Controlled traffic to increase productivity of irrigated row crops in the semi-arid tropics

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Summary. The tropical environment generally allows 2 crops/year to be grown. Controlled traffic has been suggested as a means of improving soil conditions, which may also lead to increased crop yield. A field trial at Millaroo Research Station, North Queensland, on a cracking clay (Entic Chromustert) studied the effect of controlled traffic (in conjunction with direct drilling and tillage) and conventional ridging on soil properties and crop yield. Maize (*Zea mays* L. cv. Hybrid 50) was grown as the winter crop and soybean [*Glycine max* (L.) Merr. cv. Canapolis] as the summer crop.

With few exceptions, there was no significant difference between any pair of treatments in sowing line water content, bulk density, aggregate size distribution, seedling emergence, mean time of seedling emergence, and final yield. Differences that did occur between crop cycles were due to climatic variation.

Cone index measurements indicated no lateral spread of compaction from the traffic lanes in the controlled traffic system to the soil in the plant growth area. Under the ridged area, however, it appeared that a plough pan began to develop just below the depth of tillage.

Although no marked benefit in soil properties or plant yield resulted from controlled traffic, it was possible to grow 2 crops/year for the duration of the experiment. In one season, only the controlled traffic treatments could be planted, due to unsuitable conditions for seedbed preparation. Double cropping under conventional cultivation systems is unreliable, due to the limited opportunity for seedbed preparation at the beginning of the wet season and the large number (up to 8) of operations required to prepare a seedbed.

Controlled traffic, restricting soil compaction to the traffic lanes, is a system that helps to maintain a zone more favourable for plant growth, as indicated by the cone index measurements.

Introduction

Land degradation and loss of productivity through soil structural instability and soil compaction is of increasing concern in agricultural areas. These problems can result from excessive tillage (Adem *et al.* 1984) and traffic from machinery of high axle load at inappropriate soil water contents (Voorhees *et al.* 1986).

It has long been recognised that soil conditions optimal for traction and traffic during field operations (firm, compacted) are not those desired for plant growth and crop production (loose, friable). Hence, there is a conflict between the requirements for traffic and crop growth. A system of management that permanently separates the traffic zone from the crop growth zone, called 'controlled traffic', has been investigated in Australia (Murray and Tullberg 1986; Tisdall and Adem 1988), the United States (Taylor 1983), the Netherlands (Perdok and Lamers 1985), and the UK (Campbell *et al.* 1986). The crop zone may be managed with cultural techniques ranging from direct drill to conventional tillage. Due to the compacted traffic lanes, timeliness of operations and tractive efficiency may be improved (Dumas *et al.* 1975). Also, the necessity for deep ripping or deep tillage will be reduced since soil compaction is restricted to the traffic lanes. This eliminates a high cost, high energy operation, leading to savings in the cost of production (Taylor 1983) and reducing the time required for seedbed preparation. Most previous research has been in temperate regions of the world (Taylor 1983; Perdok and Lamers 1985; Tisdall and Adem 1988).

The distinct wet and dry seasons and inherent variability of rainfall in the tropics place constraints on agricultural production unless irrigation is used. Smith and McShane (1981) suggest that a cropping system under an irrigated, tropical regime in Australia should aim to maximise returns per unit area per year, rather than per crop. That is, a double-cropping rotation should be adopted. This maintains plant cover, which protects the soil surface from high intensity summer rain and reduces surface crusting and erosion. Under

Table 1. Physical and chemical properties of the Ug5.29 (Northcote 1979) soil type from a typical soil profile

Depth (cm)	pH[A]	EC (mS/cm)	Clay (<2 μm)	Silt (2–20 μm)	Fine sand (20–200 μm)	Coarse sand (200–2000 μm)	Plastic limit (%)	Organic C (g/100 g)	CEC (mg/100 g)	Soil moisture[B] (% w/w) 33 kPa	1500 kPa
0–10	7.5	0.05	51	20	18	8	22	0.92	34	38	18
20–30	8.6	0.06	52	20	15	6	—	0.58	35	38	19
50–60	9.0	0.20	54	21	19	8	—	—	35	40	19

[A] 1 : 5 soil : water. [B] Measured at a soil suction of 33 and 1500 kPa.

conventional management with cultivating and ridging for each crop, however, summer rainfall may prevent planting of a second crop, resulting in bare soil exposed to the risk of erosion and weed proliferation.

Controlled traffic offers many potential advantages for irrigated cropping. Soil compaction can be a serious problem under irrigated cropping, as soils tend to remain wetter at a given depth than in dryland situations (Probert *et al.* 1987), making it difficult to achieve a desirable result from primary tillage. Also, seedbed preparation and subsequent agronomic operations may result in recompaction of soil loosened by earlier tillage operations.

This work was one component in the development of a cropping system where maize, soybean, and rice are double-cropped in rotation (Garside *et al.* 1992). It was hypothesised that a controlled traffic system would cause less soil degradation, due to the restriction of soil compaction to traffic lanes. The compacted traffic lanes could subsequently improve trafficability and increase the probability of growing 2 crops/year and of maintaining agricultural productivity under tropical conditions. This study compared the effect of controlled traffic and conventional ridging on soil properties and crop yield on an irrigated clay soil under tropical conditions.

Materials and methods

A pre-experiment maize crop was grown on the experimental plots in 1988 and slashed to establish stubble cover for the cultural treatments at the beginning of summer 1988–89. The trial was conducted from January 1989 to December 1990 at the Millaroo Research Station of the Queensland Department of Primary Industries (20°03'S, 147°17'E), North Queensland. The soil is locally known as a Barratta clay [Ug5.29 (Northcote 1979); Entic Chromustert (Soil Survey Staff 1975)]. Some physical and chemical properties of the soil are presented in Table 1. The soil shows slight self-mulching characteristics and hardsets on drying.

Site preparation

The site had been under pasture for about 5 years before cultivation. The soil was initially cultivated to a depth of 10 cm with a tined implement and then cross-cultivated so that the final depth of loose material was about 15–17 cm. The site was subsequently worked twice with offset discs and finally with a rotary hoe, leaving the surface relatively flat and with a fine tilth. The soil was cultivated at a water content of about 21% (w/w) (0–20 cm), which corresponded to 0.96 of the plastic limit (PL) (Braunack and McPhee 1991*a*). Soil tends to be most friable around 0.9 of PL (Utomo and Dexter 1981) and produces the smallest number of large voids (Ojeniyi and Dexter 1979) when cultivated at that water content.

An experimental controlled traffic (CT) system (Fig. 1*a*) consisted of beds about 1 m wide (top width) with furrows at 1.5-m spacing formed by a specially constructed bed former (Adem and Tisdall 1984; McPhee and Braunack 1990). Equipment was modified to run on a 1.5-m wheel spacing, and all traffic was confined to the furrows.

The conventional ridging (R) system (Fig. 1*b*) consisted of ridges formed by Lister-type furrowing tools spaced at 0.75 m. This area was recultivated and ridged for each crop, and traffic occurred randomly. Tillage was purposely started in a different position each

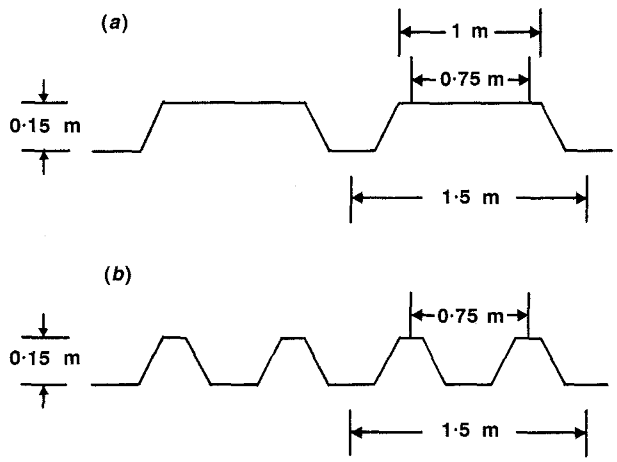

Figure 1. Cross-sectional view of the layout of beds and furrows in (*a*) controlled traffic and (*b*) conventional ridge management systems.

season, and tillage equipment width differed (rotary hoe 2 m, discs 2.7 m, chisel plough 3 m), ensuring a random spread of traffic.

The CT treatments consisted of a central bed (datum area) with a guard bed on either side. The R treatments consisted of 2 ridges (datum area) with 2 guard ridges on either side. Plots were 50 m long.

The ability always to follow the same track is essential in a controlled traffic system. It is difficult to traffic the same track each time, and this has been overcome to some extent by the preparation of raised traffic lanes (Monroe *et al.* 1989). To reduce this problem in our system, we fitted the tractor with narrow tyres and drove in the irrigation furrows. This formed an effective guidance system that limited expansion of the compacted lanes.

Experimental design and analysis

The experimental design was a split-plot with main plots being management (CT, R) for each crop, and subplots treatments of direct drilling (DD) and cultivation (C) randomly allocated within main plots. There were 3 replicates. Tillage operations required for the R management effectively buried all stubble. Because of this, and time constraints, the DD treatment was abandoned within the R management, leaving 3 treatments (CTC, CTDD, RC). Analysis on the basis of a split-plot was no longer appropriate, and due to initial randomisation restrictions, analysis as a randomised block was also inappropriate. Therefore, data were analysed using analysis of variance to compare pairs of treatments. The data for each crop were analysed separately.

The proportion of the plots subjected to wheel traffic in the RC treatment was 36% for each operation in each season of the trial. The proportion trafficked in the CT plots was 33%.

Cultural practices

A rotation of 2 crops/year was established with maize (*Zea mays* L. cv. Hybrid 50) as the winter crop and soybean [*Glycine max* (L.) Merr. cv. Canapolis] as the summer crop. All treatments were planted on the same day. A precision planter with a spear point opener and seed-firming wheels was used to plant both crops at a 0.75-m spacing on the beds and ridges (i.e. 2 rows of crop/bed and 1 row/ridge). The target plant population for maize was 90 000/ha, and for soybean 120 000/ha. The depth of planting, confirmed by excavation, was 25–30 mm. A pre-emergent herbicide was used to control early weed growth, and insecticide was broadcast after planting to control soil insects. Subsequent weed control was with glyphosate (360 g/L, 1 L a.i./ha). Irrigation water (furrow) was applied the day after planting, with no further irrigation before crop emergence. After emergence, irrigation was applied on a 10-day cycle, which corresponded, on average, to 55 mm evaporation (class A pan). The flow rate per furrow was about 4.5 L/min, and irrigation lasted for 8–10 h. This was sufficient to wet across the beds and ridges and to generate outflow into the tail drain. The low flow rate ensured that the soil was wetted largely by capillarity, thus preventing slaking and the formation of a hardset condition.

Measurements

Immediately after planting the crop, samples were taken to determine gravimetric water content and bulk density (cores 75 mm diameter, 50 mm high) along the sowing line (in the seed trench) at the 0–5 and 5–10 cm depths. Sowing line water content (0–5 and 5–10 cm depths) was monitored at planting, 4–5 days after irrigation ceased (this was to prevent undue damage to furrows and plot surfaces), and thereafter every day until emergence. Samples were always located between the wheel tracks (in the actual sowing line). Three samples per replicate were collected from the CTDD and CTC treatments and 4 from RC.

Aggregate size distribution in the sowing line of the seedbed was determined immediately after sowing by sieving a dry bulk sample (about 1.5 kg) from the 0–5 and 5–10 cm depths. Water contents were 6.3, 7.2, and 11.4% (w/w) for the 0–5 cm depth, and 8.3, 9.6, and 15.5% (w/w) for the 5–10 cm depth in RC, CTC, and CTDD treatments, respectively. Aggregate stability was determined by wet sieving 50 g (oven-dry basis) of aggregates (>4 mm) through a nest of sieves (4, 2, 1 mm; 500, 250 μm) for 15 min and correcting for primary particles (Kemper and Rosenau 1986). Wetting was by direct immersion. Mean weight diameter was calculated from the weight of aggregates remaining on the sieves after sieving.

Soil temperature was measured with T-type thermocouples every 3 h at 5 and 10 cm depths in the sowing line for the period from planting to emergence (6–7 days). These measurements were made on 2 replicates only.

Cone index was measured for the maize crops sown in 1989 and 1990. This was done 4 days after the last irrigation to ensure uniform soil wetness conditions for all treatments. Readings were taken with a recording cone penetrometer, to a depth of 45 cm (1-cm^2 tip, 30° included angle) at 40-cm intervals across the beds and furrows and across the ridges and furrows, to determine whether lateral spread of compaction from the traffic lanes had occurred. Mean profile (10, 20, 30, 40 cm depths) water contents for the furrows were 22.6, 22.2, and 22.9% (w/w) for the CTDD, CTC, and RC treatments, respectively. Similarly, the corresponding water contents for the areas between wheel tracks were 22.8, 22.6, and 23% (w/w). Profiles were constructed using the software package SURFER. The average number

Table 2. Effect of treatment on crop emergence (%) and mean day of emergence after sowing (MDE) for the several cropping cycles

Within columns, means followed by the same letter are not significantly different at $P = 0.05$

Letters in parentheses are for comparisons between controlled traffic, cultivated (CTC) and ridged, cultivated (RC); letters not in parentheses are for comparisons between CTC and controlled traffic, direct drill (CTDD)

Crop and sowing date:	Soybean 26.i.89		Maize 27.ix.89		Soybean 12.xii.89		Maize 18.vii.90	
	Emergence	MDE	Emergence	MDE	Emergence	MDE	Emergence	MDE
CTDD	65a	8.59a	91a	8.12a	72a	7.77a	87a	8.90a
CTC	75a	8.03a	95a(a)	8.69a(a)	87a(a)	9.74b(a)	70a(a)	9.70b(a)
RC	n.p.	n.p.	99(a)	8.54(a)	56(b)	10.02(b)	79(a)	9.60(a)

n.p., not planted due to wet weather.

of traffic passes for field operations (i.e. seedbed preparation, furrow cleaning, planting) was 3, 9, and 8 for CTDD, CTC, and RC, respectively. However, the number of passes varied with season depending on climatic conditions, with CTDD always having the least number of passes.

The time between sowing and emergence was recorded, and the mean day of emergence (Edwards 1957) and percentage emergence (as a percentage of viable seed sown) were determined. These measurements were made along adjacent 5-m lengths of row randomly selected in each plot. Seed that did not emerge was excavated to determine the cause. Laboratory germination tests indicated 82 and 91% germination for the soybean and maize seed, respectively.

Hand-harvested yield assessments were made for all experimental crops. Plants were removed from 8 m of randomly selected row in each plot. Soybean yields and maize yield for the crop sown on 18 July 1990 were determined as grain weight per ha. Excessive bird damage prevented an assessment of grain yield for the maize crop sown 27 September 1989. However, dry matter yields were measured and grain yield was estimated on the basis of a 45% harvest index (Pearson and Jacobs 1987). The amount of stubble and groundcover provided was not assessed.

Results

Plant response

There were no significant differences in seedling emergence between treatments except for the soybean crop sown 12 December 1989, for which the CTC treatment had higher emergence than the RC treatment (Table 2). Emergence was always >70% for the maize crops but not for the soybean crops. Seedlings in the CTDD treatment tended to emerge earlier than those in the other 2 treatments (Table 2), with significant differences between treatments for the soybean crop sown 12 December 1989 and the maize crop sown 18 July 1990, where the CTDD treatment emerged significantly earlier than the CTC treatment, which emerged earlier than RC.

Soybean yield for the crop sown 26 January 1989 was low (Table 3). Dry matter yield for the maize crop sown 27 September 1989 corresponded to 1.22, 1.26, and 0.74 kg/m^2 for the CTDD, CTC, and RC treatments, respectively. There was no significant difference in yield between treatments, except for the estimated yields of maize sown 27 September 1989, for which the CTC treatment yielded higher than RC.

sowing line water content

The relative difference in sowing line water content between treatments was similar for each cropping cycle; therefore, only data for the maize crop sown 18 July 1990 are presented (Fig. 2). The water content at planting was relatively low (6–12% w/w), with the 5–10 cm depth being slightly wetter than 0–5 cm for all crops (Fig. 2). The sowing line water content rapidly increased to about 30–35% (w/w) at 7 days after irrigation. This was slightly below the field capacity of 38% (w/w) (Table 1).

In all treatments, the 5–10 cm depth was wetter than 0–5 cm and remained so for the duration of monitoring. The 0–5 cm depth dried rapidly for 2 crop sequences

Table 3. Effect of treatment on crop yield (t/ha) for the various tillage treatments

Within columns, means followed by the same letter are not significantly different at $P = 0.05$

Letters in parentheses are for comparisons between controlled traffic, cultivated (CTC) and ridged, cultivated (RC); letters not in parentheses are for comparisons between CTC and controlled traffic, direct drill (CTDD)

	Soybean	Maize[A]	Soybean	Maize
Sowing date:	26.i.89	27.ix.89	12.xii.89	18.vii.90
CTDD	1.3a	10.9a	2.6a	8.3a
CTC	1.2a	11.1a(a)	2.5a(a)	7.5a(a)
RC	n.p.	9.0(b)	2.2(a)	6.8(a)

n.p., not planted.

[A] Yield estimate based on 45% harvest index (Pearson and Jacobs 1987) and dry matter harvest.

(maize sown 27 September 1989 and soybean sown 12 December 1989) to a level approaching that at sowing and to the wilting point of 18% (w/w) (Table 1), before the next irrigation. The sowing line water content for the RC treatment was significantly higher than for the CTC treatment, while there was no significant difference between CTC and CTDD (Fig. 2). This was consistent for all crops.

There was no rainfall between sowing and emergence for any crop, except for 31 mm that fell after the soybean crop was sown on 12 December 1989. This resulted in the sowing line not drying out as much as in other crops.

Sowing line temperature

The mean daily sowing line temperature cycle (3-hourly means each day over 7 days) for each treatment at the 5-cm depth for the maize crop sown on 18 July is presented (Fig. 3). Due to logger problems, soil temperature was not monitored for the maize crop sown 27 September 1989.

The RC treatment was cooler than CTC and CTDD at night, while the reverse occurred during the day (Fig. 3). Also, the 5-cm depth tended to be warmer (even with mulch) than the 10-cm depth (data not presented), but this was not consistent across all treatments or for all seasons. This inconsistency may have been due to occasional periods of excess water when rain fell after irrigation.

Sowing line bulk density

Sowing line bulk density was only significantly different between treatments in the last season of the trial for the 5–10 cm depth (Table 4). The 5–10 cm depth always had a higher bulk density across all treatments and for all crops than the 0–5 cm depth (Table 4). There was very little difference in the corresponding water content (data not presented).

Aggregate size distribution and stability

For any particular crop, seedbed conditions (as measured by dry sieving) were similar between

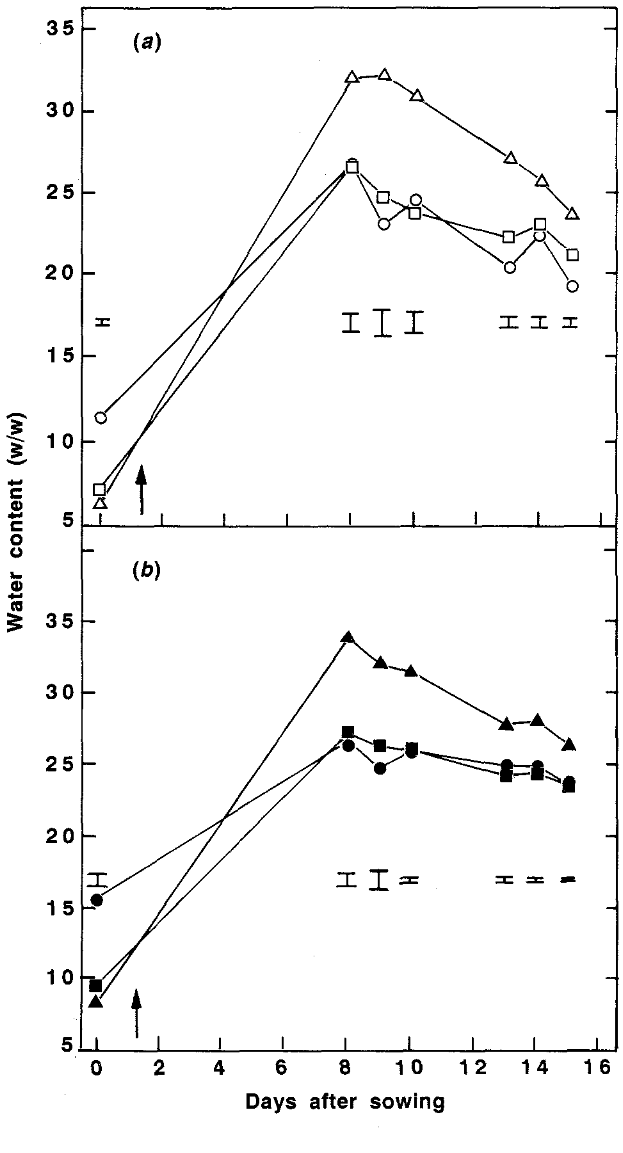

Figure 2. Sowing line water content between sowing and emergence for CTDD (○, ●), CTC (□, ■), and RC (△, ▲) treatments at a set depth of (*a*) 0–5 cm (open symbols) and (*b*) 5–10 cm (closed symbols) for the maize crop sown 18 July 1990. Timing of irrigation is arrowed. Vertical bars are the average standard error of the means.

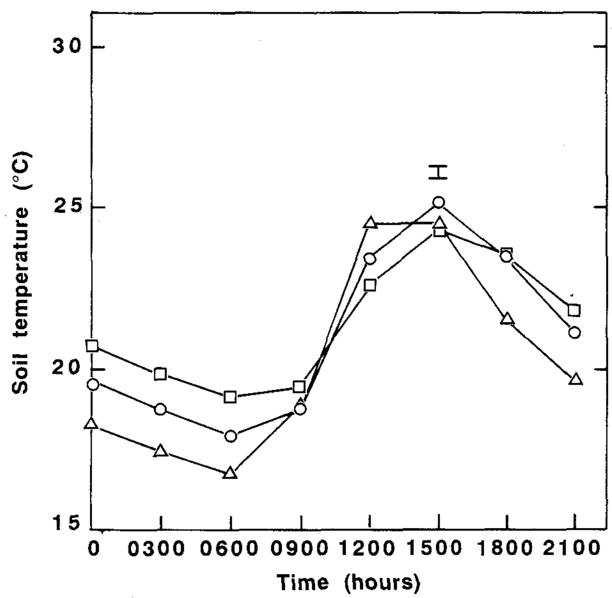

Figure 3. Mean daily sowing line soil temperature (5 cm) between sowing and emergence for CTDD (○), CTC (□), and RC (△) treatments for the maize crop sown on 18 July 1990. Vertical bar is the standard error of difference between two means.

Table 4. Effect of treatment on sowing line bulk density (Mg/m^3) for the various cropping cycles

Within columns, means followed by the same letter are not significantly different at $P = 0.05$
Letters in parentheses are for comparisons between controlled traffic, cultivated (CTC) and ridged, cultivated (RC); letters not in parentheses are for comparisons between CTC and controlled traffic, direct drill (CTDD)

Crop and sowing date:	Soybean 26.i.89		Maize 27.ix.89		Soybean 12.xii.89		Maize 18.vii.90	
Soil depth:	0–5 cm	5–10 cm	0–5 cm	5–10 cm	0–5 cm	5–10 cm	0–5 cm	5–10 cm
CTDD	0.98a	1.27a	0.97a	1.27a	0.97a	1.27a	0.93a	1.23a
CTC	0.95a	1.27a	0.95a(a)	1.22a(a)	0.98a(a)	1.18a(a)	0.89a(a)	1.15a(a)
RT	n.p.	n.p.	1.00(a)	1.24(a)	0.98(a)	1.28(a)	0.88(a)	1.01(b)

n.p., not planted due to wet weather.

Table 5. Seedbed aggregate size distribution (%) for each treatment and cropping cycle, as measured by dry sieving

Significant differences ($P<0.05$) between treatment means in any one column within a crop cycle and depth are indicated by letters
Letters in parentheses are for comparisons between controlled traffic, cultivated (CTC) and ridged, cultivated (RC); letters not in parentheses are for comparisons between CTC and controlled traffic, direct drill (CTDD)

	<1 mm	1–2 mm	2–5 mm	5–15 mm	>15 mm
		Soybean (26.i.89)[A]			
0–5 cm					
CTDD	3.1a	1.3a	5.2a	28.9a	61.4a
CTC	5.0b	3.3b	12.5b	43.2b	36.0b
5–10 cm					
CTDD	4.1	2.5	9.1	26.8	57.5
CTC	4.6	3.3	7.6	24.7	59.8
		Maize (27.ix.89)			
0–5 cm					
CTDD	9.0	6.3	13.8	21.3	49.6
CTC	7.6	5.9	15.3	26.2	45.0
RC	8.9	7.5	16.2	25.4	42.1
5–10 cm					
CTDD	2.7	2.8	3.9	8.1	82.5
CTC	2.4	2.4	3.7	7.0	85.1
RC	9.3	7.0	15.8	24.4	43.5
		Soybean (12.xii.89)			
0–5 cm					
CTDD	16.5	16.4	19.2	14.4	33.5
CTC	14.4	14.6	19.7	15.9	35.4(a)
RC	11.9	11.6	11.4	10.9	54.3(b)
5–10 cm					
CTDD	9.9	10.7	10.3	9.9	59.2
CTC	8.2	13.1	6.6	8.2	64.0
RC	12.8	12.4	9.7	9.6	55.6
		Maize (18.vii.90)			
0–5 cm					
CTDD	5.8	5.5	17.8	18.7	52.2
CTC	4.5	3.5	11.1	15.1(a)	65.7
RC	2.7	1.3	3.1	4.3(b)	88.6
5–10 cm					
CTDD	3.4a	3.1a	9.4a	10.4a	73.6a
CTC	8.2b(a)	7.6b	20.1b	16.5b	47.6b
RC	10.7(b)	8.1	19.3	16.7	45.2

[A] RC treatment not planted.

treatments; 0–5 cm for soybean sown 26 January 1989 was an exception (Table 5). There were differences between seasons, which reflect differences in soil water content when seedbed preparation commenced (for the CTC and RC). The largest variation between treatments occurred for the large aggregates (>15 mm) in the 0–5 cm layer, which tended to vary with the amount of cultivation and, to some extent, with the season, with an increasing number of cultivation operations tending to result in a decrease in large aggregates for the first 2 crops, while the reverse trend occurred for the last 2 crops (Table 5). The 2–5-mm size range tended to show an increase with number of cultivation operations in the first 2 crops (Table 5).

For both the CTDD and CTC treatments there was generally a greater proportion of large aggregates (>15 mm) in the 5–10 cm layer than in the 0–5 cm layer. There were 2 exceptions, one of which was pronounced (CTC for maize sown on 18 July 1990), the other slight (CTDD for soybean sown 26 January 1989). For RC, the proportion of large aggregates in the 5–10 cm layer was similar to, or less than, in the 0–5 cm layer. Also, with the last 2 crops there was a tendency for a higher proportion of 1–5-mm aggregates in the CTDD treatment than in the other treatments at 0–5 cm depth (Table 5). In the earlier crops the trend was reversed.

The mean weight diameter was determined on unreplicated samples for each treatment and for each crop cycle to determine whether treatments were

Table 6. Effect of treatment on aggregate stability as measured by mean weight diameter (mm) for the 0–10 cm depth

CTDD, controlled traffic, direct drill; CTC, controlled traffic, cultivated; RC, ridged, cultivated

Crop:	Soybean	Maize	Soybean	Maize
Sowing date:	26.i.89	27.ix.89	12.xii.89	18.vii.90
CTDD	2.52	2.05	2.21	2.12
CTC	1.80	1.64	2.45	1.41
RC	n.p.	1.32	1.13	2.40

n.p., not planted.

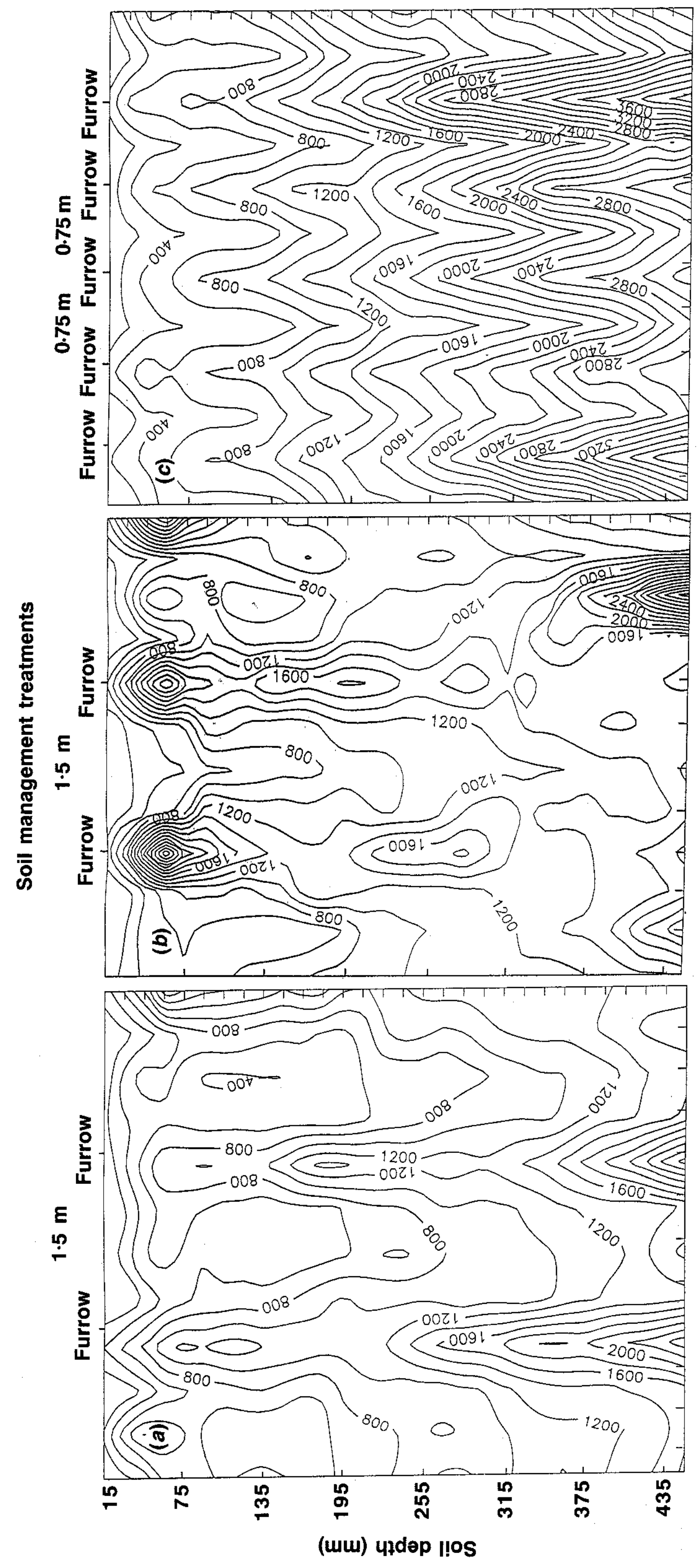

Figure 4. Profiles of soil cone resistance (kPa) in the maize crop sown 27 September 1989 for (*a*) CTDD, (*b*) CTC, and (*c*) RC treatments.

beneficial or detrimental to wet soil stability. The results were variable, with aggregates from the CTDD treatment being more stable in some seasons, while aggregates from CTC and RC were more stable in others (Table 6).

Cone penetration resistance

Cone index profiles for each treatment for the maize crop sown 27 September 1989 are shown in Figure 4. The CTDD treatment showed a distinct columnar development of soil cone resistance (Fig. 4*a*). There was no evidence of lateral spread of compaction outward from the furrows to under the beds.

In contrast, the CTC treatment had distinct high cone resistance zones under each furrow and a less distinct columnar formation (Fig. 4*b*). Higher cone resistance (1600 kPa) areas occurred closer to the surface under CTC than CTDD (4.5 and 19.5 *v*. 25.5 cm), which probably reflects the difference in the number of passes between the 2 treatments. Again, there was little evidence of lateral spread of compaction from the traffic lanes to under the beds.

There was a more uniform distribution of soil cone resistance with depth for the RC treatment, with peaks occurring under the rows that were trafficked most (Fig. 4*c*). High cone resistances (1600 kPa) approached closer to the surface (19.5 cm), which may indicate the beginning of plough or traffic pan formation.

A similar pattern was observed for the cone resistance measured in 1990.

Discussion

A system of controlled traffic and permanent beds has been proposed to increase the probability of growing 2 crops per year and to reduce soil degradation for irrigated row crops under semi-arid tropical conditions. This study reports results from a comparison between controlled traffic and conventional cultivation for crop response and soil properties. The results are not always consistent or significant, suggesting that such comparisons should be made over a longer period to establish reliability and benefits.

There was only one instance of significantly different emergence between treatments (soybean sown 12 December 1989). The low emergence for soybean was due to waterlogging in 1 replicate of the first crop, and 2 unscheduled irrigations causing short periods of excess water for the second soybean crop. However, the levels of emergence were higher than reported previously for the same soil type (Braunack *et al.* 1988). Early emergence of a crop is an advantage in soils that hardset or crust, since the crop will have a better chance of emerging before it is impeded by the hardset layer or crust. Treatment CTDD tended to emerge earlier than the other treatments, a result similar to that of Tisdall and Adem (1986).

A significant yield difference occurred in only 1 crop, maize sown 27 September 1989: CTC yield (estimated) was higher than RC yield. A lack of yield response under controlled traffic has also been observed in cotton (Williford 1982, 1985; Gerik *et al.* 1987), but many studies have demonstrated significant yield increases from the adoption of controlled traffic (Dumas *et al.* 1975; Perdok and Lamers 1985; Hadas *et al.* 1990). We suggest that where yield increases have been achieved, an impediment to crop growth (e.g. subsoil compaction or a plough pan) has been removed and the crop has responded accordingly. It is recognised, however, that climate may be overriding and the determinant of final yield. Although the CTDD or CTC treatments did not result in greater yields than RC, 2 crops could be grown per year even with unfavourable weather. One of the crops for the RC treatment (soybean 26 January 1989) was not planted because seedbed preparation was not completed. This resulted from continued rainfall maintaining the soil above the plastic limit, and when soil conditions were suitable, the date was outside the recommended range for soybean planting. The onset of the wet season often hampers seedbed preparation and increases the risk of missing a summer crop (Smith and McShane 1981).

For the maize and soybean crops sown in 1989, the sowing line water content (0–5 cm) dried to about the wilting point before the next irrigation after planting. These plants may have suffered water stress, but the water content in the sowing line between planting and emergence was apparently adequate for imbibition and emergence of both crops. Also, the observation that sowing line water content for RC was higher than that for CTC, while no such difference existed between CTC and CTDD, may have been due to differences in wetting. The CTC and CTDD treatments were wet by capillarity rather than by water moving through large interspaces of loose material as in the RC treatment. The ridges tended to be lower in height compared with the beds, which resulted in submergence and rapid wetting. This aspect is important in preventing crusting and hardsetting, to which the soil in this study is susceptible (Smith and McShane 1981).

The CTDD and CTC treatments were warmer at night and cooler during the day than the RC treatment, suggesting less variation with ambient temperature. This may be due to the greater volume of soil in the beds providing more insulation than ridges.

Surface mulch reduces surface soil temperature during the day (Lal 1974; Tisdall and Adem 1986; Abrecht and Bristow 1990). There was no evidence in this study that stubble reduced soil temperature, as there was no difference between the CTC and CTDD treatments. The CTC and RC treatments had stubble incorporated by cultural operations, whereas stubble was retained on the surface for the CTDD treatment. The surface stubble consisted mainly of individual stalks of maize, both standing and lying on the soil surface. The soybean stubble decomposed and disappeared very rapidly. The level of surface stubble may have been insufficient to affect soil temperature.

Sowing line bulk density was significantly different (P<0.05) only between treatments for the 5–10 cm depth in the last season of the trial. This suggests that soil physical properties change relatively slowly and may also explain the lack of plant response over the trial. Gerik *et al.* (1987) also found no difference in bulk density (0–20 cm depth) across tillage treatments under controlled traffic. Adem and Tisdall (1984), however, found that bulk density (2–6 cm depth) was greater under a mulched, shallow-tilled system than a non-mulched, deep-tilled system. The depth of tillage in our treatments varied, with the CTDD treatment being disturbed only to the depth of sowing across the width of the sowing line, compared with the CTC and RC treatments, which were tilled to a depth of 5–10 cm and 10–15 cm, respectively. We suggest that the density of individual aggregates, rather than the soil bulk density, may show treatment differences more clearly, since some would be formed by compression and others by tensile failure; this would correspond to tillage wetter and drier than optimum, respectively.

Aggregate size range in the seedbed is important for seed-to-soil contact and for providing conditions suitable for germination and emergence. There was a tendency during the later crop cycles for CTDD to contain a higher proportion of aggregates 1–5 mm in the seedbed (0–5 cm depth) than the other treatments. This size range may be the result of the self-mulching tendency of this soil with time. The other treatments, which were cultivated, had a greater proportion of the larger size range (>5 mm) at 0–5 cm. Further wetting and drying would be required for these larger aggregates to break down to a suitable tilth. Therefore, direct drilling may be beneficial for this soil type. The finding of a low proportion of aggregates <1 mm and a high proportion of aggregates >15 mm in the seedbed on the heavy clay soil of our study tends to be the reverse of the finding of Lamers *et al.* (1986) on a loam and a light clay soil.

Hadas and Russo (1974) suggest that to maximise seed-to-soil contact, aggregates should be one-fifth to one-tenth the diameter of the seed. This corresponds to about 0.6–1 mm for both maize and soybean. All treatments generally contained similar proportions of aggregates in the size range 1–2 mm at 0–5 cm depth. This may explain why there was little difference in emergence between treatments.

There was a trend over the experiment for the aggregates from the CTDD treatment to be more stable than those from CTC and RC. In fact, the mean weight diameter for CTDD was more consistent across all crop cycles than for the other treatments. Adem and Tisdall (1984) also observed higher soil stability under controlled traffic than with conventional tillage. It appears that less soil disturbance may lead to increased wet aggregate stability and, hence, to improvements in soil structure. European experience suggests that these differences only become significant after ≥3 years of treatment (I. Håkansson pers. comm.).

Hadas *et al.* (1990) observed cone resistance profiles similar to ours. Young *et al.* (1985), however, found that their controlled traffic lanes tended to increase in width, but their lanes were flat, in contrast to the furrows used in our work.

The range of values of cone index at which root growth is affected varies between 800 and 4000 kPa (Greacen *et al.* 1969), with 2000–4000 kPa most likely to reduce elongation. Based on these criteria and the matric suction (30 kPa) at which soil cone resistance was measured, we suggest that root growth would be less restricted under the CT management than under RC, where soil cone resistances of 2000 kPa occur at 25 cm depth. This may not have been so at other matric suctions. Root ramification would also depend on occurrence of cracks and distribution of water in the profile.

Any restriction of root growth under the RC treatment was not critical to grain yields, since irrigation was applied on a regular basis ensuring an adequate water supply to the crop. Under dryland conditions, however, a restricted root system may result in water stress of the crop and subsequent yield loss. So RC management could restrict root development to the top 25 cm of the soil, particularly under dryland conditions, limiting utilisation of soil water and nutrients.

Although few differences in soil properties were evident in this study, benefits from the CT management system could manifest with time. The relatively short duration of this trial may have been insufficient for changes in soil conditions to develop, hence the lack of response in the parameters. There was a trend with respect to aggregate stability, which was more consistent under CTDD than the treatments involving cultivation each year. Other factors indicating some benefit of the CTDD treatment over systems involving cultivation were an earlier mean day of emergence for the last 2 crops grown; and a higher proportion of 1–5-mm, and a lower proportion of >15-mm, aggregates in the seedbed. These trends may increase in time, affording greater advantage to the CTDD management over RC management with cultivation for each crop and traffic over previously loosened material.

Yields were not compromised by the CTDD treatment, and over the experiment CTDD allowed 2 crops/year to be grown, thereby increasing productivity and reducing the impact of high intensity summer rainfall by maintaining surface cover. This has implications for productivity for irrigated tropical agriculture especially when used in conjunction with minimum tillage or conservation tillage techniques, which allow savings in energy input (McPhee and Braunack 1990; Braunack and McPhee 1991*b*).

A major constraint to productivity on this soil type in this environment is the narrow time window for seedbed preparation and for optimum planting time. A management system using controlled traffic and direct drilling eliminates seedbed preparation and increases the number of days when planting is possible, resulting in more reliable cropping and improved productivity. Direct drilling also maintains the soil resource by reducing structural degradation, which should, in time, result in improved crop performance.

Conclusions

Although our hypothesis was not clearly supported by this research, a number of points were evident.

(i) Mean day of emergence was earlier on the CTDD treatment for the last 2 crops grown.

(ii) There was a tendency to a higher proportion of 1–5 mm, and a lower proportion of >15-mm, aggregates in the CTDD treatment than RC for the last 2 crops.

(iii) Compaction was restricted to the traffic lanes under CT treatments, compared with a more even distribution under the RC treatment.

(iv) Yields were not compromised by the use of controlled traffic and minimum tillage compared with conventional seedbed preparation.

Controlled traffic did not appear to offer large benefits in soil physical conditions or higher seasonal crop yields for this particular soil type, although in time it may. For the period of the trial, controlled traffic enabled 2 crops/year to be grown, whereas when climatic conditions were not favourable a crop could not be planted using conventional seedbed preparation.

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