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Effect of plant density on grain yield and yield stability of sorghum hybrids differing in maturity

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Summary. The extent and significance of the maturity x density interaction in dryland grain sorghum, and its implications for yield stability, were examined for 3 hybrids over 6 locations. Site mean grain yield ranged from 0.44 to 4.96 t/ha. Early maturity was superior in environments truncated by water stress, while late maturity was superior in favourable environments. Mid-season maturity provided greater stability of grain yield. Maximum yield by each hybrid at each yield level did not differ significantly from yield at a density of 75 000 plants/ha. The highest grain yields should be obtained with plant densities of 50 000–100 000 plants/ha under rainfed conditions, where yield expectations range from 0 to 5.0 t/ha. The results demonstrate the stability of sorghum grain yield over a wide range of plant density and crop maturity. Regression analysis aided data presentation and interpretation.

Introduction

Grain sorghum (*Sorghum bicolor* (L.) Moench), a crop well adapted to semi-arid environments, is grown in areas of northern Australia in which seasonal water deficits are common. Plant spacing and crop maturity are 2 components of the cropping system that interact strongly with water supply. These factors influence mean plant size and the proportion of its final dry matter allocated to grain (Gardner and Gardner 1983).

Plant spacing has 2 components: (i) plant density, the number of plants/m^2; and (ii) plant arrangement, the distribution of those plants within each square metre of crop (Wade *et al.* 1988). Plant density determines the number of individuals amongst which the limiting resource must be shared, whilst plant arrangement controls interception or retrieval of that resource (Jones 1987). Regression methods which examine density–yield relationships in terms of the mean contribution of the individual plant and the area available to it have been effective in defining optimal plant densities for different crop maturities and yield levels (Wade and Foreman 1988).

Thomas *et al.* (1981) examined the effects of plant density and plant arrangement on grain yield of sorghum at 15 locations in Australia. They concluded that row spacings of 33–107 cm should result in optimum yields over a wide range of seasonal conditions, for plant densities of 60 000–80 000 plants/ha. Because row spacing was the focus, however, these studies involved density comparisons which were limited and non-orthogonal. Myers and Foale (1981) found optimum row spacing was related to expected crop yield but were unable to find any comparable relationship between plant density and expected crop yield. The work of Thomas *et al.* (1980) in Central Queensland involved a full density x row spacing factorial experiment, but over a narrower yield range. Using 2 cultivars, Thomas *et al.* (1980) obtained inconsistent grain yield responses to row spacing and plant density. They concluded that densities of 86 000–136 000 plants/ha were equally optimum over the range of yield levels (1.54–3.07 t/ha) and row spacings (36–107 cm) involved. Both cultivars they studied, however, were slow maturing.

Myers and Foale (1980) have suggested that different growth cycle periods could influence response to plant density and row spacing. This interaction has been examined at high yield levels (Heslehurst and Wilson 1986) but not at yield levels more commonly attained under dryland conditions (Douglas and Wade 1986). Reported studies were conducted either with a single cultivar at each location (Thomas *et al.* 1981) or with cultivars of similar maturity (Thomas *et al.* 1980).

We conclude that the maturity x density interaction in grain sorghum under water limited conditions requires further investigation. The Central Highlands of Queensland provide a suitable environment for this work. Commercial crops of sorghum generally yield 1.5 t/ha in this area, with a standard deviation of 0.5 t/ha, but yields as high as 5.0 t/ha have been recorded (Milne *et al.* 1988). The crop is commonly grown in rows spaced 60–100 cm apart, at an intended plant density of 50 000–100 000 plants/ha.

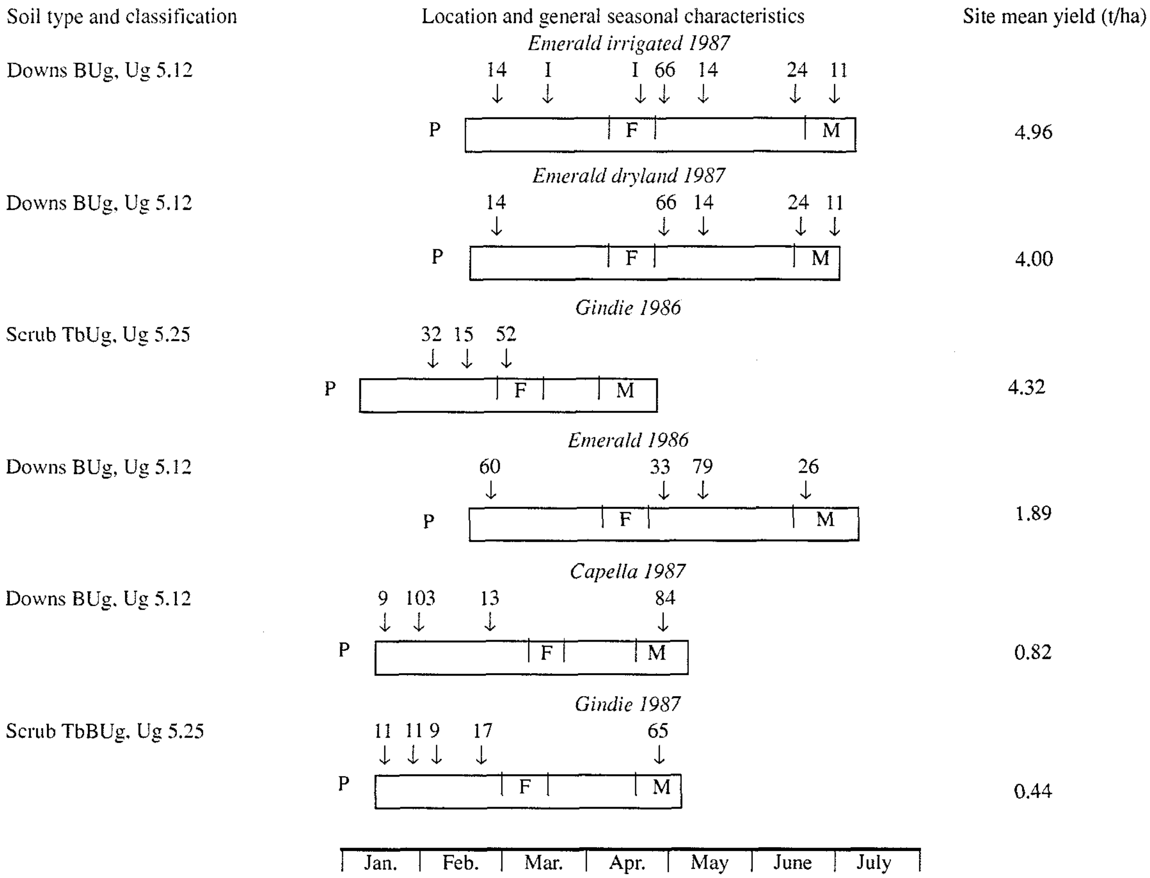

Fig. 1. Site details. Arrows denote the timing of rainfall (mm) and of profile replenishment by irrigation (I), in relation to planting time (P), flowering period (F), and maturity period (M) of the 3 hybrids grown at each of 6 locations. Soil type (McDonald and Baker 1986), soil classification (Northcote 1979), and site mean yield (t/ha) are also shown for each site.

In this paper, we examine the interaction between crop maturity and plant density in dryland grain sorghum. Analysis of variance and regression approaches are utilised in studying this interaction.

Materials and methods

The experiment was conducted at 6 locations near Emerald, Queensland (latitude 23°28'S., longitude 148°11'E.). Details of soil types, planting times and seasonal characteristics are presented in Fig. 1. At each site, 3 hybrids differing in maturity (Pride, E57+ and A6990/REx16–6) were planted in 80 cm rows at 6 densities (25 000, 50 000, 75 000, 100 000, 125 000 and 150 000 plants/ha), in a randomised block design with 3 replicates.

At each site, the crop was planted into a full profile of soil moisture. Each plot occupied 4 rows of 12 m length. The desired plant densities were obtained by over-sowing and hand-thinning. There were no problems with insects, diseases, weeds or birds. The crops were grown with adequate nutrition and, if irrigated, with adequate water. Grain yield was determined from an 8.0 m^2 quadrat from the inner 2 rows of each plot. Heads were harvested by hand, and grain was separated using a stationary thresher.

Statistical analysis

The data were subjected to a combined analysis of variance. The trials were then grouped by seasonal characteristics into the following combinations, and variances of the data were analysed for each group:

(i) low, 2 low yielding sites which encountered increasingly severe water stress throughout the growing season;

(ii) mid, 2 sites which each encountered 1 major period of water stress;

(iii) high, 2 high yielding sites which encountered minimal water stress.

Variation in hybrid yield response to density was further examined using the reciprocal relationship between grain weight per plant and density (Willey and Heath 1969). Equation 1, which indicates the parabolic relationship between grain weight per plant and area per plant (Wade *et al.* 1988; Wade and Foreman 1988), was fitted to the mean data for each hybrid at each site. The equation is:

$$W = a + bA + cA^2 \qquad (1)$$

where W is grain weight/plant (g), A is area/plant (m^2) and a, b and c are constants.

Interactions between maturity and density for grain yield in sorghum were considered by comparing the constants from the fitted regressions, and by comparing the grain yield responses derived from them (equation 2). The equation is:

$$Y = aP + b + cA \qquad (2)$$

where Y = grain yield (g/m^2), P is plant density ($plants/m^2$), and a, b and c are constants.

Grain yields predicted from equation 2 were presented graphically for each hybrid at each site and provided the basis for interpreting maturity x density interactions. Mean yield responses to density at each yield level were then compared with data presented by Thomas *et al.* (1980, 1981).

Results

Averaged over the 6 sites, E57+ flowered in 63 days, with Pride flowering 10 days earlier and A6990/REx16–6 five days later. This flowering pattern was consistent over the 6 sites (Fig. 1).

Trials on farm (Gindie and Capella) were planted a month earlier than those at the Emerald Research Station (Fig. 1). Although all sites commenced with full profiles of soil moisture, they differed in the amount and distribution of rainfall received. In 1987, both on-farm sites were subjected to increasingly severe moisture stress through the life cycle, more so at Gindie than Capella. The 1986 sites received inadequate rainfall at different periods of growth, with Emerald being dry

Table 1. Regression equations for yield response to density in three sorghum hybrids at six locations

W, grain weight/plant; *A*, area/plant (m^2)

Name and location	Regression equation	R^2
	Low yield group (severe water stress)	
Pride		
Capella 1987	$W = -5.4\ (\pm 3.7) + 139.5\ (\pm 43.3)\ A - 111.7\ (\pm 89.9)\ A^2$	0.97
Gindie 1987	$W = 0.3\ (\pm 4.6) + 119.6\ (\pm 53.3)\ A - 110.6\ (\pm 110.2)\ A^2$	0.94
E57+		
Capella 1987	$W = -2.6\ (\pm 1.1) + 122.3\ (\pm 13.1)\ A - 33.6\ (\pm 28.4)\ A^2$	0.99
Gindie 1987	$W = -1.1\ (\pm 1.1) + 32.0\ (\pm 12.8)\ A - 27.6\ (\pm 26.6)\ A^2$	0.95
A6990/REx16–6		
Capella 1987	$W = -4.4\ (\pm 1.8) + 127.5\ (\pm 21.0)\ A - 83.0\ (\pm 43.1)\ A^2$	0.99
Gindie 1987	$W = -1.7\ (\pm 1.9) + 27.0\ (\pm 21.4)\ A - 20.7\ (\pm 43.6)\ A^2$	0.82
	Mid yield group (1 major period of water stress)	
Pride		
Gindie 1986	$W = -10.0\ (\pm 9.9) + 674.5\ (\pm 116.0)\ A - 474.0\ (\pm 240.2)\ A^2$	0.99
Emerald 1986	$W = -5.3\ (\pm 3.2) + 245.6\ (\pm 36.0)\ A - 96.6\ (\pm 73.9)\ A^2$	0.99
E57+		
Gindie 1986	$W = -18.3\ (\pm 8.3) + 694.9\ (\pm 97.1)\ A - 695.7\ (\pm 201.4)\ A^2$	0.97
Emerald 1986	$W = -6.3\ (\pm 4.1) + 297.3\ (\pm 54.6)\ A - 245.5\ (\pm 122.9)\ A^2$	0.97
A6990/REx16–6		
Gindie 1986	$W = -7.4\ (\pm 1.7) + 515.9\ (\pm 20.2)\ A - 566.7\ (\pm 42.9)\ A^2$	0.96
Emerald 1986	$W = -2.1\ (\pm 5.3) + 267.3\ (\pm 62.1)\ A - 420.2\ (\pm 128.8)\ A^2$	0.75
	High yield group (minimal water stress)	
Pride		
Emerald irrigated 1987	$W = 5.7\ (\pm 1.9) + 418.4\ (\pm 18.4)\ A + 24.6\ (\pm 35.7)\ A^2$	0.99
Emerald dryland 1987	$W = -7.4\ (\pm 10.1) + 508.0\ (\pm 117.9)\ A - 364.3\ (\pm 244.7)\ A^2$	0.98
E57+		
Emerald irrigated 1987	$W = 7.3\ (\pm 10.9) + 444.2\ (\pm 136.6)\ A + 11.0\ (\pm 288.0)\ A^2$	0.99
Emerald dryland 1987	$W = 1.2\ (\pm 6.4) + 417.9\ (\pm 75.1)\ A - 107.9\ (\pm 155.8)\ A^2$	0.99
A6990/REx16–6		
Emerald irrigated 1987	$W = -6.6\ (\pm 4.5) + 666.8\ (\pm 52.7)\ A - 607.8\ (\pm 111.4)\ A^2$	0.98
Emerald dryland 1987	$W = -0.3\ (\pm 8.9) + 456.6\ (\pm 102.7)\ A - 327.1\ (\pm 211.1)\ A^2$	0.98

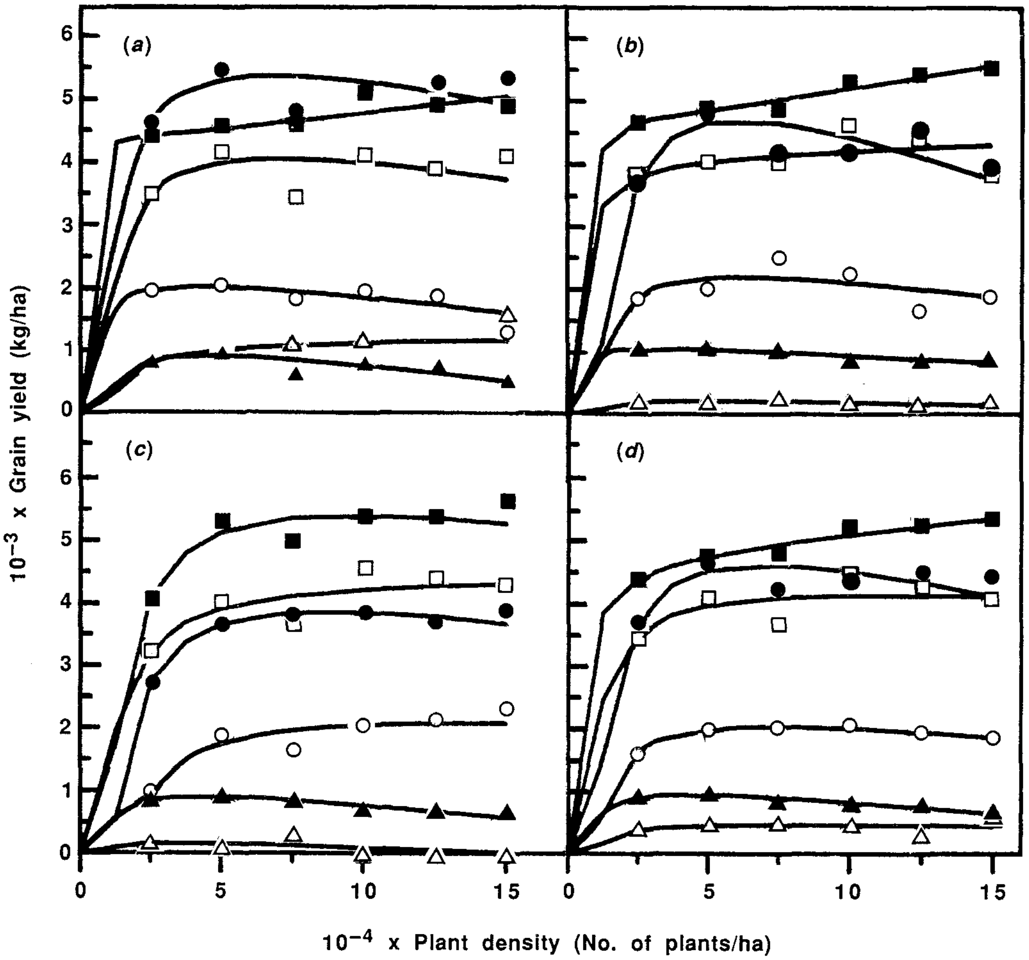

Fig. 2. The grain yield responses to density of 3 sorghum hybrids at each of 6 locations: (*a*) Pride (*b*) E57+ (*c*) A6990/REx16–6 and (*d*) mean of 3 hybrids. The symbols represent actual data for the 6 sites: ■ Emerald irrigated 1987, □ Emerald dryland 1987, ● Gindie 1986, ○ Emerald dryland 1986, ▲ Capella 1987 and △ Gindie 1987. The curves are derived from regressions between mean grain weight per plant and area per plant at each site.

before flowering and Gindie dry from flowering to maturity. The 2 trials at the Research Station in 1987 did not encounter major water stress. One trial received supplementary irrigation prior to flowering, and both had favourable moisture conditions for grain filling because 66 mm of rain fell shortly after flowering. In contrast to the Dryland 1987 site at the Emerald Research Station, water stress at and after flowering was not fully alleviated for a further 11 days at the Emerald 1986 site, after which 79 mm of rain fell (Fig. 1).

The regressions (with adjusted R^2 and s.e.) fitted to the data for each hybrid at each site are presented in Table 1.

The grain yield responses predicted from the regressions are shown in Fig. 2 for each hybrid at each site, together with mean yield data. The fitted curves adequately represented the responses to plant density of each hybrid at each site. These responses are compared in Fig. 3. Many of the statistically significant interactions from the analyses of variance presented in Table 2 are readily apparent in Fig. 3.

With site mean yield ranging from 0.44 to 4.96 t/ha, it is not surprising that site dominated the combined analysis of variance (Table 2). Yields were reduced in the lowest density treatment on average, but more so at high yielding locations and for the late hybrid. The earliest maturing hybrid was highest yielding in environments truncated by water stress (Gindie 1986,

Table 2. Values of *F* for main effects and interactions between hybrid, density and site for grain yield, for the full data set, and for high, mid and low yielding site groups

Residual error degrees of freedom were adjusted for 14 missing plots

Treatment combination	Overall d.f.	Overall *F*	High d.f.	High *F*	Mid d.f.	Mid *F*	Low d.f.	Low *F*
Site (*S*)[A]	5	390.52**	1	27.14**	1	391.31**	1	17.86*
Density (*D*)	5	11.09**	5	11.40**	5	4.37**	5	1.33
Hybrid (*H*)	2	16.51**	2	6.43**	2	20.45**	2	38.86**
D x *H*	10	1.73†	10	1.00	10	1.46	10	0.87
D x *S*	25	2.67**	5	1.09	5	0.94	5	2.17†
H x *S*	10	18.10**	2	1.10	2	20.66*	2	56.95**
D x *H* x *S*	50	1.02	10	0.86	10	0.95	10	1.46
Between site error	12	519 048	4	929 542	4	408 696	4	218 874
Residual error	190	164 145	68	194 549	54	261 547	68	55 812

† $P<0.10$; * $P<0.05$; ** $P<0.01$.

[A] Site was tested against between site error, and the remaining treatment combinations were tested against residual error.

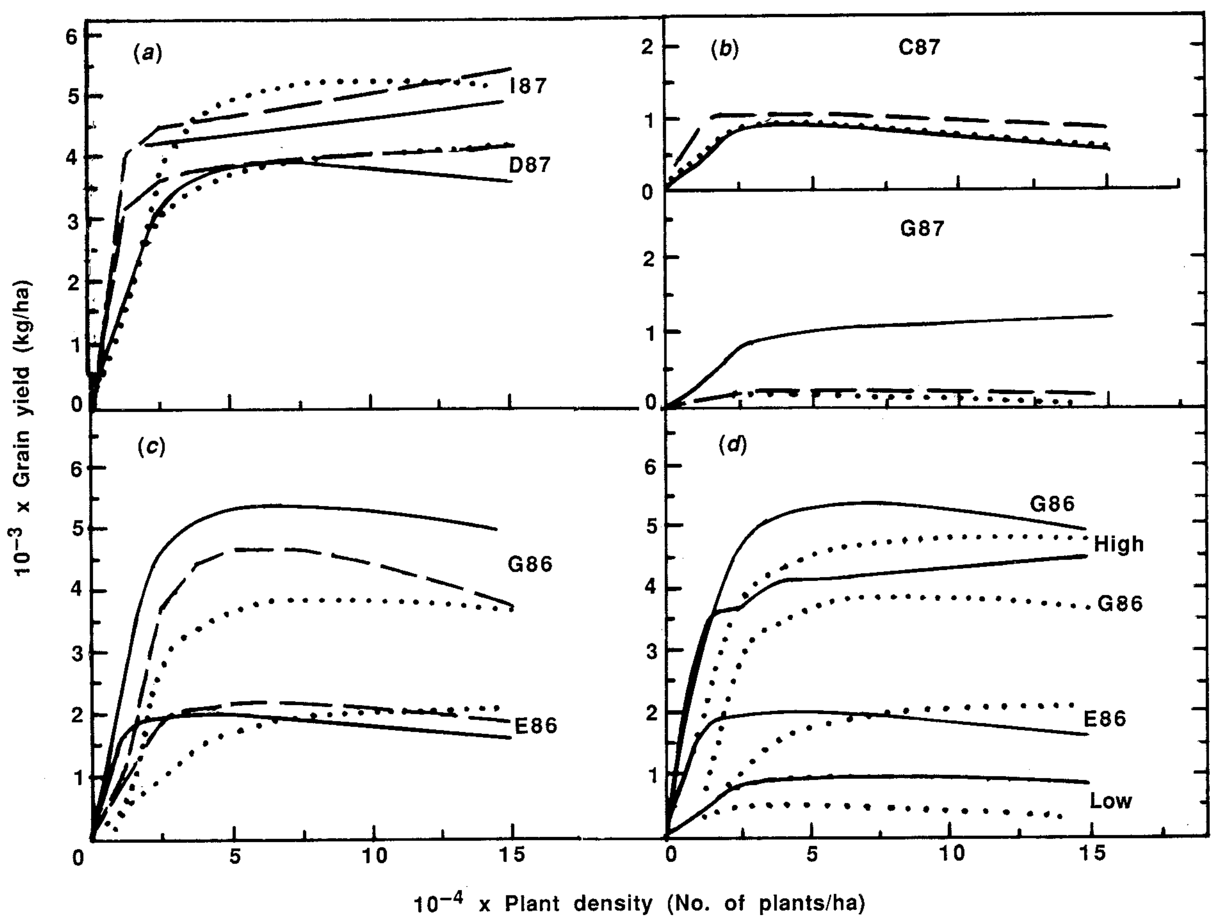

Fig. 3. The grain yield responses to density of 3 sorghum hybrids (—— Pride,– – – E57+, . . . A6990/REx16–6) at each of 6 locations: (*a*) high yield group, Emerald irrigated and dryland 1987 (I87 and D87), (*b*) low yield group, Capella and Gindie 1987 (C87 and G87), (*c*) mid yield group, Gindie and Emerald 1986 (G86 and E86), and (*d*) G86, E86, and low (C87 and G87) and high (I87 and D87) yield groups for Pride and A6990/REx16–6 only. The curves are derived from regressions between grain weight per plant and area per plant.

and especially Gindie 1987). The later maturing hybrids were superior in more favourable environments. Interactions between density and hybrid, density and site, and hybrid and site were statistically significant in the overall analysis of variance.

The sites were then grouped by seasonal favourability and yield level as follows: low (0.63 t/ha, Capella 1987 and Gindie 1987), mid (3.11 t/ha, Gindie 1986 and Emerald 1986) and high (4.48 t/ha, Irrigated 1987 and Dryland 1987). Grouping the sites greatly simplified the interactions within groups, and their interpretation.

For the high yield group, grain yield increased with plant density, with later maturity, and with supplementary irrigation (Fig. 3*a*). The absence of higher order interactions indicates that the maturity groups were not differentially affected by water stress at the Dryland 1987 site, prior to the 66 mm of rain early in grain fill. Grain yields at the 2 sites comprising the high yield group therefore responded similarly to all treatments, with the Irrigated 1987 site generally yielding about 1.0 t/ha more grain. Still higher yields may have been expected for the irrigated site with full irrigation and earlier planting.

At low yield locations the later hybrids were lower yielding, on average, due to severe yield reduction under terminal water stress conditions at Gindie 1987 (Fig. 3*b*). High density depressed yield of all hybrids to a greater extent at Capella 1987, but yield failure only occurred in A6990/REx16–6 at densities greater than 100 000 plants/ha at Gindie 1987. Responses in grain yield to density were similar among hybrids at the low yield sites.

In the mid yield group, the lowest density reduced grain yield at both sites (Fig. 3*c*). Differential water stress over maturity groups resulted in the statistical significance of the hybrid × site interaction. Hybrid superiority at each site was dependent upon the timing of rainfall relative to the timing of critical development events. In contrast to the high and low yield groups, grain yield responses were not consistent between the sites comprising the mid yield group.

All of the above interactions are summarised in Fig. 3*d*, which compares the grain yield responses to plant density of the early and late hybrids over environments (Gindie 1986, Emerald 1986, and low and high yield groups). The responses of E57+ fall between those of the early and late hybrids.

Responses in grain yield to density are shown in Fig. 4 for the mid-season hybrid E57+ at each of 6 locations. For comparison, mean data for 7 sites in Central Queensland (Thomas *et al.* 1980) and mean data for 1 m rows in low (Wallumbilla C and Miles) and mid (Theodore, Roma, Biloela C and Biloela D) yield groups in Queensland (Thomas *et al.* 1981) are also shown. The form of the density response at each yield level was consistent across these groups.

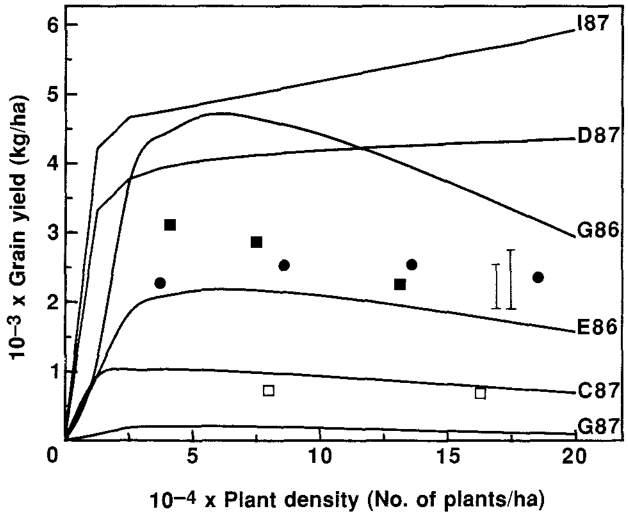

Fig. 4. The relationship between density and grain yield of sorghum hybrid E57+ at each of 6 sites (I87, Emerald irrigated 1987; D87, Emerald dryland 1987; G86, Gindie 1986; E86, Emerald 1986; C87, Capella 1987; G87, Gindie 1987), and at 3 yield levels from the literature: (● Thomas *et al.* 1980; ■ mid and □ low yield groups from Thomas *et al.* 1981). Vertical bars indicate l.s.d. at P=0.05 or 0.01.

Discussion

Wade *et al.* (1988) and Wade and Foreman (1988) attributed biological significance to the constants of equations 1 and 2, for situations in which b is positive and a and c are zero or negative. Specifically, b indicated crop yield potential, c the proportion of space not utilised at low density, and a the proportional change in dry matter distribution, with less dry matter allocated to reproductive components at high density.

These criteria were generally satisfied by the regressions presented, in which each accounted for significant proportions of the total variation (75–99%). The higher yield potential of the later hybrids under favourable conditions, and of the early hybrid under low yield or terminal stress conditions, is demonstrated in Fig. 3. The positive a values for Pride and E57+ in high yield locations, whilst generally not statistically significant, indicated that a maximum grain yield was not attained over the density range examined. This is evident in Figs 2 and 3, indicating that the b values alone for those equations do not represent their crop yield potentials. When a was negative, significant differences in b among hybrids at each yield level were reflected in Fig. 3.

In high yield environments, grain yield would be expected to approach a plateau as density increased. This occurred in favourable environments and is indicated by the small and generally non-significant a values in those regressions. Under water stress conditions, the combination of late maturity and high density would be expected to affect grain yield adversely. This occurred at Capella 1987, where *a* was negative and statistically significant. This is interpreted as representing an overcommitment in early dry matter production, resulting in reduced grain yield and a lower harvest index under conditions of depleted soil water towards maturity (Jones 1987). A similar response was evident at Gindie 1986. Low yield potential (*b*) precluded the expression of this interaction at Gindie 1987.

At Emerald 1986 (Fig. 3*c*), grain yield continued to increase with plant density for the late hybrid (*c* large and negative) under conditions in which water stress increased through the flowering period (Fig. 1). The reason for this response is not clear but may be associated with an altered pattern of water use through the growing season. Blum and Naveh (1976) obtained higher yields in Israel by using wide rather than narrow rows at the same density, when water supply was limiting. In their wide row configuration, greater competition between neighbouring plants within the row restricted early dry matter production and water use, allowing more water to be available later for grain filling. Enhanced inter-plant competition may explain the increase in yield of the late hybrid at high density at Emerald 1986. At high density, greater competition between neighbouring plants within the row may have restricted early dry matter production and water use, enabling more grains to be set than at low density. The relief of water stress early in grain filling would then permit the differential in grain number to be expressed as grain yield. This response to high density in the late maturing hybrid is not worth pursuing, however, as yield failure may result in dry seasons, such as Gindie in 1987.

Later maturing hybrids would be expected to utilise space at low density (*c*) better than early maturing hybrids. This was the case for low yield locations, in which the early hybrid, Pride, had the lowest *c* values. In high yield locations, the mid-season hybrid E57+ generally had a higher *c* value than either the early or the late hybrid. The response of the late hybrid may be due to the development of a higher yield potential than the earlier hybrids at low density, but an inability to express this potential in its later tillers before the cessation of the growing season. Mid-season maturity provided greater stability of grain yield, due to the more consistent *c* values.

These complex interactions between crop maturity, plant density and yield level have little consequence for commercial density recommendations. Maximum yield by each hybrid at each yield level did not differ significantly from yield at a density of 75 000 plants/ha (Fig. 3). The results support the current recommendations of 50 000–100 000 plants/ha for grain sorghum on the Central Highlands of Queensland (Douglas and Wade 1986). Whilst maximum yields for the low yield sites were recorded at densities of 40 000–70 000 plants/ha, little decline in yield was evident as plant density increased to 150 000 plants/ha in these hand-thinned experiments. When plant stands are uneven, however, plant densities greater than 75 000 plants/ha may result in significantly lower grain yields (Wade *et al.* 1988). In commercial production, the difficulty remains in establishing the desired plant density uniformly in each square metre of crop (Spackman 1985). Consequently, it would be better to aim for a density of 75 000 plants/ha in all circumstances. This would provide insurance against poor crop establishment, whilst retaining the capacity to fully utilise favourable seasonal conditions.

In Fig. 4, the responses obtained here are compared with evidence from other literature. At each yield level, the results are consistent over sites, years and planting times. This suggests, as Wade and Foreman (1988) concluded for sunflower, that valid agronomic recommendations over regions may be based on data from 1 region, if a suitable data set covering the range of yield expectations is obtained. With the timing of water limitation relative to critical development events dominating the response (Fukai and Foale 1988), this is not unexpected. Consequently, the general conclusions of Thomas *et al.* (1980; 1981) and Myers and Foale (1981) are confirmed.

The results demonstrate the stability of sorghum grain yield over a wide range of plant density and crop maturity. Highest grain yields should be obtained with plant densities of 50 000 to 100 000 plants/ha under rainfed conditions, where yield expectations range from 0 to 5.0 t/ha. Regression analysis aided data presentation and interpretation.

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References

Blum, A., and Naveh, M. (1976). Improved water-use efficiency in dryland grain sorghum by promoted plant competition. *Agronomy Journal* **64**, 775–8.

Douglas, A. C. L., and Wade, L. J. (1986). Grain sorghum—possible effects of maturity on optimum density. *Queensland Agricultural Journal* **112**, 123–4.

Fukai, S., and Foale, M. A. (1988). Effects of row spacing on growth and grain yield of early and late sorghum cultivars. *Australian Journal of Experimental Agriculture* **28**, 771–7.

Gardner, W. R., and Gardner, H. R. (1983). Principles of water management under drought conditions. *Agricultural Water Management* **7**, 143–55.

Heslehurst, M. R., and Wilson, G. L. (1986). The influence of plant population on canopy structure, grain yield and grain yield components for a range of cultivars. *In* 'Proceedings First Australian Sorghum Conference, Gatton, February 1986'. (Eds M. A. Foale and R. G. Henzell.) pp. 5.66–5.73. (Queensland Branch of Australian Institute of Agricultural Science: Brisbane.)

Jones, M. J. (1987). Plant population, rainfall and sorghum production in Botswana. I. Results of experiment station trials. *Experimental Agriculture* **23**, 335–47.

McDonald, R. C., and Baker, D. E. (1986). Soils of the left bank of the Nogoa River, Emerald Irrigation Area, Queensland. Queensland Department of Primary Industries, Brisbane. Agricultural Chemistry Branch Technical Report Number 15.

Milne, G. D., Spackman, G. B., and Barnett, R. A. (1988). The Central Highlands. *Queensland Agricultural Journal* **114**, 247–56.

Myers, R. J. K., and Foale, M. A. (1980). Row spacing and population density in Australian grain sorghum production. *Journal of the Australian Institute of Agricultural Science* **46**, 214–20.

Myers, R. J. K., and Foale, M. A. (1981). Row spacing and population density in grain sorghum—a simple analysis. *Field Crops Research* **4**, 147–54.

Northcote, K. H. (1979). 'A Factual Key for the Recognition of Australian Soils.' 4th Edn. (Rellim Technical Publications: Glenside, S. Aust.)

Spackman, G. B. (1985). Establishment of raingrown summer crops in the Central Highlands. Queensland Department of Primary Industries, Brisbane. Project Report QO85017.

Thomas, G. A., French, A. V., Ladewig, J. H., and Lather, C. J. (1980). Row spacing and population density effects on yield of grain sorghum in Central Queensland. *Queensland Journal of Agricultural and Animal Sciences* **37**, 67–77.

Thomas, G. A., Myers, R. J. K., Foale, M. A., French, A. V., Hall, B., Ladewig, J. H., Done, A. A., Taylor, G. K., Lefroy, E., Wylie, P., and Stirling, G. D. (1981). Evaluation of row spacing and population density effects on grain sorghum over a range of northern Australian environments. *Australian Journal of Experimental Agriculture and Animal Husbandry* **21**, 210–7.

Wade, L. J., and Foreman, J. W. (1988). Density x maturity interactions for grain yield in sunflower. *Australian Journal of Experimental Agriculture* **28**, 623–7.

Wade, L. J., Norris, C. P., and Walsh, P. A. (1988). Effects of suboptimal plant density and non-uniformity in plant spacing on grain yield of raingrown sunflower. *Australian Journal of Experimental Agriculture* **28**, 617–22.

Willey, R. W., and Heath, S. B. (1969). The quantitative relationships between plant population and crop yield. *Advances in Agronomy* **21**, 281–321.

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