CSIRO PUBLISHING
www.publish.csiro.au/journals/cp *Crop & Pasture Science*, 2009, **60**, 544–554

Row spacing and planting density effects on the growth and yield of sugarcane. 2. Strategies for the adoption of controlled traffic

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Abstract. Controlled traffic (matching wheel and row spacing) is being promoted as a means to manage soil compaction in the Australian sugar industry. However, machinery limitations dictate that wider row spacings than the standard 1.5-m single row will need to be adopted to incorporate controlled traffic and many growers are reluctant to widen row spacing for fear of yield penalties. To address these concerns, contrasting row configuration and planting density combinations were investigated for their effect on cane and sugar yield in large-scale experiments in the Gordonvale, Tully, Ingham, Mackay, and Bingera (near Bundaberg) sugarcane-growing regions of Queensland, Australia. The results showed that sugarcane possesses a capacity to compensate for different row configurations and planting densities through variation in stalk number and individual stalk weight. Row configurations ranging from 1.5-m single rows (the current industry standard) to 1.8-m dual rows (50 cm between duals), 2.1-m dual (80 cm between duals) and triple (65 cm between triples) rows, and 2.3-m triple rows (65 cm between triples) produced similar yields. Four rows (50 cm apart) on a 2.1-m configuration (quad rows) produced lower yields largely due to crop lodging, while a 1.8-m single row configuration produced lower yields in the plant crop, probably due to inadequate resource availability (water stress/limited radiation interception).

The results suggest that controlled traffic can be adopted in the Australian sugar industry by changing from a 1.5-m single row to 1.8-m dual row configuration without yield penalty. Further, the similar yields obtained with wider row configurations (2 m or greater with multiple rows) in these experiments emphasise the physiological and environmental plasticity that exists in sugarcane. Controlled traffic can be implemented with these wider row configurations (>2 m), although it will be necessary to carry out expensive modifications to the current harvester and haul-out equipment.

There were indications from this research that not all cultivars were suited to configurations involving multiple rows. The results suggest that consideration be given to assessing clones with different growth habits under a range of row configurations to find the most suitable plant types for controlled traffic cropping systems.

Additional keywords: multiple rows, row configuration, soil compaction, cane harvesters.

Introduction

Australia was the first country to adopt mechanical harvesting of sugarcane. When this occurred the harvester and haul-out wheel spacings were set at 1.8–1.9 m while the traditional row spacing for sugarcane was 1.5-m single rows. The choice of the wider wheel spacing on the harvesters and haul-outs (used to carry cane from the field) was largely due to concerns about the stability of the heavy harvesting equipment (16–21 t for the harvester and up to 30 t for a loaded haul-out) on undulating land (Robotham 2000).

Once a cane crop is planted, growers aim for a cycle of at least 4–5 crops (plant and several ratoons) from the one planting. The heavy biomass produced by sugarcane (100–200 t/ha fresh weight) has restricted the rate at which cane can be harvested to one row with each pass. This results in each inter-row being trafficked by harvesting equipment at least 4 times for each harvest and up to 20 times during a cycle. With row spacing at 1.5 m and harvester and haul-out wheel spacing at 1.8–1.9 m, 70% of a field is trafficked with each pass of the machine with perfectly straight driving, while the area of fields trafficked can be up to 90% with normal driver error (Robotham 2000).

The combination of mis-matched wheel and row spacing and heavy axle loads results in severe soil compaction, not only in the inter-row but also in the area adjacent to the row and even the row itself (Garside *et al.* 2008). Stool damage and reduced yields in the following ratoon crops often result, particularly following wet harvests (Braunack and Peatey 1999; Braunack *et al.* 1999; Garside 2004). Consequently, there are likely to be advantages in matching wheel and row spacing. Given the large investment in harvesting and haul-out equipment (around $1 000 000 for a

10.1071/CP08312 1836-0947/09/060544

harvesting unit, comprising a harvester and 2 haul-outs) the most economic approach is likely to be the adoption of controlled traffic by widening row spacing to 1.8–1.9 m to match wheel spacing, providing yields can be maintained.

Industry concerns regarding productivity losses with row spacings wider than 1.5 m have hindered the adoption of controlled traffic in the Australian sugar industry. These concerns are understandable as research reviewed by Ridge and Hurney (1994) indicated yield penalties if row spacing was increased beyond 1.65 m. In other studies it was shown that yields could be increased with wider row spacing by using a dual row configuration (Roach 1976, 1977). However, the initial commercial application of dual rows during the late 1970s did not support the research results, with large-scale field experiments providing no improvement in yield (Hurney *et al*. 1979).

It is not known whether poor soil health could have been a significant factor in these previous studies. In the first paper of this series, Garside and Bell (2009*a*) demonstrated that if soil health was adequate, the capacity of sugarcane to produce similar yields across a range of row spacing and planting densities was enhanced. This suggested that if soil health is improved through the inclusion of break crops between sugarcane cycles (Garside *et al*. 1999, 2000, 2002) there may be potential to adopt wider row configurations that suit controlled traffic without yield penalty.

In this paper we report the results of large-scale, semi-commercial experiments in northern, central, and southern Queensland, which involved different row configurations suitable for controlled traffic, and compare the production from them with the conventional 1.5-m single row configuration. The experiments followed break crops of soybean and were subject to harvester and haul-out traffic.

Materials and methods

This paper reports the results of 5 experiments conducted in sugarcane-growing regions in Queensland, Australia, at Gordonvale near Cairns, Bingera near Bundaberg, Ingham, Mackay, and Tully (Table 1). A common randomised complete block design was used at all sites, but the experiments differed in soil types, number of replicates, row configuration treatments, planting and harvest dates, rainfall and irrigation availability, and cultivar (Table 1). Management practices and data collection also differed between experiments and are detailed in Tables 2 and 3, respectively. The reason for different treatments, management practices, and data collection between the different experiments was largely due to their being located on commercial sugarcane farms where limitations were imposed by the farm management, equipment available, general timing of

Table 1. Details of experiment sites, soil type, replicates, length of crop cycle, planting and harvest dates, seasonal rainfall (mm) (including long-term averages, LT), irrigation details (mm), row configurations, and cultivars for experiments at Gordonvale, Bingera, Ingham, Mackay, and Tully

PC, Plant cane; R, ratoon; Conv., conventional sugarcane planting on flat ground in 1.5-m single row configuration; WS, whole stalk planter; BP, billet planter. Figures in parentheses in the row configuration column are number of rows on the bed top in each configuration, with distances referring to the distance between the midpoints of adjacent interspaces. Spacings between individual rows on the bed tops were 50 cm (for 4 rows), 65 cm (3 rows), 50 cm (2 rows on 1.8-m), and 80 cm (2 rows on 2.1-m beds)

Experiment site	Soil type[A]	No. of replications	Length of crop cycle	Planting date	Harvest date	Seasonal rainfall (mm)	Irrigation (mm)	Treatments	
								Row configuration	Cultivar
Gordonvale	Brown dermosol	2	PC	9–12 June 2002	29–31 July 2003	1320	5 × 50	Conv. WS	Q186$^{\phi}$
17°4′S, 145°46′E			R1		5–8 Aug. 2004	1984	2 × 85	1.5 m Beds (1)	
			R2		21–22 Oct. 2005	1657	2 × 85	1.8 m Beds (2)	
						(LT ave. 2078)		2.3 m Beds (3)	
Bingera	Red ferrosol	4	PC	15–18 Sept. 2003	13–15 Sept. 2004	891	4 × 35	Conv. WS	Q138
24°56′S, 152°10′E			R1		30–31 Aug. 2005	921	6 × 35	Conv. BP	
			R2		5–6 Oct. 2006	778	4 × 35	1.5 m Beds (1)	
						(LT ave. 953)		1.8 m Beds (1)	
								1.8 m Beds (2)	
								2.1 m Beds (2)	
								2.1 m Beds (3)	
								2.1 m Beds (4)	
Ingham	Grey chromosol	2	PC	20 July 2002	25 Sept. 2003	933	Nil	Conv. WS	Q157
18°41′S, 146°09′E						(LT ave. 2047)		1.5 m Beds (1)	
								1.8 m Beds (2)	
Mackay	Red chromosol	2	PC	26–27 May 2003	11–12 Aug. 2004	1120	3 × 50	Conv. WS	Q170$^{\phi}$
21°10′S,149°05′E			R1		16–17 Aug. 2005	1452		1.5 m Beds (1)	
						(LT ave. 1624)		1.8 m Beds (2)	
Tully	Redoxic hydrosol	4	PC	15 July 2002	10 June 2003	2077	Nil	1.8 m Beds (1)	Q187$^{\phi}$
17°58′S, 145°55′E			R1		15 July 2004	3021		1.8 m Beds (2)	
			R2		7 July 2005	2405			
						(LT ave. 4110)			

[A] Isbell (1996).

Table 2. Details of cultural practices for row configuration experiments at Gordonvale, Bingera, Ingham, Mackay, and Tully

WS, Whole-stalk; BP, billet; MB, mouldboard opener; DD, double disc opener. Data in parentheses in row configuration column represent number of rows on the bed top for each configuration

Experiment	Row configuration	Planter type	Cane planting density (t/ha)	Plot size	Fertiliser (kg/ha)	Chemicals
Gordonvale	Conv. WS	MB	5.0	15–20 m × 100 m	100 K as muriate of potash	Shirtan® fungicide and suSCon® insecticide at planting. Weed control with Dual Gold® and Atrazine®
	1.5 m Beds (1)	DD	4.0			
	1.8 m Beds (2)	DD	7.0			
	2.3 m Beds (3)	MB	12.0			
Bingera	Conv. WS	MB	5.0	15–20 m × 75 m	Nil. Soil tests indicated adequate supply of all nutrients	Shirtan® fungicide at planting. Weed control with atrazine®, stomp® and grammoxone®. Confidor® used for cane grub control 2 months after planting
	Conv. BP	MB	12.0			
	1.5 m Beds (1)	DD	3.7			
	1.8 m Beds (1)	DD	3.1			
	1.8 m Beds (2)	DD	6.1			
	2.1 m Beds (2)	DD	5.2			
	2.1 m Beds (3)	DD	7.9			
	2.1 m Beds (4)	DD	10.5			
Ingham	Conv. WS	MB	5.0	27 m × 150 m	100 K as muriate of potash. All other nutrients deemed adequate	Shirtan® at planting. Weed control with Dual® and Atrazine®
	1.5 m (1)	DD	4.0			
	1.8 m (2)	DD	7.0			
Mackay	Conv. WS	MB	5.0	20–25 m × 100 m	100 N as sulfate of ammonia at 4 months, 100 K as sulfate of potash, 160 S from sulfates of ammonia and potash	Shirtan® at planting. Weed contro with Dual Gold® and Atrazine®
	1.5 m (1)	DD	4.0			
	1.8 m (2)	DD	7.0			
Tully	1.8 m (1)	DD	3.5	7.2 m × 15 m	20 P as triple superphosphate, 100 K as muriate of potash	Shirtan® fungicide at planting. Weed control with Dual Gold® and Atrazine®
	1.8 m (1)	DD	7.0			

operations, and distance between locations (Gordonvale and Bingera are over 1200 km apart).

Planting details

All cane planting in these experiments followed well-grown fallow soybeans, which were managed as green manure crops. Land preparation before soybean planting generally involved discing, ripping, and rotary hoeing of the whole experimental area. For all the treatments where cane was planted with a double disc (DD) opener planter (Table 2), beds were formed before planting the soybean crops, with bed height varying from being only slightly raised at Bingera and Mackay to being 0.10–0.12 m high at Gordonvale, Tully, and Ingham. The higher beds were used at sites where a substantial amount of wet-season rainfall and the possibility of intermittent water-logging could be expected.

After the soybean crops were finished, all plots to be planted to cane with a DD opener planter were split to subplots in which the soybean residue was either left standing or was lightly incorporated into the bed surface without destroying the integrity of the beds. By contrast, all plots in which cane was to be planted with a mouldboard (MB) opener planter had the soybean material incorporated and were fully prepared, generally by discing, ripping, and rotary hoeing. As a result, full cultivation was applied before cane planting in all the 'conventional' treatments, the billet planted treatment at Bingera, and the 2.3-m configuration at Gordonvale (Table 2). With the exception of the billet planting (BP) at Bingera, all planting was carried out with whole-stalk (WS) planters.

Row configuration details

Reference to row configuration in these experiments refers to the distance between the mid-points of adjacent inter-row spaces, where machinery wheels would travel in a controlled traffic system. This term 'row configuration' has been adopted in this paper to avoid confusion with actual row spacing distances in multiple row plantings. Thus, reference to 2.3-m row configuration means that the machinery to handle that configuration in a controlled-traffic system would have wheel centres 2.3-m apart. In treatments where row configuration is wider than the standard 1.5 m, such as 1.8, 2.1, and 2.3 m, it is feasible to establish more than one sugarcane row on the available bed top. For example, in the Gordonvale experiment, 3 rows spaced 65-cm apart were established with the 2.3-m row configuration (Table 1), while in the Bingera experiment, 2, 3, and 4 rows each 80, 65, and 50-cm apart, respectively, were established on the beds with 2.1-m row configuration. Details of the number of rows sown in each configuration are provided in Tables 1 and 2. The ultimate aim of this research was to identify row configurations that would suit a controlled traffic farming system without having adverse effects on productivity.

Fertiliser details

All the soybean crops grew well and so none of the experiments required any nitrogen fertiliser except for the Mackay experiment (Table 2), where 100 kg N/ha was applied at 4 months. This was deemed necessary as the soybean crop was grown over the 2001–02 summer but drought conditions precluded cane planting until May 2003 instead of the intended May 2002. It was thought that the N provided by the legume may well have been lost during the extended fallow period. The requirement for other nutrient inputs was determined on the basis of soil testing and locally recommended practices, with details of other fertilisers used provided in Table 2.

Table 3. Details of measurements made in the plant crop for row configuration experiments at Gordonvale, Bingera, Ingham, Mackay, and Tully
WS, Whole-stalk; BP, Billet. Data in parentheses in row configuration column represent number of rows on the bed top for each configuration

Experiment	Row configuration	Shoot/stalk counts during the season	In-season biomass accumulation (t/ha) in plant crops	Cane yield (t/ha) Hand harvest[A]	 Machine harvest	CCS	Sugar yield (t/ha)
Gordonvale	Conv. 1.5 m Beds (1) 1.8 m Beds (2) 2.3 m Beds (3)	Temporal counts in 4 × 15 m^2 marked areas per plot	Sample areas of 15 m^2 harvested from all plots on 8 October (4 months) and 29 January (8 months)	Four 15-m^2 shoot count areas hand harvested from each plot	Remainder of plot machine harvested	Yes	Yes
Bingera	Conv. WS Conv. BP 1.5 m Beds (1) 1.8 m Beds (1) 1.8 m Beds (2) 2.1 m Beds (2) 2.1 m Beds (3) 2.1 m Beds (4)	Temporal counts in 2 × 15 m^2 marked areas per plot	Sample area of 15-m^2 harvested from all plots on 22 March (6 months)	Two 15-m^2 shoot count areas hand harvested from each plot	Remainder of plot machine harvested	Yes	Yes
Ingham	Conv. WS 1.5 m (1) 1.8 m (2)	No	No	No	Whole plot machine harvested	Yes	Yes
Mackay	Conv. WS 1.5 m (1) 1.8 m (2)	Temporal counts in 4 × 15 m^2 marked areas per plot	Two 15-m^2 shoot count areas harvested from each plot on 6 January (6 months)	Four 15-m^2 shoot count areas hand harvested from each plot	Remainder of plot machine harvested	Yes	Yes
Tully	1.8 m (1) 1.8 m (2)	No	No	Two 15 m^2 areas hand harvested from each plot	Remainder of plot machine harvested. No yields recorded	Yes	Yes

[A] Cane yield determined by weighing total fresh biomass from harvested area then randomly selecting 15 stalks and dividing stalk from tops between fifth and sixth leaves from the top. Fresh weights of both sections were measured and used to calculate the % millable stalk which was used to determine the cane yield.

Data collection and harvesting details

Temporal shoot counts were carried out in the plant crop in all experiments except Tully and Ingham, while in-season biomass accumulation was measured by destructive sampling at Gordonvale, Bingera, and Mackay (Table 3). In all experiments except Ingham and Tully, plant crop yields were determined by both hand harvesting of designated subplots and machine harvesting of the remainder of the plot (Table 3). At Ingham, only machine-harvested yields were measured, while at Tully, only hand-harvested yields were measured.

Yields of all ratoon crops were measured by both hand harvesting of designated subplots and machine harvesting of the remainder of the plot, although only yields of the hand-harvested subplots are presented for the ratoon crops in this paper. This is because confounding was introduced into the experiments by having machine harvesting (of the plant and subsequent ratoon crops) conducted with equipment in which wheel spacing and row spacings were not matched in all treatments. Damage to some plots and treatments in some experiments was obvious following plant crop harvest so areas were selected where soil compaction and stool damage appeared to be minimal and these were designated areas for hand harvesting in the ratoons. Even with this approach the ratoon yields for some row configurations suffered because of harvesting issues with the previous plant crop. CCS was determined on subsamples of millable stalk (harvestable cane) for all hand-harvested areas using the small-mill method (BSES 1984), while CCS determined at the sugar mill for the machine-harvested plots at Mackay is also reported.

All ratoon crops were treated with standard fertiliser and weed control measures used in the particular region. No in-season growth assessments were made on the ratoon crops, with final cane yield, CCS, and sugar yield measured from hand-harvested subplots.

Cumulative yield and economic considerations

Cumulative yields were calculated for the experiments at Gordonvale, Bingera, Mackay, and Tully and an economic assessment of the different row configurations was carried out for the Bingera experiment. In this assessment we assumed that all land preparation was similar before planting the soybean, so for all of the treatments on beds, we have only considered the cost of the light rotary hoeing of the soil surface to break down the soybean residue before cane planting ($34/ha). The conventional and billet planted treatments had the added land preparation costs between the soybean and the sugarcane planting (two discings, one ripping, and one rotary hoeing) estimated to cost $166/ha. All plots except those that were billet planted were planted with whole-stalk planters and so required additional labour to feed the planter. One labourer per row has been allowed for this operation, so configurations of 4 rows on a 2.1-m bed required 4, and dual-row configurations 2 labourers.

All treatments were assessed as using a 90-horsepower tractor consuming 10 L fuel/h at a cost of diesel of $1.50/L. Planting speed was assumed to be 2.5 km/h for the whole-stalk planters and 8 km/h for the billet planter, with field efficiency rates of 50 and 80%, respectively. A sugar price of \$280/t was used. Cane price was calculated from the standard cane pricing formula using a CCS of 14:

$$\text{Cane price/t} = (0.009 \times \text{sugar price} \times (\text{CCS} - 4) + 0.578)$$

Statistical analysis

Data for each experiment were analysed using standard analysis of variance techniques in the GENSTAT statistical package. In addition, for row configuration treatments that were common to more than one experiment, cane yield data were re-analysed including site as a factor. This latter analysis was relevant for the plant crop on 1.5-m single rows and 1.8-m dual rows on beds at Gordonvale, Ingham, Mackay, and Bingera and for the ratoon crop at Gordonvale, Mackay, and Bingera. The 1.5-m conventional planting (also common to these experiments) was not included in this analysis because relative to the other two treatments, any row configuration response comparisons would have been confounded by substantial differences in land preparation.

Results

Seasonal conditions

All experiments received below-average rainfall for their entire duration and in some cases, rainfall was well below average (Table 1). For example, the Ingham experiment experienced one of the driest years on record during the plant crop, with only 46% of the long-term average. The absence of irrigation at this site ensured extreme water stress during the plant crop, which affected the longevity of the experiment. The crop was continued into the ratoons and machine harvested each year, but performance was variable and unrelated to treatment.

Fortunately, irrigation was available at Gordonvale, Bingera, and Mackay and this allowed meaningful results to be obtained, although particularly in the case of Bingera, irrigation was limited in the plant and second ratoon crops and moisture stress was still an issue (Table 1). Conversely, while the Tully experiment also experienced well below-average rainfall (Table 1) the sugarcane crop probably benefited. In that environment, excessive rainfall and associated cloud cover are limiting factors to crop growth in many years (Muchow *et al.* 1997).

Given the dry seasonal conditions that occurred, the decision to use raised beds at Gordonvale and Ingham was not warranted and probably had a significant adverse effect on crop yields at both sites as the soil surface tended to seal, shedding the water from small rainfall events from the bed surface, which had an adverse effect on crop establishment.

Shoot and stalk development

The effect of row configuration on the temporal pattern of shoot and stalk development for the Bingera plant crop is presented in Fig. 1. Similar trends were recorded at Gordonvale and Mackay (data not shown). Essentially, there were more early shoots with higher planting densities and narrower rows. This response was accentuated in the conventional billet planted treatment at Bingera, where the high planting density of 12 t/ha (Table 2) produced the largest number of early shoots (Fig. 1).

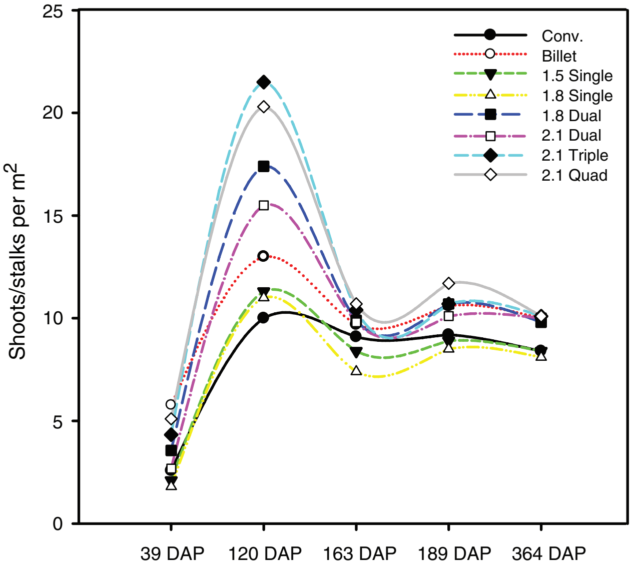

Fig. 1. Temporal change (days after planting, DAP) in shoot/stalk no. per m^2 for different row configurations in the Bingera experiment. Statistics: $P < 0.001$ for each sample date, l.s.d.s are 0.72 (39 DAP), 3.57, 0.73, 0.94, and 0.84 (364 DAP).

The row configurations with high early shoot numbers were also those that consistently suffered the greatest shoot mortality when rapid stalk elongation commenced (after 120 DAP, Fig. 1). As a result of the differential shoot loss there were only small but statistically significant differences between row configurations at final harvest (Fig. 1, Table 6). The relatively low stalk numbers throughout the season for the conventional, 1.5-m, and 1.8-m single-row beds at Bingera were probably associated with the low planting densities in those treatments (Table 2), combined with poor quality seed cane.

Biomass production

Temporal biomass production data for the plant crops at Gordonvale and Bingera are shown in Table 4. The pattern of biomass accumulation was quite different in the two experiments. There were large increases in biomass between samplings at 4, 8, and 12 months at Gordonvale but only limited biomass accumulation after the 6-month sampling at Bingera. These different patterns largely reflect early growth at Gordonvale occurring during the winter period, whereas the Bingera experiment, planted in spring, experienced the cooler winter temperatures during the second half of the growing period. In addition, the latter half of the growing period at Bingera was very dry. Between 23 March and 14 September (the second 6 months) the site received only 162 mm or 18% of the annual rainfall, with only an additional 70 mm of supplementary irrigation applied.

At both sites there was significantly less biomass in the 1.5-m and/or 1.8-m single-row beds for the early sample dates, but these differences had substantially reduced by 8 months (Gordonvale) and disappeared completely at both sites by final harvest (12 months). The dynamics of biomass production between

Table 4. Biomass production (t/ha dry weight) for samplings during growth at 4, 8, and 12 months after planting at Gordonvale and 6 and 12 months after planting (MAP) at Bingera

Treatment	Sample date		
	23 Mar. 2003 (6 MAP)		14 Sept. 2003 (12 MAP)
	Bingera		
Conv.	35		35.34
Billet	36		36.74
1.5 m	31.88		35.22
1.8 m	28.68		33.79
1.8 m duals	38.93		39.11
2.1 m duals	36.3		36.91
2.1 m triples	37.53		36.77
2.1 m quads	38.85		32.61
Level of sig.	$P < 0.001$		n.s.d.
l.s.d. 5%	3.23		
	2 Oct. 2002 (4 MAP)	30 Jan. 2003 (8 MAP)	29 July 2003 (12 MAP)
	Gordonvale		
Conv.	1.86	11.17	35.7
1.5 m	0.78	7.92	35
1.8 m dual	1.06	10.44	33
2.3 m triple	2.01	10.92	39
Level of sig.	($P = 0.10$)	n.s.d.	n.s.d.

the different row configurations reflected advantages with conventional, billet, and multi-row plantings during early growth but higher rates of biomass accumulation late in the growing period with 1.5- and 1.8-m single rows on beds. In some instances (e.g. quad rows at Bingera, Table 4) there was a loss of biomass in the latter half of the growing period. This row configuration was characterised by substantial crop lodging.

Cane yield and yield components

There was no effect of surface tillage of beds on cane yield in the DD opener planted plots at Gordonvale, Bingera, Ingham, and Mackay so data for tilled and non-tilled beds in each experiment have been pooled in the subsequent analyses. Overall, there was no significant effect of row configuration on cane yield in either the plant or ratoon crops at Gordonvale, Ingham, and Mackay. However, the limited replication (only 2) in these large-scale experiments may have contributed to the lack of statistical significance for what appeared to be quite large numerical differences in cane yield between the conventional and other treatments at both Gordonvale and Mackay (Table 5).

In an attempt to explore this further, it was decided to use samples as replicates (2 reps. × 4 samples = 8 replicates) and re-analyse the data for the Gordonvale and Mackay experiments. The large plot size (Table 2) and the considerable distance between sample sites within plots gave some confidence to using such an approach. The outcome of these analyses was that yield differences achieved statistical significance ($P < 0.01$), but these simply showed that the treatments cultivated before cane planting (conventional 1.5-m single rows and the triple rows on 2.3-m beds at Gordonvale and conventional 1.5-m single rows at Mackay) were producing significantly higher yields than the arrangements on the previously established beds that were not cultivated before planting (DD-planted 1.5-m single rows and 1.8-m dual rows). There was no difference between configurations within each of the cultivated and non-tilled treatments.

There were significant cane yield differences between the row configurations at Bingera in the plant, first, and second ratoon crops (Table 5). In large part, these differences reflected poor yields for the quad rows in all phases of the crop cycle and the 1.8-m single rows in the plant and second ratoon. The 1.5-m single rows in the conventional and DD-planted beds also yielded poorly in the plant crop, but in the first and second ratoon they yielded as well as any other configuration. Most of the poor yielding configurations in the plant crop at Bingera suffered from poor establishment (1.5-m single rows in the conventional and DD-planted beds and the 1.8-m single rows), subsequent moisture stress (1.8-m single rows), and lodging (2.1-m quad rows). The poor establishment resulted from the combination of poor quality planting material and low planting densities through a whole-stalk planter (both MB and DD) (Table 2) and was evident in early shoot numbers (Fig. 1).

The combined analysis for cane yield across experiments for the 1.5-m single and 1.8-m dual rows planted on beds in the plant crop (Table 6) showed that there were significant differences between experiments but not between the two row configurations within experiments and there was no experiment × row configuration interaction, indicating that similar yields could be expected with these two row configurations across environments and different cultivars. The trend for lower yields in the 1.5-m single rows at Bingera in the plant crop (Table 6) was probably associated with the poor quality planting material and a relatively low planting density discussed above rather than any limitation of row configuration *per se*.

In the first ratoon crop there was again a significant difference between experiments, but in this case there was also a significant row configuration effect (Table 6). The row configuration effect was largely due to relatively poor yields in 1.8-m dual rows where excessive lodging and/or harvesting damage occurred (Mackay and Bingera). In the Mackay experiment the plant crop of cultivar Q170$^{\phi}$ lodged badly in the bed plantings, especially in the dual rows, and this resulted in harvester damage and stool removal that confounded comparisons between row configurations in the first ratoon. At Bingera, necessary adjustments to the harvester to efficiently harvest 1.8-m dual rows in the plant crop not possible and this resulted in some stool damage, which was probably responsible for the lower yield relative to the 1.5-m single row (Table 6). No deficiencies were recorded in harvesting the 1.8 m dual rows at Gordonvale where cane yields were similar between the two configurations.

In the two experiments where single and dual rows were compared on 1.8-m row configuration (Bingera and Tully), the dual rows out-yielded the single rows by around 20% in the plant crop but there was no difference in the first ratoon and no difference at Tully in the second ratoon (Table 5). The yield difference between 1.8-m dual and single rows in the plant crop was remarkably similar at both sites and was probably associated with restricted growth rates during the second half of the growing period limiting the ability of individual stalk weights to

Table 5. Cane yield (t/ha), CCS (%), and sugar yield (t/ha) for plant, first ratoon, and second ratoon and cumulative cane and sugar yield for row configuration experiments at Gordonvale, Bingera, Ingham, Mackay, and Tully

HH, Hand harvest; MH, machine harvest

Experiment	Treatments	Plant cane				First ratoon			Second ratoon			Cumulative yield	
		Cane (HH)	Cane (MH)	CCS	Sugar	Cane	CCS	Sugar	Cane	CCS	Sugar	Cane	Sugar
Gordonvale	Conv.	113	102	14.5	16.36	119	14.44	17.18	116	13.09	15.18	348	48.72
	1.5 m Beds (1)	102	92	14.39	14.68	106	14.02	14.86	125	13.36	16.7	333	46.24
	1.8 m Beds (2)	101	93	14.62	14.79	106	14	14.84	119	13.26	15.78	326	45.41
	2.3 m Beds (3)	112	95	14.12	15.84	96	14.4	13.82	120	12.77	15.32	328	44.98
Level of sig.		n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	$P=0.03$
l.s.d 5%													2.94
Bingera	Conv. WS	101	90	13.63	13.8	135	13.05	17.57	109	15.41	16.77	345	48.14
	Conv. BP	112	93	14.11	15.7	127	13.08	16.62	106	15.43	16.4	345	48.72
	1.5 m Beds (1)	103	86	14.46	14.8	134	13.44	17.98	114	14.13	17.29	351	50.07
	1.8 m Beds (1)	99	74	14.67	14.5	125	13.93	17.3	95	15.44	14.67	319	46.47
	1.8 m Beds (2)	119	94	14.22	16.9	120	12.94	15.44	112	14.97	16.84	351	49.18
	2.1 m Beds (2)	115	85	14.17	16.2	125	13.07	16.36	119	15.1	18.02	359	50.58
	2.1 m Beds (3)	112	84	13.7	15.3	122	13.13	15.98	111	14.75	16.44	345	47.72
	2.1 m Beds (4)	100	68	14.76	14.7	100	13.67	13.73	101	15.08	15.28	301	43.71
Level of sig.		$P<0.05$	$P<0.01$	$P=0.01$	$P<0.05$	$P<0.01$	n.s.d.	$P<0.05$	$P<0.05$	n.s.d.	n.s.d.	$P<0.01$	$P<0.05$
l.s.d. 5%		13.4	13.56	0.64	1.66	13.8		2.37	13.32			27.5	3.58
Ingham	Conv. WS		84	11.95	10.04								
	1.5 m (1)		75	12.6	9.45								
	1.8 m (2)		81	12.8	10.37								
Level of sig.			n.s.d.	n.s.d.	n.s.d.								
Mackay	Conv. WS	120	106	11.87	14.23	120	14.16	17.06				240	31.29
	1.5 m (1)	109	94	14.47	15.78	119	14.16	16.88				228	31.35
	1.8 m (2)	107	89	14.86	15.95	107	13.83	14.81				214	29.67
Level of sig.		n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.				n.s.d.	n.s.d.
Tully	1.8 m (1)	98		9.15	8.97	109	13.27	14.46	88	12.48	10.98	295	34.41
	1.8 m (2)	123		9.03	11.11	109	13.22	14.41	93	12.53	11.65	325	37.17
Level of sig.		$P<0.05$		n.s.d.	$P=0.02$	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d.	n.s.d	n.s.d	n.s.d
l.s.d. 5%		15.2			1.39								

compensate for the lower stalk numbers in 1.8-m single rows (Fig. 1). However, there were probably different causes of the yield difference in the two experiments. At Bingera, it is suspected that water stress in the second half of the growing period limiting stalk filling (Table 1) was the main reason for the 1.8-m single rows not reaching their potential. At Tully it was more likely due to radiation limitation. The reason for the lower yield in the 1.8-m singles in the second ratoon at Bingera is unclear, but appears to be due to both fewer and lighter stalks (data not presented) in the overall dry growing conditions in 2005–06 (Table 1).

Yield component data (stalk number and individual stalk weight) were quantified in all except the Ingham experiment, with data for Bingera (Table 7) representing the trends in all of the experiments. In general, there were significant differences in final stalk number between treatments, with more stalks being present in the row configurations characterised by higher planting densities. Individual stalk weight data tended to show compensatory responses to differential stalk numbers, such that where there were low stalk numbers (conventional, 1.5-, and 1.8-m singles) there were higher individual stalk weights (Table 7). This compensation was likely the major reason for relatively small differences in final yield between most configurations (Table 5), except where late-season growth rates were limited by environmental factors.

CCS and sugar yield

In large part, CCS was unaffected by row configuration with the exception being the plant crop at Bingera (Table 5), where the conventional planting and the 2.1-m triple row produced lower CCS than the other treatments. The reasons for these responses are unclear, although it is worth noting that in terms of sugar yield the 2.1-m triple rows were not significantly different from any other treatment.

There were some interesting trends in the CCS data for the plant crop in the Mackay experiment, in which the cv. Q170$^{Ⓐ}$ lodged very badly and suffered from rat damage in the DD-planted 1.8-m dual row and 1.5-m single-row beds, but not in the conventionally planted 1.5-m rows, which remained erect. As noted above, this differential lodging was probably a significant contributor to the lower cane yields with the 1.5- and 1.8-m beds.

Table 6. Plant cane and first ratoon cane yields across experiments for 1.5-m single rows and 1.8-m dual rows planted on beds with a double disc opener planter

Experiment	Row configuration		Mean
	1.5-m single rows	1.8-m dual rows	
	Plant crop		
Gordonvale	103	102	102
Ingham	74	81	78
Mackay	109	108	108
Bingera	103	120	111
Mean	98	106	
Level of sig.	n.s.d.		($P < 0.001$)
l.s.d. 5%			8.7
	First ratoon		
Gordonvale	107	106	106
Mackay	120	107	113
Bingera	134	120	127
Mean	123	113	
Level of sig.	$P = 0.05$		($P < 0.05$)
l.s.d. 5%	10		15

Table 7. Final harvested stalk number (stalks/m^2) and individual stalk weight (ISW) in the plant crop for different row configurations in the Bingera experiment

Row config.	Stalks/m^2	ISW (kg)
Conv.	8.44	1.4
Billet	10	1.27
1.5 m	8.4	1.39
1.8 m	8.08	1.44
1.8 m duals	9.75	1.41
2.1 m duals	10	1.32
2.1 m triples	10.08	1.25
2.1 m quads	10.11	1.09
Level of sig.	$P < 0.001$	$P < 0.001$
l.s.d. 5%	0.86	0.14

However, with the CCS analysis, whole-stalk samples taken from the hand-harvested areas and analysed using the small-mill technique (BSES 1984) showed a trend ($P = 0.15$) for a reduction in CCS with the conventional 1.5-m planting (11.87%) relative to the 1.8-m dual-row (14.86%) and 1.5-m single-row (14.47%) bed plantings (Table 5). The reason for these trends in CCS is unknown but whole stalks from the 1.8-m dual-row and 1.5-m single-row bed plantings were drier at harvest than whole stalks from the 1.5-m conventional planting, the average dry matter percent being 29.3, 29.0, and 26.4 for the 1.8-m dual-row and 1.5-m single-row beds and the 1.5-m conventional planting, respectively. Greater concentrations of sucrose in the drier treatments could have been part of the reason. After mechanical harvesting, CCS was assessed at the sugar mill as 13.32, 13.53, and 12.96 for the 1.8-m dual and 1.5-m single-row beds and 1.5-m conventional planting, respectively. Essentially, CCS analysis from the sugar mill was higher for the conventional planting and lower for the bed plantings compared with the small-mill analysis. The data for mill CCS with the bed plantings are not surprising given the lodging (Singh *et al.* 2002) and rat damage on the beds, which was not accounted for with the small-mill analysis, where only whole stalks were assessed. However, the increased CCS in the mechanically harvested conventional 1.5-m planting was unexpected and cannot be explained, although machine harvesting was carried out 2 weeks after hand harvesting when the conventional configuration was probably drier. Regardless, these data are indicative of the CCS losses that can be incurred through lodging and rat damage.

Cumulative yield and economic considerations

Cumulative yields across the crop cycle for Gordonvale, Bingera, Mackay, and Tully are shown in Table 5, while an economic assessment of the costs and returns for the different planting methods and row configurations in the Bingera experiment is shown in Table 8. Cumulative yields were considered relative to the 1.5-m DD-planted single row. At Gordonvale the 1.8-m dual row and 2.3-m triple row configurations produced cumulative cane and sugar yields that were 98–99% of those achieved in the 1.5-m single row DD-planted treatment, while the conventionally planted 1.5-m single rows yielded 5% more cane and sugar. Similar trends were evident at Mackay, although the yield penalty for the lodged and subsequently rat and harvester damaged 1.8-m dual rows was 6% (cane) and 5% (sugar) lower yields. Differences at Bingera were similarly small, although at this site there was no advantage with conventional or billet planted 1.5-m single rows. The only significant yield penalties were a 5% sugar yield reduction in the 2.1-m triple rows and a 13–14% reduction in both cane and sugar yield in the 2.1-m quad rows (Table 5). At sites where 1.8-m DD-planted single and dual rows were included (Bingera and Tully), dual rows out-yielded the single rows by 6–10%.

Overall differences in cost and returns were recorded for the different planting configurations across the plant and two ratoon crops at Bingera. In particular, the 2.1-m quad rows showed a substantial reduction in gross margin relative to the conventional planting (Table 8). The billet planting, 1.5-m beds, 1.8-m dual rows, and 2.1-m dual rows showed positive gross margins relative to the conventional planting, with the improvement being quite substantial for the 1.5-m DD single rows and the 2.1-m dual rows (Table 8). However, over the total duration of the crop (4 years if the fallow is taken into account) the differences were relatively minor and as with crop growth and yield results, these economic data emphasise that there is an enormous amount of flexibility with regard to row configuration for sugarcane growing.

Discussion

All five experiments established in the main cane-growing areas from northern to southern Queensland were planted after well-grown soybean fallows and so it could be assumed that constraints due to poor soil health were minimised (Garside *et al.* 1999, 2000, 2002; Garside and Bell 2009*a*). The yields from many of the different configurations were remarkably similar within experiments, e.g. the 1.5-m single rows and the 1.8-m dual rows at Gordonvale, Bingera, and Ingham (Table 5). Further, at Bingera, the only experiment where the 2.1-m dual row configuration was included, yields were similar. It is

Table 8. Costs and returns for the different row configurations in the Bingera Experiment

Configuration	Planter type	Land prep. ($/ha)[A]	Actual planting density (km/h)[B]	Time (h/ha)[C]	Fuel ($/ha) at $1.50/L[D]	Labour ($/ha) at $18/unit.h[E]	Cane costs ($/ha)[F]	Total planting costs ($/ha)	Cum. cane yield (t/ha) from Table 5	Harvest costs ($/ha)[G]	Total costs ($/ha)	Return at $280/t sugar[H]	Gross margin ($/ha)	GM relative to 1.5-m DD single rows
Conv. WS	MB	166	1.25	5.3	79	95	129	469	345	2415	2884	13 479	10 595	–
Conv. BP	MB	166	6.4	1	15	Nil	310	491	345	2415	2906	13 642	10 736	141
1.5 m Beds (1)	DD	34	1.25	5.3	79	95	95	303	351	2457	2760	14 020	11 260	665
1.8 m Beds (1)	DD	34	1.25	4.4	66	79	80	259	319	2233	2492	13 012	10 520	–75
1.8 m Beds (2)	DD	34	1.25	4.4	66	158	157	415	351	2457	2872	13 770	10 898	303
2.1 m Beds (2)	DD	34	1.25	3.8	66	137	134	371	359	2513	2884	14 162	11 278	683
2.1 m Beds (3)	DD	34	1.25	3.8	66	205	204	509	345	2415	2924	13 362	10 438	–157
2.1 m Beds (4)	DD	34	1.25	3.8	66	274	271	545	301	2107	2408	12 239	9 831	–764

[A] Based on 2 discings, 1 ripping, and 1 rotary hoeing for mouldboard planter (MB) and 1 light rotary hoeing of bed surface for double disc opener planter (DD).

[B] Based on planting speed of 2.5 km/h and field efficiency of 50% for whole stalk planter and 8 km/h and field efficiency of 80% for billet planter.

[C] Based on travelling 6667, 5556, and 4762 m/ha for 1.5-, 1.8-, and 2.1-m row configurations.

[D] Based on fuel usage of 10 L/ha.

[E] Based on number of units required to feed cane with WS planter, allowing 1 unit per row, *viz*. 4 labour units to plant quad row.

[F] Based on cane price of $25.80/t and planting densities shown in Table 2.

[G] Based on harvesting cost of $7.00/t.

[H] Based on sugar yields for Bingera in Table 5.

reasonable to assume that had 2.1-m dual rows been included in the other experiments, yields similar to those with 1.5-m single and 1.8-m dual rows would have been recorded, particularly in that conventional plantings on 1.5-m single rows and 2.3-m triple rows produced similar yields at Gordonvale.

When yield differences did occur between different configurations, specific adverse factors were generally operating against one of the row configurations. For example, there was severe lodging (probably cultivar related) in the dual rows at Mackay, heavy lodging with the quad rows at Bingera, and suspected insufficient late-season inputs to maximise growth with the 1.8-m single rows in the plant crops at Bingera (probably water limitation) and Tully (probably radiation limitation). These data therefore provide further evidence that sugarcane possesses a degree of physiological and environmental plasticity that allows similar yields to be produced across a range of row configurations, although there do appear to be limits beyond which compensation cannot occur. Data from these experiments suggest that at the low planting densities in single rows with whole-stalk planters, suboptimal plant stands arising from poor quality seed cane cannot be compensated for later in the growing period. Relative to treatments with higher planting densities, 1.8-m single rows, and the lower final stalk populations they produce, are a risky proposition if growing conditions are marginal (plant crops at Bingera and Tully). However, results also suggest that under good growing conditions (Bingera first ratoon in these experiments and Garside and Bell 2009*b*), 1.8-m single rows have the potential to yield as well as other spacings and are likely to be well suited to fully irrigated situations.

The economic assessment applied to the Bingera data (Table 8) provides further incentive to avoid major modifications to harvesting equipment in the change to row configurations that suit controlled traffic. The difference in gross margins over a 3-year crop cycle was relatively small, suggesting that little additional financial return would be gained by funding major expenditure on machinery modifications to suit different row configurations. However, some caution needs to be exercised in considering this result. All machine harvests across all of these experiments were carried out under dry conditions and so, despite using a machine on 1.8-m wheel spacings, there were no instances of major damage because of wet harvesting, such as that reported by Garside (2004). This allowed results such as those from Bingera that suggested there is little to be gained from going away from 1.5-m rows. However, matched wheel and row configuration will be more beneficial under wet harvesting, and if such conditions had occurred the advantage of configurations with row spacings $\geq$1.8 m may have been more evident, especially in ratoon crop performance.

These experiments indicate that controlled traffic can be implemented without risks of yield penalties by adopting 1.8-m dual rows and undertaking minor modifications to the harvesting equipment, although planter modifications to achieve the dual rows are needed. Matched wheel and row spacings can also be achieved with 2.1- or 2.3-m rows and our gross margin analysis from Bingera suggested that the 2.1-m configuration with dual rows at 80 cm provided the best gross margin benefit. However, 2.1- and 2.3-m row configurations do require substantial and expensive harvester and haul-out modifications.

There is little doubt that the easiest way to adopt controlled traffic would be to adopt 1.8–1.9-m single rows and use existing equipment, with only some form of elevator extension needed to allow haul-outs to remain an appropriate distance from the harvester without travelling on crop rows. However, unless ways of overcoming the risks of lower yields are developed, adoption will likely be poor. At least part of this risk may be addressed by increased planting densities in 1.8-m single rows through billet planting and/or wide throat mouldboard openers. Whether utilising these modifications will overcome the apparent individual stalk weight limitation and yield susceptibility to adverse conditions during stalk filling is not clear and requires further study.

Finally, there is little information on the possible interactions between cultivars and row configuration, and hence little information on the suitability of cultivars for row configurations wider than 1.5 m. This needs further investigation as all the cultivars used in the Australian sugar industry are currently selected under 1.5-m single-row spacing, and there is emerging evidence that at least some of the cultivars selected under that system do not perform well in dual rows (e.g. Q170$^{\Phi}$, Mackay). If controlled traffic on rows wider than 1.5 m is to be widely adopted it will necessitate the most suitable cultivars being available. Research is needed to identify the important characteristics that are required in cultivars to best suit wider/dual row configurations as opposed to standard 1.5-m single rows. In the third paper of this series the results of experiments that combined cultivars expressing different growth habits with a range of row configurations are discussed (Garside and Bell 2009*b*).

Acknowledgments

The research reported in this paper was carried as part of the Sugar Yield Decline Joint Venture program and was funded by the Sugar Research and Development Corporation, BSES LTD (formerly the Bureau of Sugar Experiment Stations), and the Queensland Department of Primary Industries and Fisheries. Technical assistance was provided by John Berthelsen, Win Chappell, and Neil Halpin. We also thank the canegrowers who provided the experiment sites: Tom and Gaynor Watters (Gordonvale), BSES Tully Experiment Station (Tully), Morris Brothers (Ingham), Charles McLennan (Mackay), and Bundaberg Sugar Limited (Bingera). Helpful comments on the manuscript were provided by Drs Peter Allsopp, Bob Lawn, and Geoff-Inman Bamber.

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Manuscript received 15 September 2008, accepted 3 March 2009