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Row spacing and planting density effects on the growth and yield of sugarcane. 1. Responses in fumigated and non-fumigated soil

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Abstract. It has been reported that high-density planting of sugarcane can improve cane and sugar yield through promoting rapid canopy closure and increasing radiation interception earlier in crop growth. It is widely known that the control of adverse soil biota through fumigation (removes soil biological constraints and improves soil health) can improve cane and sugar yield. Whether the responses to high-density planting and improved soil health are additive or interactive has important implications for the sugarcane production system.

Field experiments established at Bundaberg and Mackay, Queensland, Australia, involved all combinations of 2-row spacings (0.5 and 1.5 m), two planting densities (27 000 and 81 000 two-eyed setts/ha), and two soil fumigation treatments (fumigated and non-fumigated). The Bundaberg experiment had two cultivars (Q124, Q155), was fully irrigated, and harvested 15 months after planting. The Mackay experiment had one cultivar (Q117), was grown under rainfed conditions, and harvested 10 months after planting.

High-density planting (81 000 setts/ha in 0.5-m rows) did not produce any more cane or sugar yield at harvest than low-density planting (27 000 setts/ha in 1.5-m rows) regardless of location, crop duration (15 *v.* 10 months), water supply (irrigated *v.* rainfed), or soil health (fumigated *v.* non-fumigated). Conversely, soil fumigation generally increased cane and sugar yields regardless of site, row spacing, and planting density. In the Bundaberg experiment there was a large fumigation × cultivar × density interaction ($P < 0.01$). Cultivar Q155 responded positively to higher planting density in non-fumigated soil but not in fumigated soil, while Q124 showed a negative response to higher planting density in non-fumigated soil but no response in fumigated soil. In the Mackay experiment, Q117 showed a non-significant trend of increasing yield in response to increasing planting density in non-fumigated soil, similar to the Q155 response in non-fumigated soil at Bundaberg.

The similarity in yield across the range of row spacings and planting densities within experiments was largely due to compensation between stalk number and stalk weight, particularly when fumigation was used to address soil health. Further, the different cultivars (Q124 and Q155 at Bundaberg and Q117 at Mackay) exhibited differing physiological responses to the fumigation, row spacing, and planting density treatments. These included the rate of tiller initiation and subsequent loss, changes in stalk weight, and propensity to lodging. These responses suggest that there may be potential for selecting cultivars suited to different planting configurations.

Additional keywords: cultivars, high-density planting, soil health, CCS.

Introduction

Optimising the combination of row spacing and planting density has been a major issue in sugarcane production systems for at least the past half century, with the considerable amount of agronomic research conducted over many years producing variable results. Irvine and Benda (1980) reviewed research into the effects of sugarcane row spacing. They concluded that increasing planting density by reducing inter- and intra-row spacing resulted in cane yield increases with little effect on sucrose content. Matherne (1972) recorded cane yield increases of 55% as row spacing was reduced from 1.82 m to 0.61 m, while Irvine *et al*. (1980) recorded an 80% yield increase for the same reduction in row spacing (1.82 to 0.61 m). Matherne (1972) also recorded a small but significant cane yield increase by increasing the planting rate within the different row spacings, although the effect was more significant in the wider rows. However, Irvine and Benda (1980) noted that the majority of the research they reviewed was from relatively short-duration sugarcane crops (9–10 months). Where crops were of longer duration (12 months or more) the benefits from reducing both inter- and intra-row spacing were more equivocal (Thompson and du Toit 1965; Rice 1978).

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Bull (1975), working in Australia, reported cane yield increases of 60% for a plant crop as row spacing and planting density were increased from 1.4 m and 2.6 setts/m^2 to 0.5 m and 14.8 setts/m^2, respectively. While this response was similar to the larger responses cited by Irvine and Benda (1980), it was obtained from small plots (4 m by 3 m). In more recent field studies into what was termed high-density planting (HDP), Bull and Bull (2000*a*, 2000*b*) reported a 50% yield increase by reducing row spacing from 1.5 m to 0.5 m and planting the same number of setts per row, thus increasing planting rate 3-fold.

In Australia, sugar yield per harvested hectare plateaued between 1970 and 1990 (Garside *et al*. 1997). This plateau was attributed to a declining agro-environment, as demonstrated genetic gains indicated that yield should have been increasing by 1% per year (Berding and Skinner 1987; Chapman 1996). The declining agro-environment was referred to as yield decline. Many and varied reasons were put forward for yield decline and numerous research disciplines were involved in trying to understand the cause (Garside *et al*. 1997). Large yield responses to soil fumigation in early research indicated that root pathogens were a major part of the problem, particularly the fungus *Pachymetra chaunorhiza* (Magarey 1994). However, the development of cultivars resistant to *Pachymetra chaunorhiza* only partly overcame the problem as fumigation responses of ~35% were obtained even when using these resistant cultivars (A. P. Hurney, pers. comm.). Further research into identifying additional root pathogens resulted in limited success.

The Sugar Yield Decline Joint Venture (SYDJV) was established in 1993 to identify the cause/causes of yield decline and to develop solutions to the problem. Initially the SYDJV focused on rotation experiments to quantify the effect of breaking the long-term sugarcane monoculture with other crop species, pastures, or bare fallow. The cane growth following breaks was compared with that in a sugarcane monoculture with or without soil fumigation. Yield increases in response to both breaks and field fumigation varied between 20 and 50% (Garside *et al*. 1999, 2000, 2002). The positive response to breaks and fumigation was largely due to more vigorous crop growth because of improved soil health (Pankhurst *et al*. 1999; Bell *et al*. 2000, 2002; Stirling *et al*. 2001).

Given the yield increases of 50% with HDP (Bull and Bull 2000*a*, 2000*b*), and an average of 35% following rotation breaks and/or soil fumigation, there were expectations of potential yield increases of 85% in the Australian sugar industry if both HDP and crop rotation were adopted. There were therefore clear imperatives to investigate whether the responses to HDP and to removing soil biological constraints on soil biota were additive.

In this paper, we report results from experiments where row spacing and planting density were varied in fumigated and non-fumigated sugarcane land. The studies were conducted so as to deliberately exclude harvesting and haul-out machinery, thus avoiding any confounding of growth differences with machinery damage to the sugarcane plant during field operations.

Materials and methods

Experiment details

Two experiments were carried out under different conditions in sugarcane-growing regions of coastal Queensland, Australia. They were planted on 16 September 1999 on a Red Chromosol at Mackay (21°10′S, 149°5′E) and on 13 March 2000 on a Red Ferrosol at Bundaberg (24°51′S, 152°24′E) (Isbell 1996). The previous crop at both sites was sugarcane. Both experiments were terminated after the plant crop was harvested, 10 and 15 months after planting at Mackay and Bundaberg, respectively. Rainfall and temperature data for the growing period of each experiment are shown in Table 1. The Mackay

Table 1. Monthly rainfall (mm) and average daily maximum and minimum temperature (°C) for each month between September 1999 and July 2000 at Mackay and March 2000 and June 2001 at Bundaberg

Mackay				Bundaberg			
Month	Rain	Max. temp.	Min. temp.	Month	Rain	Max. temp.	Min. temp.
Sept. 1999	24	26.6	14.6	Mar. 2000	10	29	19.4
Oct.	5	29.9	17.2	Apr.	35	26.8	17.8
Nov.	176	29.7	19.4	May	88	24.3	13.9
Dec.	169	28.8	19.9	June	59	21.8	10.5
Jan. 2000	40	31	20.7	July	11	22.2	7.7
Feb.	893	28.4	22.5	Aug.	11	23.9	9.4
Mar.	36	29.7	20.6	Sept.	–	25.8	12
Apr.	494	27.9	19.3	Oct.	176	26.4	15.9
May	106	26.1	16.1	Nov.	156	26.4	17.8
June	15	23	11.5	Dec.	73	28.9	19.3
July	8	24.5	7.8	Jan. 2001	90	29.1	19.9
				Feb.	133	29	20
				Mar.	89	30.3	21
				Apr.	46	26.9	16.6
				May	32	25.1	12.7
				June	3	23.8	11.5
Total		1966				1012	

experiment was only irrigated twice using a water winch (spray irrigation) during the early crop establishment period, after which it was entirely rain grown and received very little rainfall in the latter part of the growing period. The amount of water applied with each irrigation was 38 mm. By contrast the Bundaberg experiment was fully trickle irrigated throughout growth, with the soil being restored to field capacity after every 40 mm nett class A pan evaporation. This generally resulted in irrigating for 6 h every 5–7 days during periods of rapid crop growth in spring and summer and less during the winter period.

In each experiment, treatments involved fumigation (fumigated with methyl bromide under plastic covers or not fumigated), low and high planting densities (27 000 or 81 000 two-eyed setts/ha), and inter-row spacings of 0.5 m or 1.5 m. The Bundaberg experiment included two cultivars, Q124 and Q155, while only one cultivar (Q117) was used in Mackay.

The experimental design was a 2^3 factorial for all combinations of fumigation, density, and row spacing in the Mackay experiment. At Bundaberg the use of a commercial soil-fumigation rig necessitated a split-plot design, with fumigation treatments as main plots and subplots consisting of all combinations of row spacing, density, and cultivar randomised within each main plot. There were 3 replications in each experiment. Plots in each experiment were 9 m wide and consisted of 6 by 1.5 m rows and 18 by 0.5 m rows. Plot length was 8 m and 15 m at Mackay and Bundaberg, respectively.

Land was prepared by ploughing, ripping, and rotary hoeing. After land preparation, all planting, maintenance, and harvesting operations were carried out by hand to ensure that responses were not confounded by the operation of heavy machinery. At Mackay, plots designated for fumigation were covered with black plastic and gaseous methyl bromide was applied 1 week before planting through trickle tape under the plastic at 90 g/m^2. The plastic was removed 3 days after fumigation. The same rate of methyl bromide was used at Bundaberg, but it was applied with a commercial applicator to a depth of 100 mm. Plots were not covered with plastic in Bundaberg.

Fertiliser was hand applied to all plots and incorporated before soil fumigation and subsequent planting. The Mackay experiment received 50 kg N/ha, 20 kg P/ha, and 100 kg K/ha as ammonium nitrate, single superphosphate, and muriate of potash, respectively. The Bundaberg experiment received 1000 kg/ha of a compound fertiliser that supplied 100 kg N/ha, 80 kg P/ha, 250 kg K/ha, and 37 kg S/ha. Additional fertiliser was also applied during crop growth. At Mackay, additional nitrogen as ammonium nitrate was surface applied at 50 kg N/ha on 11 November (56 days after planting, DAP) and 100 kg N/ha on 13 December (88 DAP), providing a total of 200 kg N/ha to the crop. The Bundaberg experiment received additional nitrogen and phosphorus on 8 occasions via the trickle irrigation system. This amounted to 120 kg N/ha as urea and mon-ammonium phosphate (MAP) and 40 kg P/ha as MAP, making a total of 220 kg N/ha. The additional P was needed to overcome transitory phosphorus deficiency noted in the fumigated plots in early September. The deficiency was transient and was possibly due to the negative effects of fumigation on populations of vesicular arbuscular mycorhizzae (VAM).

After initial fertiliser application and incorporation, 2-eyed setts (approx. 25 cm in length) of each cultivar were hand-cut, dipped in a mixture of Shirtan® fungicide, and hand-planted in furrows. Sett populations of 27 000 and 81 000/ha in 0.5- and 1.5-m rows were achieved by the following planting procedure. In 1.5-m rows, 27 000 setts/ha were planted by placing setts end on end, while for 81 000 setts/ha, setts were placed end on end with 3 setts side by side. In 0.5-m rows, setts were planted end on end for 81 000 setts/ha, while each sett had a 2-sett gap to the next sett in the treatments planted at 27 000 setts/ha. A planting density of 27 000 setts/ha used ~5 t/ha of seed cane. Immediately after planting, both experiments were sprayed with herbicide for weed control and then irrigated.

Measurements and data collection

Immediately after crop establishment, 15-m^2 datum areas were permanently pegged in the centre rows in each plot. These consisted of 5-m lengths of either 6 rows × 0.5-m inter-rows or 2 rows × 1.5-m inter-rows in each plot. All datum areas were bordered by a minimum of 1.5 m on all sides. These datum areas were used to measure crop establishment (number of primary shoots that emerged), sequential stalk counts, and final cane harvest. Crop establishment was a somewhat arbitrary measurement due to the dual effects of varying degrees of eye dormancy and tiller production. In some instances, tillers were emerging from some setts at a similar time as the more dormant eyes on other setts were producing their primary shoots. We thus selected the time immediately before rapid tiller development as the time when primary shoot emergence was complete, and at both sites this occurred around 42 DAP.

Two interim harvests were carried out at Bundaberg at 60 and 192 DAP. On each occasion a 4.5-m^2 area was harvested from each plot from outside the 15-m^2 datum area. Shoots/stalks were counted, fresh weight was determined, and a subsample was dried at 70°C for 72 h to allow dry weight determination. The plot size was too small to permit destructive sampling at Mackay.

Light interception measurements were taken between planting and full canopy development at Bundaberg. Daily incident shortwave radiation was measured with an integrating pyranometer located at the site. On 4 occasions between planting and full canopy development the incident photosynthetic photon flux density (PPFD) above each plot, and PPFD transmitted to ground level below each canopy, were measured around solar noon on clear days. Measurements were made using a line quantum sensor (LI 191SB, LI-COR, Lincoln, NE, USA). The sensor length was varied to match plot row spacing, and was inserted 5 times across the inner rows of each plot on each occasion. Values of fractional interception were calculated for each sampling date, with average interception for the interval between sampling dates calculated as the arithmetic mean of successive measurements. The amount of intercepted radiation was calculated from the product of cumulative incident radiation between sample dates and the fractional interception during the same period. Intermittent cloud cover during the first half of the growing season thwarted attempts at making similar measurements at Mackay.

At final harvest, stalks from the 15-m^2 datum areas were cut at ground level, counted, and weighed. Six stalk samples were set aside from each plot to determine commercially recoverable sugar (CCS) using the small-mill technique (BSES 1984). A subsample of the total harvest biomass (15–30 stalks) was selected at random and separated into millable stalk (harvestable cane) and tops (immature stalk and leaves). The millable stalk and tops were separated between nodes subtending the fifth and sixth youngest leaves. The fresh weight of both portions was recorded and the fraction of the total weight present as millable stalk was used to calculate cane yield from the total biomass. Portions of stalk and tops were mulched, weighed, dried at 70°C for 72 h and re-weighed to allow calculation of dry biomass.

All data were analysed using standard analysis of variance techniques in the GENSTAT statistical package.

Results

Crop establishment

There were significant row spacing and density effects on crop establishment in both experiments. A greater percentage of eyes produced primary shoots with 0.5-m rows and low density at Mackay and with 0.5-m rows at Bundaberg. There was also a row spacing × density interaction at Bundaberg with similar establishment for high and low density in 0.5-m rows but better establishment for low density in 1.5-m rows (Table 2). The worst establishment was recorded in 1.5-m rows with high-density planting in both experiments. The reason for the poor establishment in this treatment is not known but it may be associated with the close proximity of setts (3 setts side by side) promoting sett diseases (R. C. Magarey, pers. comm.).

Fumigation improved establishment at Bundaberg (79% *v.* 61%, $P < 0.05$), mainly through improving establishment of the high-density planting in 0.5-m rows to similar levels as the low-density planting in 0.5-m rows (86% and 90% for high and low density, respectively). There was no significant effect of fumigation at Mackay, although similar trends to those recorded at Bundaberg were apparent. Cultivar differences were significant ($P < 0.05$) in the Bundaberg experiment, but these were relatively minor (67% for Q124, 72% for Q155).

Table 2. Crop establishment (% eyes planted) for cane planted at two row spacings (0.5 and 1.5 m), and low (LD) and high (HD) planting densities at Bundaberg and Mackay

For each experiment, data are the mean of both fumigation treatments and the two cultivars at Bundaberg

Site	Row spacing	HD	LD
Mackay	0.5	58	84
	1.5	45	54
		n.s.d.	
Bundaberg	0.5	79	77
	1.5	55	69
		$P < 0.05$, l.s.d. 5% = 6.8	

Tillering and shoot development

Tillering and secondary shoot development commenced by 42 DAP at both sites, although the subsequent rate of shoot development was considerably faster at Mackay (Fig. 1) where the crop was growing into summer, than at Bundaberg where early growth was into autumn and winter (Figs 2, 3). As a consequence of these seasonal differences, maximum shoot populations were recorded at Mackay around 104 DAP, but not until around 222 DAP at Bundaberg. After this, shoot loss occurred quite rapidly and was more pronounced in the treatments with higher maximum shoot populations, e.g. fumigated, high planting density, narrow rows (Figs 1–3). These differential rates of tiller loss resulted in the magnitude of the differences between treatments being substantially reduced later in the growing period in both experiments (Table 3, Figs 1–3).

Fumigation, narrow rows, and high planting densities resulted in greater shoot populations at both sites, while Q155 produced more shoots than Q124 at Bundaberg (Table 3). However, the fumigation response at Bundaberg was only significant for counts made before achieving maximum shoot populations (before 222 DAP), while at Mackay there were higher shoot populations with fumigation at all sample dates. Row spacing and density effects remained significant throughout crop growth at both sites, although the actual numerical differences between treatments reduced substantially as the growing period progressed (Table 3). Shoot/stalk populations recorded at the final count were similar to those at final harvest at both Mackay and Bundaberg.

Radiation interception

High planting densities and narrow rows enhanced the interception of radiation at Bundaberg early in the growing

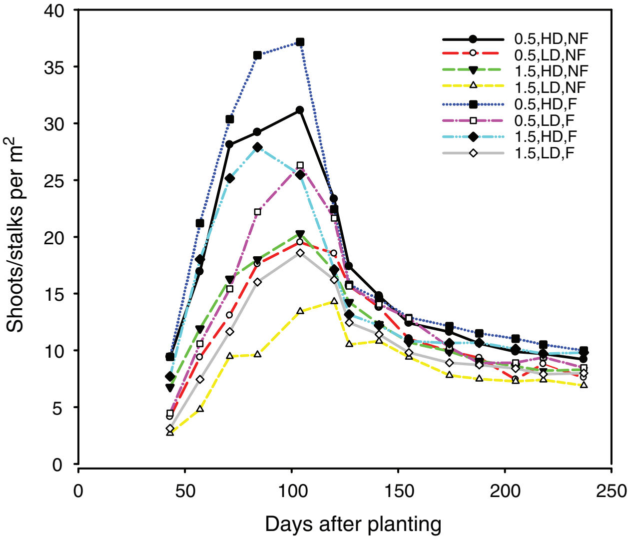

Fig. 1. Temporal shoot/stalk development (shoots/stalks per m^2) for two row spacings (0.5, 1.5 m), low (LD) and high (HD) planting densities in fumigated (F) and non-fumigated (NF) soil with cv. Q117 at Mackay. l.s.d. 5% for each sample date = 2.44 (43 DAP), 5.87, 5.81, 5.53, 4.57, 5.51, 1.84, 1.97, 1.57, 1.13, 1.49, 1.34, 1.71, 1.44 (237 DAP).

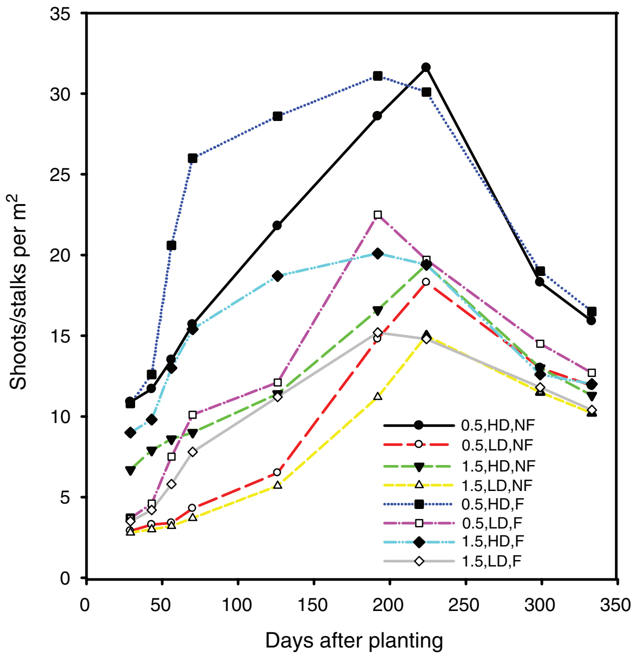

Fig. 2. Temporal shoot/stalk development (shoots/stalks per m^2) for two row spacings (0.5, 1.5 m), low (LD) and high (HD) planting densities in fumigated (F) and non-fumigated (NF) soil with cv. Q124 at Bundaberg. l.s.d. 5% for each sample date = 1.02 (29 DAP), 1.32, 2.08, 2.18, 5.2, 3.3, 3.75, 2.26 (299 DAP).

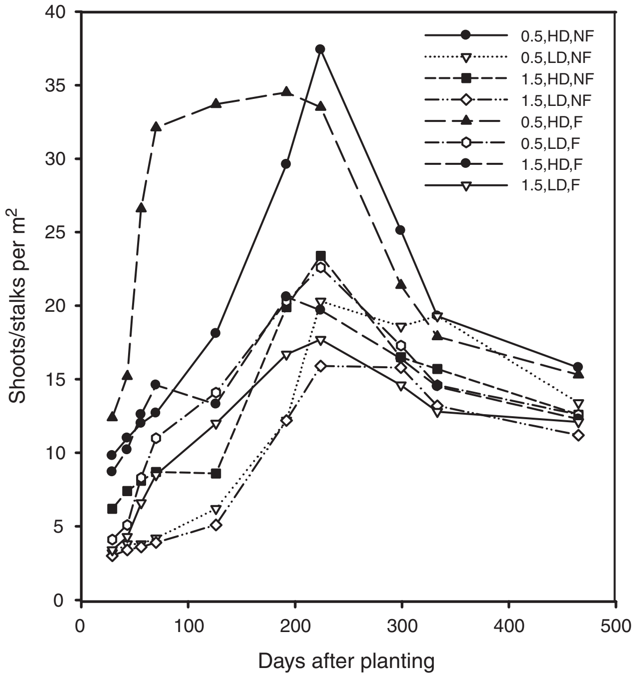

Fig. 3. Temporal shoot/stalk development (shoots/stalks per m^2) for two row spacings (0.5, 1.5 m), low (LD) and high (HD) planting densities in fumigated (F) and non-fumigated (NF) soil with cv. Q155 at Bundaberg. l.s.d. 5% for each sample date = 1.02 (29 DAP), 1.32, 2.08, 2.18, 5.2, 3.3, 3.75, 2.26 (299 DAP).

season (Fig. 4). However, by 300 DAP when light interception measurements were halted due to difficulties in access caused by lodging of the crop canopy, all treatments were intercepting 85–95% of incident radiation (Fig. 4). Assuming that radiation interception was similar for all treatments after this time, the radiation intercepted for the duration of the crop (465 days) is shown in Table 4. These data show that in the non-fumigated plots, only 11% more incident radiation was intercepted by the 0.5-m high-density planting than the 1.5-m high-density planting, while with low-density planting, each row spacing intercepted similar amounts of radiation (Table 4). This suggests that on the basis of radiation intercepted, the maximum potential yield increase with narrow rows in the absence of fumigation should have been 11%. However, a comparison between fumigated 0.5-m high-density and non-fumigated 1.5-m low-density planting showed that the former intercepted 41% more incident radiation, with much of this interception occurring early in crop growth (Fig. 4). Further, the amount of radiation intercepted for low-density fumigated and high-density non-fumigated planting was remarkably similar for the wide rows (5176 MJ/m^2 *v.* 5215 MJ/m^2, respectively) and the narrow rows (5561 MJ/m^2 *v.* 5723 MJ/m^2, respectively), indicating that fumigating the soil can produce equivalent canopies with low planting density to those achieved with high planting density in the absence of fumigation.

Seasonal biomass production

Early crop growth (60 and 192 DAP) was enhanced by fumigation, narrow rows, and high density, and was greater in Q124 than in Q155 (Table 4). Conversely, by the final harvest (465 DAP) the only significant dry matter response ($P < 0.05$) was more biomass being produced in the low-density planting, the opposite of the earlier sample dates, although there was still a suggestion of a positive response to fumigation ($P = 0.08$). There was also a highly significant ($P < 0.01$) fumigation × cultivar interaction at the final harvest, which was not evident at 60 or 192 DAP. This response was due to more biomass being produced by Q155 than Q124 in fumigated treatments (56.6 *v.* 50.5 t/ha), but there was no significant difference between the cultivars without fumigation (48.4 *v.* 51.1 t/ha). The significant interaction was mainly due to severe lodging occurring in Q124 in fumigated soil with high planting density. In earlier samples, Q124 easily produced more biomass than Q155 in both fumigated and non-fumigated soil (Table 4). The very limited treatment differences in biomass production recorded at the end of the season were consistent with the narrowing in the difference in stalk numbers (Table 2).

Cane yield and yield components

Cane yield was significantly increased by fumigation at both Bundaberg ($P < 0.05$) and Mackay ($P < 0.001$) (Table 5*b*). However, there was no significant response to row spacing and no overall response to planting density in the non-fumigated soil, although there was a trend for increasing yield with increasing density in the non-fumigated soil at Mackay (Table 5*a*). Further, there was a cultivar × density interaction in the non-fumigated soil at Bundaberg where the yield of

Table 3. Shoots/stalks per m^2 measured at days after planting (DAP) that represented peak shoot number (PSN), final stalk number (FSN), and mid-way (MWSN) between, for cane planted at two row spacings (0.5 and 1.5 m), low (LD) and high (HD) planting densities in fumigated (F) or non-fumigated (NF) soil at Bundaberg and Mackay

Cultivars Q124 and Q155 were included at Bundaberg and Q117 at Mackay

	PSN		MWSN		FSN	
			Bundaberg			
	222 DAP		333 DAP		465 DAP	
	NF	F	NF	F	NF	F
Q124						
0.5 HD	31.6	30.1	15.9	16.5	14.4	11.2
0.5 LD	18.3	19.7	11.9	12.7	10.1	10.6
1.5 HD	19.4	19.4	11.3	12	10.4	10.6
1.5 LD	15	14.8	10.2	10.4	8.9	9.8
Q124 Mean	21.1	21	12.3	12.9	11	10.5
Q155						
0.5 HD	37.4	33.5	19.3	17.9	15.8	15.3
0.5 LD	20.3	22.6	15.7	14.6	13.4	12.6
1.5 HD	23.3	19.7	15	14.5	12.6	12.3
1.5 LD	15.9	17.7	13.2	12.8	11.2	12.1
Q155 Mean	24.2	23.4	15.8	15	13.3	13.1
Fumigation means	22.7	22.2	14.1	13.9	12.1	11.8
l.s.d. 5%	n.s.d.		n.s.d.		n.s.d.	
Row space means	26.7 (0.5)	18.2 (1.5)	15.6	12.4	12.9	11
l.s.d. 5%	1.41 ($P < 0.001$)		0.65 ($P < 0.001$)		0.71 ($P < 0.001$)	
Density means	26.8 (HD)	18.0 (LD)	15.3	12.7	12.8	11.1
l.s.d. 5%	1.41 ($P < 0.001$)		0.65 ($P < 0.001$)		0.71 ($P < 0.001$)	
Cultivar means	21.0 (Q124)	23.8 (Q155)	12.6	15.4	10.8	13.2
l.s.d. 5%	1.41 ($P < 0.001$)		0.65 ($P < 0.001$)		0.71 ($P < 0.001$)	
			Mackay			
	104 DAP		237 DAP		306 DAP	
	NF	F	NF	F	NF	F
Q117						
0.5 HD	31.1	37.2	9.2	10	9.6	10.9
0.5 LD	19.5	26.3	7.6	8.5	8	10
1.5 HD	20.3	25.5	8.3	9.8	8.3	9.9
1.5 LD	13.4	18.6	6.9	7.9	6.7	8.1
Fumigation means	21.1	26.9	8	9	8.2	9.7
l.s.d. 5%	2.75 ($P < 0.001$)		0.72 ($P = 0.009$)		0.92 ($P = 0.003$)	
Row space means	28.5 (0.05)	19.4 (1.5)	8.8	8.2	9.6	8.3
l.s.d. 5%	1.27 ($P < 0.001$)		n.s.d.		0.92 ($P < 0.01$)	
Density means	28.5 (HD)	19.4 (LD)	9.3	7.7	9.7	8.2
l.s.d. 5%	1.27 ($P < 0.001$)		0.72 ($P < 0.001$)		0.92 ($P = 0.004$)	

Q155 increased while that of Q124 decreased with increasing planting density (Table 5*a*). When fumigation was included there was an overall trend for any responses to high density to be substantially reduced and/or completely negated. For example, at Mackay a 24% response to high density with no fumigation was reduced to 7% with fumigation, while with Q155 at Bundaberg a 17% response to high density without fumigation became a –9% response with fumigation (Table 5*b*).

There was a highly significant ($P < 0.001$) fumigation × density × cultivar response at Bundaberg. This reflected yield increases with fumigation regardless of planting density in Q155 but not with Q124. This interaction was surprising given the large positive responses to fumigation in both cultivars, and particularly Q124, with earlier biomass samplings (Table 6). In fact, the samplings at 60 and 192 DAP indicated that both cultivars were responding positively to fumigation, with Q124 growing at a faster rate than Q155 (Table 6). However, both cultivars had similar biomass at final harvest (465 DAP), indicating that Q155 must have produced more biomass than Q124 during the latter part of the growing period. This change in relative growth rate between the two cultivars was probably more associated with biomass loss through lodging in Q124 than enhanced biomass production in Q155 (Singh *et al*. 2002).

In this experiment, Q124 lodged more extensively than Q155. While only the high-density fumigated treatment lodged late in the growing period with Q155, all Q124 treatments, except for low-density non-fumigated, lodged in the order of high-density fumigated, earlier than high-density non-fumigated, earlier than low-density fumigated.

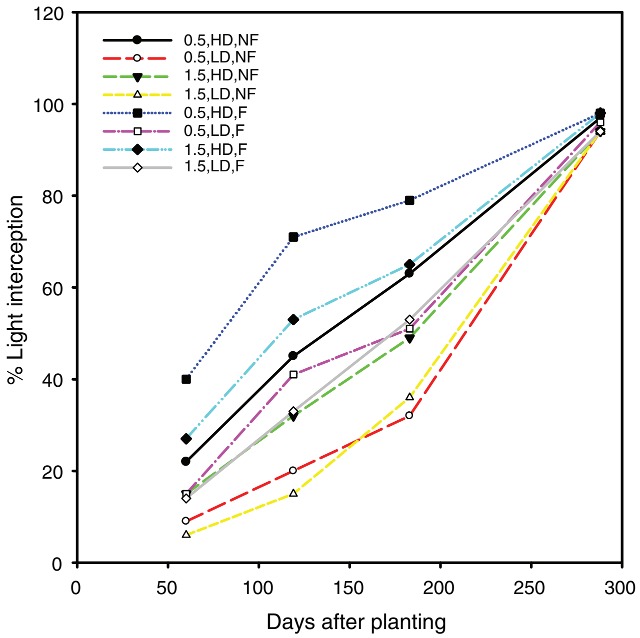

Fig. 4. Percent light intercepted (photosynthetic photon flux density) by two row spacings (0.5, 1.5 m), low (LD) and high (HD) planting densities in fumigated (F) and non-fumigated (NF) soil for cv. Q124 at Bundaberg. l.s.d. 5% for each sample date = 6.9% (May 12), 9.4% (July 10), 10.2% (Sept. 12), and 2.0% (Jan. 5).

The late lodging in Q155 resulted in only small effects on crop yield, explaining the persistence of the fumigation response through to harvest with high-density planting in this cultivar. However, in Q124 the significantly lower yields with high density in non-fumigated soil, and the lack of any significant advantage of high-density planting in fumigated soil, probably reflect the confounding effects of differences in timing and degree of lodging. Thus it could have been expected that the most substantial yield reduction due to lodging should have been with the high-density, fumigated treatments of Q124. This did not occur as high-density, fumigated Q124 out-yielded high-density, non-fumigated Q124 (150 *v.* 130 t/ha, Table 5*b*). A possible explanation for these somewhat surprising responses may lie with the reported ability of early lodging crops (Q124, fumigated) to recommence biomass accumulation after a period of re-orientation of photosynthetic leaf area (Singh *et al.* 2002). This tendency to re-commence biomass accumulation may have contributed to the higher yield of Q124 in fumigated than in non-fumigated soil with high density. Regardless, the overall final yield response to fumigation was 8, 20, and 48% for Q124, Q155, and Q117 (which did not lodge), respectively, which could be related to the degree of lodging in each cultivar.

Table 4. Cumulative radiation intercepted (MJ/m^2) between planting and final harvest (465 DAP) in the Bundaberg experiment for two row spacings (0.5 and 1.5 m), low (LD) and high (HD) planting densities in fumigated (F) and non-fumigated (NF) soil

Data are means for cvv. Q124 and Q155

Fumigation	Row spacing and density			
	1.5 LD	1.5 HD	0.5 LD	0.5 HD
NF	4708	5215	4656	5723
F	5176	5886	5561	6625
Signif. effects: Fum. ($P < 0.005$), Dens. ($P < 0.001$), Row sp. ($P < 0.001$), Dens. × Row sp. ($P < 0.004$). l.s.d. 5% = 284 (Fum. * Dens. * Row sp.)				
	Relative (%) to 1.5, LD, NF			
NF	100	111	99	122
F	110	125	118	141

Cane yield responses were examined in relation to effects of treatments on the key yield components (stalk number and stalk weight), with different responses recorded between cultivars and experiments. Fumigation had no significant effect on stalk number or stalk weight at Bundaberg, but at Mackay, fumigation significantly increased both stalk number and stalk weight (Table 7). In both experiments, stalk number and stalk weight varied with row spacing and planting density, and also with cultivar at Bundaberg. Low stalk numbers were

Table 5. The interaction of (*a*) row spacing (0.5 and 1.5 m) and low (LD) and high (HD) planting densities in non-fumigated soil and (*b*) planting densities and fumigated (F) and non-fumigated (NF) soil for cane yield (t/ha) in cvv. Q124 and Q155 at Bundaberg and Q117 at Mackay

Data in *b* are averaged across row spacing

(*a*) Site	Cane yield (t/ha)							
	Row spacing		Density		Cultivar × Density			
	1.5 m	0.5 m	HD	LD	Q124		Q155	
					HD	LD	HD	LD
Mackay	56	65	67	54	130	152	129	110
	n.s.d.		n.s.d.					
Bundaberg	131	130	130	131				
	n.s.d.		n.s.d.		$P < 0.001$, l.s.d. 5% = 13			

(*b*)	Q124 (Bundaberg)		Q155 (Bundaberg)		Q117 (Mackay)	
	HD	LD	HD	LD	HD	LD
F	150	154 (0%)	147	161 (–9%)	92	86 (7%)
NF	130	152 (–14%)	129	110 (17%)	67	54 (24%)
l.s.d. 5%	$P < 0.001$, l.s.d. 5% = 15				n.s.d.	

Table 6. Total biomass (kg/ha or t/ha dry weight) at 60, 192, and 465 days after planting (DAP) for two row spacings (0.5 and 1.5 m) and low (LD) and high (HD) planting densities in fumigated (F) and non-fumigated (NF) soil at Bundaberg

Cultivars are Q124 and Q155

	Dry biomass					
	60 DAP (kg/ha)		192 DAP (kg/ha)		465 DAP (t/ha)	
	NF	F	NF	F	NF	F
Q124						
0.5 HD	572	1051	3454	4582	45.95	49.84
0.5 LD	155	273	1484	3021	54.52	50.37
1.5 HD	356	673	2503	3792	49.77	50.56
1.5 LD	142	277	1293	2077	54.21	51.07
Q124 Mean	306	568	2183	3368	51.11	50.46
Q155						
0.5 HD	398	865	2128	4490	48.94	56.89
0.5 LD	125	279	811	1783	49.32	59.31
1.5 HD	238	502	1241	2984	45.61	49.92
1.5 LD	130	222	826	1841	49.6	60.41
Q155 Mean	223	467	1252	2775	48.37	56.63
Fumigation means	265	518	1717	3071	49.74	53.54
l.s.d. 5%	225 ($P < 0.05$)		846 ($P < 0.05$)		n.s.d. ($P = 0.08$)	
Row space means	465 (0.5)	318 (1.5)	2719 (0.5)	2070 (1.5)	51.89 (0.5)	51.39 (1.5)
l.s.d. 5%	59 ($P < 0.001$)		218 ($P < 0.001$)		n.s.d.	
Density means	582 (HD)	200 (LD)	3147 (HD)	1642 (LD)	49.68 (HD)	53.60 (LD)
l.s.d. 5%	59 ($P < 0.001$)		218 ($P < 0.001$)		3.15 ($P < 0.05$)	
Cultivar means	437 (Q124)	345 (Q155)	2776	2013	50.78 (Q124)	52.50 (Q155)
l.s.d. 5%	59 ($P < 0.01$)		218 ($P < 0.001$)		n.s.d.	

Table 7. Stalks/m^2 and individual stalk weight (ISW) kg for two row spacings (0.5 and 1.5 m), low (LD) and high (HD) planting densities in fumigated (F) and non-fumigated (NF) soil at Bundaberg and Mackay

Cultivars Q124 and Q155 were included at Bundaberg and Q117 at Mackay

	Stalks/m^2		ISW kg	
	NF	F	NF	F
	Bundaberg Q124			
0.5 HD	14.4	11.2	0.89	1.32
0.5 LD	10.1	10.6	1.48	1.46
1.5 HD	10.4	10.6	1.29	1.47
1.5 LD	8.9	9.8	1.75	1.6
Q124 Mean	11	10.5	1.35	1.46
	Bundaberg Q155			
0.5 HD	15.8	15.3	0.87	1.04
0.5 LD	13.4	12.6	0.94	1.25
1.5 HD	12.6	12.3	0.96	1.1
1.5 LD	11.2	12.1	1.17	1.35
Q155 Mean	13.3	13.1	0.99	1.19
Fumigation means	12.1	11.8	1.17	1.32
l.s.d. 5%	n.s.d.		n.s.d. ($P = 0.07$)	
Row space means	12.92 (0.5)	10.55 (1.5)	1.16 (0.5)	1.34 (1.5)
l.s.d. 5%	0.71 ($P < 0.001$)		0.08 ($P < 0.001$)	
Density means	12.82 (HD)	11.09 (LD)	1.12 (HD)	1.37 (LD)
l.s.d. 5%	0.71 ($P < 0.001$)		0.08 ($P < 0.001$)	
Cultivar means	10.75 (Q124)	13.17 (Q155)	1.41 (Q124)	1.09 (Q155)
l.s.d. 5%	0.71 ($P < 0.001$)		0.08 ($P < 0.001$)	

compensated by larger stalks and *vice versa* at Bundaberg, but at Mackay, stalk weight increases in treatments with low stalk numbers were only recorded when the soil had been fumigated (Table 5). This difference in stalk number/stalk weight relationship between the two experiments was probably associated with growing conditions. Bundaberg was fully irrigated throughout crop growth, had a much longer stalk filling period, and adequate resources to fill stalks. By contrast the Mackay experiment was only irrigated during crop establishment, and had a shorter stalk filling period which probably suffered from water stress as the Mackay experiment received only 130 mm of rain in the last 3 months (Table 1).

CCS and sugar yield

Fumigation decreased CCS in both experiments (Table 8) but the positive effect of fumigation on cane yield resulted in fumigation having no effect on sugar yield at Bundaberg and increasing sugar yield at Mackay. Neither row spacing nor density had an effect on CCS or sugar yield at Bundaberg and the reduction in sugar yield with low density in Mackay was associated with the difference in cane yield between densities in the non-fumigated treatments.

Discussion

The experiments discussed in this paper were conducted to determine whether cane productivity benefits associated with removing biotic constraints from sugarcane-growing soils were additive to those reported for the adoption of HDP (i.e. narrow row spacings and high planting density within the row). Early shoot counts at both sites (Figs 1–3), early PAR interception (Fig. 4), and early biomass samples at Bundaberg (Table 6) suggested that the responses may well have been additive, as all of these parameters were highest in

Table 8. Commercial cane sugar (CCS) (%) and sugar yield (t/ha) for two row spacings (0.5 and 1.5 m), low (LD) and high (HD) planting densities in fumigated (F) and non-fumigated (NF) soil at Bundaberg and Mackay

Cultivars Q124 and Q155 were included at Bundaberg and Q117 at Mackay

	CCS		Sugar yield (t/ha)	
	NF	F	NF	F
		Bundaberg Q124		
0.5 HD	14.23	11.64	17.95	17.22
0.5 LD	14.78	11.89	22.04	17.53
1.5 HD	14.99	11.76	20.11	16.71
1.5 LD	12.61	13.64	20.71	21.69
Q124 Mean	14.15	12.23	20.2	18.29
		Bundaberg Q155		
0.5 HD	16.32	14.47	22.47	22.97
0.5 LD	15.92	13.46	20.17	21.75
1.5 HD	16.39	13.82	19.74	18.73
1.5 LD	14.76	14.67	19.52	23.45
Q155 Mean	15.85	14.1	20.47	21.85
Fumigation means	15	13.17	20.34	20.07
l.s.d. 5%	1.37 ($P < 0.05$)		n.s.d.	
Row space means	14.09 (0.5)	14.08 (1.5)	20.26 (0.5)	20.14 (1.5)
l.s.d. 5%	n.s.d.		n.s.d.	
Density means	14.20 (HD)	13.97 (LD)	19.49 (HD)	20.92 (LD)
l.s.d. 5%	n.s.d.		n.s.d.	
Cultivar means	13.19 (Q124)	14.98 (Q155)	19.24 (Q124)	21.16 (Q155)
l.s.d. 5%	0.62 ($P < 0.001$)		1.85 ($P < 0.05$)	
		Mackay Q117		
0.5 HD	15.36	13.22	10.89	11.88
0.5 LD	14.92	13.37	8.61	9.93
1.5 HD	15.26	14.41	10.68	13.45
1.5 LD	15.68	13.29	7.73	11.33
Fumigation means	15.3	13.57	9.48	11.65
l.s.d. 5%	0.51 ($P < 0.001$)		1.62 ($P = 0.01$)	
Row space means	14.22 (0.5)	14.66 (1.5)	10.33 (0.5)	10.80 (1.5)
l.s.d. 5%	n.s.d. ($P = 0.08$)		n.s.d.	
Density means	14.56 (HD)	14.32 (LD)	11.73 (HD)	9.40 (LD)
l.s.d. 5%	n.s.d.		1.62 ($P < 0.01$)	

high-density narrow rows and were further enhanced with fumigation. However, the gap between fumigated and non-fumigated treatments, wide and narrow rows, and high and low density tended to decrease as the season progressed (e.g. shoot/stalk counts, Table 3), and despite greater cumulative PAR interception (Table 4), final biomass (Table 6) and cane yields (Table 5) showed no evidence of additivity of soil health and HDP benefits. In fact, data suggested that there was an interaction between responses to soil health and HDP such that most, if not all, of the supposed HDP benefits could be achieved in standard planting arrangements if soil health was improved.

At least part of the erosion of the early season advantages of combining HDP and improved soil health may lie in the shoot/stalk death associated with the development of intense inter-plant competition in dense, vigorous canopies. Large increases in early shoot production in response to increases in planting density and reduction in row spacing had little effect on final stalk number, as a large majority of these shoots were lost (Figs 1–3) and so made little contribution to ultimate yield. It is impossible to say from these experiments whether the assimilate in these dead shoots was lost, translocated to surviving shoots, or some combination of both. However, it would seem that if cane yields are to be improved with higher planting densities, it will be dependent on cultivars maintaining higher shoot numbers and converting a higher percentage of shoots into stalks by harvest.

In the cultivars tested in these experiments, and probably the majority of current commercially available cultivars, the sequential development of tillers appears to be operating against any increase in conversion of shoots into stalks as later emerging shoots are the ones that tend to be lost, probably due to within-stool competition. These later shed shoots may, at least temporarily, be using assimilates that could be better used filling earlier developing lower order tillers. Bell and Garside (2005) reviewed stalk density/stalk weight relationships using data from several experiments and concluded that the promotion of more primary and lower order tillers at the expense of higher order tillers may be an avenue to greater shoot retention and increased yields. It is possible that shoots that emerge at a similar time will grow at a similar rate and all will contribute substantially to final yield. This type of plant structure may better suit higher density planting. Our data, particularly those relating to shoot development and loss, tend to support that view, although further research on the relationship between temporal tiller development and cane yield is required.

The second factor contributing to the erosion of the apparent advantages of combining HDP and improved soil health may lie in the differential effects of lodging on biomass accumulation and apparent radiation-use efficiency. The 41% increase in radiation interception by the fumigated narrow row/high density treatment compared with the non-fumigated wide row/low density in this experiment (Table 4) did not result in any increase in cane yield (148 *v.* 155 t/ha, respectively; data not shown in Table 5). The absence of response was most probably related to the earlier and more extensive lodging evident in the high-density treatments. Singh *et al.* (2002) reported a negative effect of lodging on biomass accumulation in other studies. Further, the lack of response in biomass accumulation to fumigation and higher density planting (Table 6) suggests a significant reduction in radiation-use efficiency in those treatments. However, it is worth noting that the cumulative PAR interception data (Table 4) were really estimates of potential interception assuming that canopy cover remained unchanged from 300 DAP until maturity, because lodging prevented access to the inner parts of the plots to undertake further measurement. It may well have been that the earlier lodging in the fumigated higher density planting of Q124 reduced canopy interception of incident PAR (either in total, or by photosynthetically capable leaf area rather than lodged stalks) during these later growth stages, thus eroding the apparent advantage in cumulative PAR interception.

Bull and Bull (2000*a*, 2000*b*) suggested that the cane yield increase of 50% that they measured in non-fumigated soil with 0.5-m rows and high-density planting compared with standard 1.5-m rows and lower density planting was probably due to comparable increases in cumulative radiation interception associated with quicker and more complete canopy closure. Our data for non-fumigated soil do not support this suggestion. If all other inputs are equal, our Bundaberg data indicate that the maximum potential cane yield increase due to increased radiation interception with high density and narrow rows will be of the order of 10% in a non-fumigated situation (Table 4), although the relative advantage may have been greater if the crop duration were shortened to 10 months like in the Mackay study. At Bundaberg it was only when soil health was addressed through soil fumigation that potential cumulative radiation interception, and thus yield potential, could be increased by a similar margin (41%, Table 4) to that reported by Bull and Bull (2000*a*, 2000*b*) with high density and narrow rows. However, as discussed above, lodging may well have reduced this potential advantage.

If benefits are to be obtained from high-density planting there would seem to be a need for cultivars that are better able to take advantage of more rapid and complete canopy closure by remaining erect throughout the growing period. In this respect, Q155 appeared to be a more suitable cultivar for higher density planting than Q124, although whether this observation is consistent across locations requires further study. Regardless, the data here indicate that Q124 and Q155 behaved quite differently under the same agronomic conditions in the Bundaberg study and this suggests that varying growth habit between different cultivars may affect the response to row spacing and planting density. This issue is addressed further in the third paper of this series (Garside and Bell 2009).

The apparent contrast between the response to narrower rows and higher planting densities in non-fumigated soil at Mackay (increased yield with higher density) and Bundaberg (no response) may well be related to differences in crop duration and late-season constraints to biomass accumulation. Bell and Garside (2005) showed that low stalk numbers were often compensated by increased individual stalk weights, but this was dependent on a long enough stalk filling period during which sufficient biomass accumulation could accrue for that compensation to occur. At Mackay, the stalk filling period was short due to the early harvest (10 months), occurred during a period of relatively low rainfall (Table 1), and there was no irrigation available to optimise growth rates. Thus it was not surprising to see the increased stalk numbers with higher density (>40%) accompanied by no real compensation in individual stalk weight (Table 7). As a result, stalk number was the prime determinant of crop yield in non-fumigated soil at Mackay. By contrast, in the fully irrigated, long stalk filling period (15-month crop) at Bundaberg the increased stalk numbers with higher density in non-fumigated soil (60% and 40% greater for Q124 and Q155, respectively) were virtually completely compensated for by greater individual stalk weights in the lower density wide-row plantings (95% and 35% greater for Q124 and Q155, respectively).

This pattern of response to higher density in these experiments was consistent with the review by Irvine and Benda (1980) that indicated that responses to narrowing row spacing and increasing planting density were largely associated with relatively short-term (9–10 month) sugarcane crops. However, the reasons for the strong contrast with the findings of Bull (1975) and Bull and Bull (2000*a*, 2000*b*) are unclear, but the detail provided in Bull (1975) suggests that at least part of the reason for the apparently strong response to HDP may lie in the experimental methods (especially plot sizes) used in those earlier studies. Plots with dimensions of 4 m by 3 m (Bull 1975) provide little opportunity for well-buffered areas not affected by light, nutrients, and water from adjacent plot edges, and in wide (1.5 m) row spacings there would have been no guarded inner rows at all. Given the plasticity evident in both stalk numbers and individual stalk weights discussed above, the seemingly inadequate plot size to ensure an accurate reflection of inter-plant competition in each plant population may be part of the reason for the apparently large HDP responses.

The ability of soil fumigation/improved soil health to overcome any high-density advantages at Mackay (and produce no further gains at Bundaberg, Table 6) suggests that at least part of the yield benefits from HDP reported by Bull and Bull (2000*a*, 2000*b*) may have been due to overcoming poor growth per plant in response to poor soil health by increasing plant populations. Poor soil health and significant growth responses to soil fumigation have been reported across all districts of the Australian sugar industry (Magarey and Croft 1996), and so it was highly likely that the soils used in these HDP studies exhibited similar poor soil health characteristics.

Soil fumigation to improve soil health for sugarcane growth is ridiculously expensive, impractical, and not conducive to the development of sustainable sugarcane cropping systems. However, breaking the sugarcane monoculture does improve soil health (Stirling *et al*. 2001, 2002; Pankhurst *et al*. 2005) and can produce a similar quantum of yield responses as soil fumigation (Garside *et al*. 1999, 2000, 2002). Thus, results from our experiments that used soil fumigation are likely to be comparable with those in a sugarcane cropping system that involves rotation breaks to the sugarcane monoculture. Such a system is now being adopted in the Australian sugar industry (Garside *et al*. 2005) and there is increasing evidence that under this system the agronomic responses to varying density and row spacing are minor.

The significance of soil health in the whole row spacing/planting density issue cannot be underestimated. The results here show that if soil health is addressed, sugarcane, or at least the cultivars used in these experiments, posses a degree of physiological and environmental plasticity that permits similar yields to be achieved across a range of planting densities and row spacings. While there may be some disadvantages with such characteristics (the potential yield loss due to excessive tiller mortality discussed above) the major advantage is that it makes cultivars adaptable to a wide range of environmental conditions and allows manipulation of row spacing and planting density without major concerns about productivity decline as long as soil health is good.

The current row spacing used in the highly mechanised Australian sugar industry is 1.5 m, while harvesting and haul-out machinery has a wheel spacing of 1.8–1.9 m. These configurations do not permit controlled traffic to be adopted. On the other hand, growers have been reluctant to widen row spacing for fear of yield penalties. However, it is now emerging that the row spacing/wheel spacing mis-match is resulting in soil compaction, stool damage, and yield loss (Braunack and Peatey 1999; Garside 2004; Garside *et al*. 2008). The physiological and environmental plasticity demonstrated under conditions of good soil health in these experiments provides optimism that widening row spacing to accommodate controlled traffic may not necessarily result in a yield penalty. This issue is explored in the next paper in this series (Garside *et al*. 2009).

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