistance is a highly water dependent measurement. Because soil water content was different between years of measurement, the original data was weighted for soil water content using equation 1.

Adjusted resistance (kPa) = Measured resistance (kPa) x (current soil water content/field water capacity) (1)

Penetration resistance data showed the same trend as discussed for soil bulk density. Resistance gradually increase from 2003 through 2004 to 2005. In general, penetration resistance was significantly lower for the control treatment compared to where vehicles had travelled, and there were no significant differences between the types of tyres used. This is probably due to the similar vertical pressures from both first axles, which had similar inflation pressures.

As was expected, soil water content was found to have a significant effect on soil penetration resistance, with a lower resistance where the water content was higher. However, not even this fact was sufficient to mask the 'resistance fingerprint' of a soil, as shown in Figure 3. Both compaction treatments (radial and high flotation tyres) at both soil water content levels showed that the depth of maximum penetration resistance was between 50 and 150 mm.

The effect of row spacing on penetration resistance was not significant, with a lower mean value recorded for the 1.5 m row spacing. This was similar to the effect that row spacing had on bulk density.

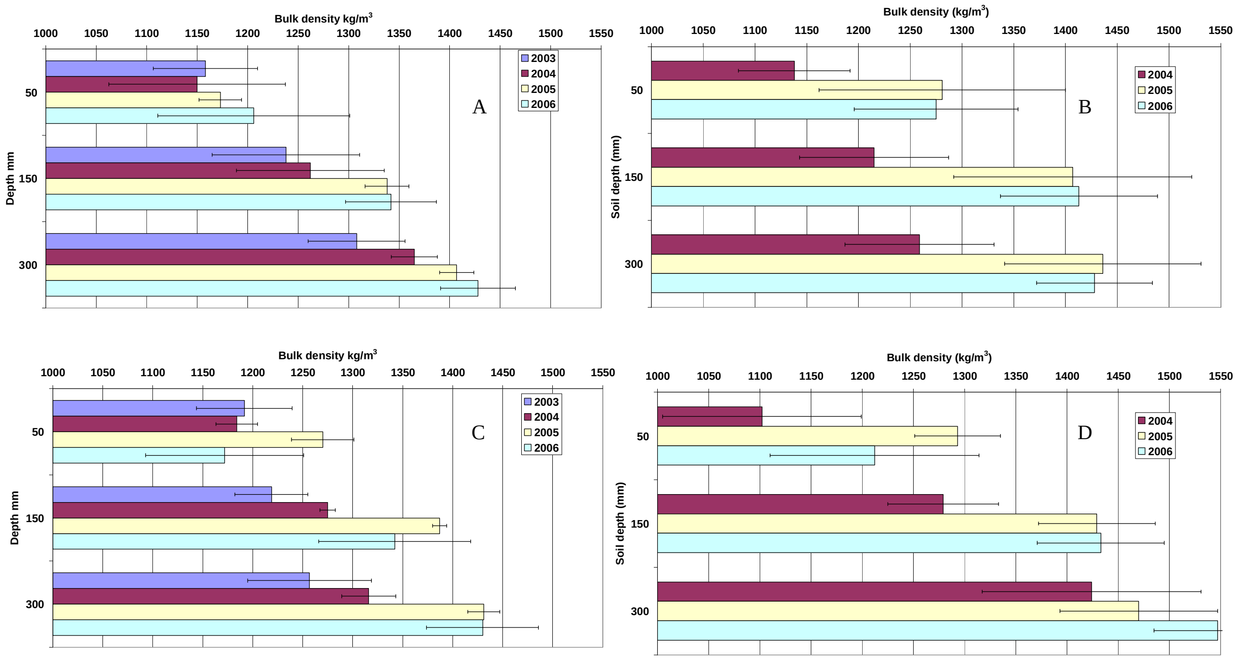

Figure 2. Changes in soil bulk density due to the annual compaction application on dry and wet soils. The 2003 measurements reflect the uncompacted virgin soil condition, and the 2004 measurements were on dry soil only (A = radial tyres on a dry soil; B = radial tyres on a wet soil; C = high flotation tyres on a dry soil; D = high flotation tyres on a wet soil).

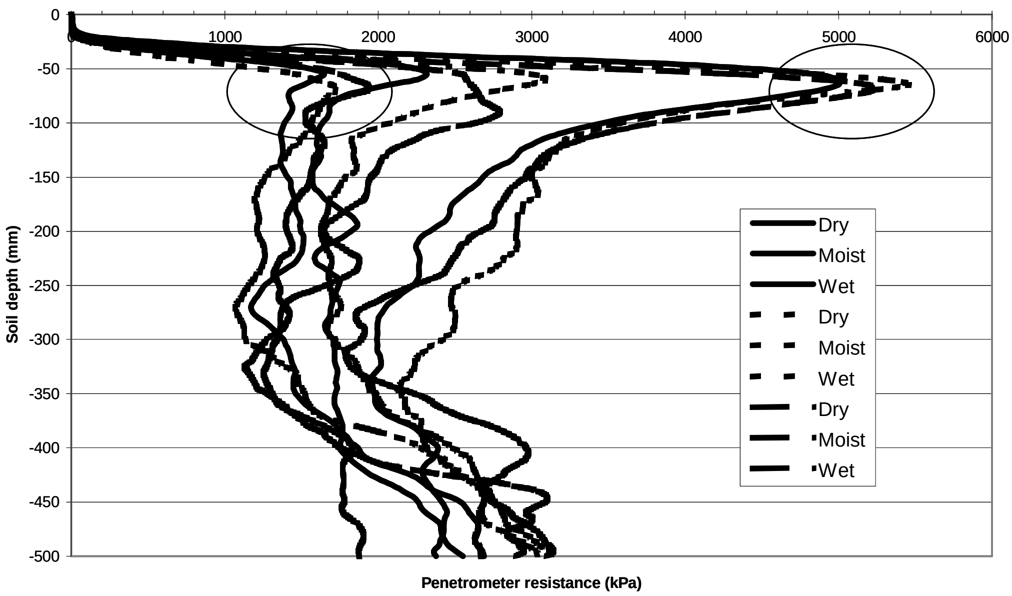

Figure 3. Penetrometer resistance for various depths and treatments as affected by soil water content. See peaks in the -50 to -100 mm soil depth layer. The highest three peaks are from dry soils and the lowest three from wet soils.

Water infiltration rates

Water infiltration rates were determined in 2006 and revealed the damaging effect of tyres relative to where no tyres had travelled (Figure 4). In general, wheel traffic (once per year for three years) reduced water infiltration rates by a factor of four compared to the control treatment where no traffic was allowed. Neither soil water content nor the type of tyre used appears to have made a difference to the severity of this reduction in the rate of water infiltration. This could be explained by the fact that the downward pressure from the front axle was comparable for both tyre types.

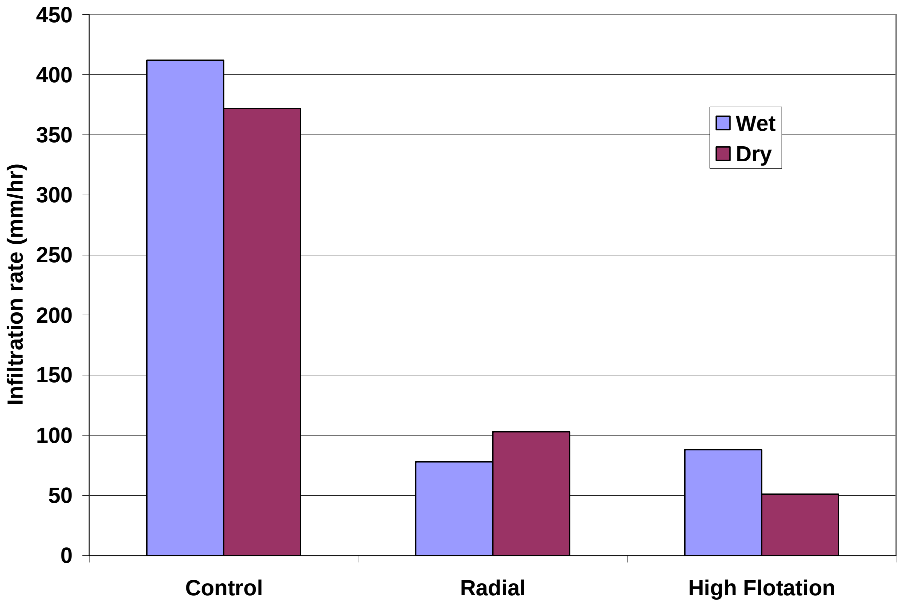

Figure 4. Water infiltration rates measured in the interrow area for three treatments and two water regimes.

Yield response to compaction treatments

Cane yields showed no significant differences between all treatments and water regimes from the plant crop to the third ratoon. In 2005 and 2006, the crop was harvested per cane row (rows 1 and 3 on either side of the truck and row 2 under the truck) to determine whether travelling on only one side of a row or on both sides (row 2) had an effect on any of these cane rows (Table 8). This had no significant yield effects on any of the cane rows. The only factor that had a significant effect on cane yield was ratoon number, showing a decrease over time.

Table 8. Cane yield (tons cane/ha/an) per cane row for the 2nd (2005) and 3rd (2006) ratoons. Compaction treatments were applied between cane rows 1 and 2 and between rows 2 and 3.

Water regime	Treatments	2nd Ratoon			3rd Ratoon		
		Row 1	Row 2	Row 3	Row 1	Row 2	Row 3
Dry	Control	96	99	88	61	74	70
	High flotation	105	108	99	72	67	70
	Radials	104	106	99	72	69	62
Wet	Control	91	96	95	64	69	73
	High flotation	99	102	95	79	75	68
	Radials	99	95	89	71	66	64
Standard deviation		22	26	28	20	17	18

Conclusions

The pristine condition of the virgin soil at the experiment site was not enough to protect it against degradation, and the soil was close to the maximum Proctor compactability rating of 1 450 kg/m^3 after only the second compaction effort.

Although this virgin soil offered some resistance to compaction it was not sufficient, and the soil was degraded to the point where it could be classified as compacted after only three once-per-annum compaction events using a laden commercial sugarcane haulage vehicle. Crop yield was not affected by the compaction which was restricted to the interrow for both row spacings, where 100 mm space between the stools and the wheels proved to be sufficient not to affect cane yields negatively. No stool damage was thus caused by driving in the interrow. It should be noted that the vehicle drivers took great care under supervision not to drive on the cane rows. However, in a commercial operation it is highly likely that, with 1.5 m row spacing, vehicles will be driven over cane rows and result in stool damage which will undoubtedly lead to yield loss (Swinford and Boevey, 1984).

The data obtain from this compaction experiment confirmed the fact that the first pass does the most damage, with smaller further increases in bulk density with repeated applications. The data showed no significant reductions in compaction with the use of high flotation tyres. The types of tyres used affected water infiltration rates equally. This is attributed to the fact that the vertical pressure from both types of tyre was the same at about 550 kPa. The effect of the pressure in the high flotation tyres on the steering axle was only 20% less than that of the radial tyres, and proved insufficient to be less damaging.

This trial on level land was irrigated with drippers on the cane row with no signs of runoff. However, where overhead irrigation is applied on sloping land, increased compaction on the interrow will need to be managed to prevent runoff losses and erosion damage. One way to achieve this is to protect the surface (i.e. trashing) from capping (crusting) and to prevent water from flowing freely downslope in the interrow area.

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