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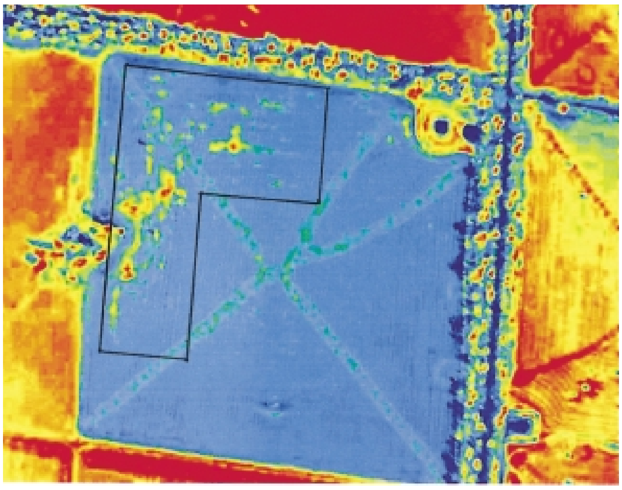

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Responses of adzuki bean as affected by row spacing, plant density and variety

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Abstract. Agronomic responses of varieties of adzuki bean, *Vigna angularis* (Willd.) Ohwi and Ohashi, to row spacing and plant density were investigated at 3 locations, Kumbia and Warwick in Queensland, and Grafton in New South Wales. The treatments were: at Kumbia and Warwick row spacings of 17.8, 35.6 and 71.1 cm, 3 densities of 250×10^3, 500×10^3 and 750×10^3 plants/ha, and 4 and 3 varieties respectively; and at Grafton 4 densities of 200×10^3, 400×10^3, 550×10^3 and 700×10^3 plants/ha and 3 varieties at 30 cm row spacing. The varieties Bloodwood and Dainagon were common across locations.

Grain yield was increased by 26% at Kumbia and 19% at Warwick for narrow rows versus wide rows, and by 31% at Kumbia, 22% at Warwick, and 19% at Grafton for high versus low plant density. These responses occurred over sites differing in environment and in mean yield. At Kumbia a significant interaction for yield occurred between plant density and row spacing and between variety and row spacing, whereas at the other locations yield responses to row spacing and to plant density were linear and additive. These responses differed for the large-seeded variety Dainagon with a trend for a yield decline at the highest plant density at Grafton.

Phenologic responses to row spacing and to plant density were significant but very small at Warwick. Ground cover percentage at mid pod fill was reduced at both low plant densities and in wide rows, with smaller differences between the intermediate and high levels of each treatment. Variety, row spacing and plant density showed interactions for expression of ground cover at Kumbia and Warwick.

Both seed weight and canopy height were less at low plant densities at Kumbia and at Warwick, but responses differed by variety at Grafton, whereas these traits were both less at wide row spacing at Kumbia but not at Warwick. Other traits with responses to plant density included; lodging percentage with a small increase at 250×10^3 ha at Kumbia, and shoot biomass which was reduced at low plant density and at wide spacing at Warwick.

There were significant varietal differences in all traits except lodging percentage. Bloodwood yielded well at each site, equivalent with Erimo at Grafton and Warwick, but Dainagon was equivalent at Kumbia only and yielded significantly less at other sites. Dainagon was shorter and with larger seed than Bloodwood at each site, it reached maturity earlier at Kumbia but later at Warwick, and it had less ground cover than Bloodwood at Warwick but not quite significantly less at Kumbia. Bloodwood and Erimo were very similar over all traits except for Bloodwood having a taller canopy and later maturity at Warwick.

Adzuki bean grain yield was strongly affected by both plant density and row spacing with increases from low to high plant densities and wide to narrow rows, in association with responses in ground cover. Shoot biomass, recorded at Warwick only, was less in wide rows but unresponsive to plant density. Harvest index increased with increased plant densities but was unresponsive to row spacing.

Introduction

Little is known about the agronomy of adzuki bean [*Vigna angularis* (Willd.) Ohwi and Ohashi], particularly in the subtropics. With interest in the production of adzuki bean for export to Japan (Redden and Desborough 1996), farmers urgently need information on response to row spacing, plant density and choice of variety. This is particularly relevant in Queensland where summer legume crops including production of adzuki bean with irrigation are mainly sown in rows 0.72–1.00 m apart (Redden 1993). At these spacings adzuki bean growth does not achieve ground cover at flowering nor during grain filling in most cases (Lawn 1983;

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R. Redden pers. comm.), hence interception of solar energy may be suboptimal particularly if water supply is non limiting (Redden *et al*. 1987).

Adzuki bean (determinate Japanese varieties Maruba and Kotubuki), and black [*Vigna mungo* (L.) Hepper] and green [*Vigna radiata* (L.) Wilcek] gram were evaluated at Lawes, south-eastern Queensland (Lawn 1983) at 3 sowing dates, November, December and January, at a constant 20 plants/m at 100, 75, 50 and 25 cm row spacings. Thus respective densities were 200×10^3, 267×10^3, 400×10^3 and 800×10^3 plants/ha, with row spacing and plant density/ha treatments confounded. The only constant effect across treatments was within row plant competition. Adzuki bean yields at 2.1 t/ha increased by 71% for narrow row/high plant density over wide row/low plant density in the January sowing, and at 1.8 t/ha increased by 26% for 50 and 25 cm spacing over wide rows with a December sowing (grain yield and dry matter production in November were both low due to lodging). Narrow rows were necessary in a January sowing of adzuki bean to ensure full light interception during the reproductive growth period. Seed size of adzuki bean declined only with 25 cm/high plant density. Adzuki bean and green gram were less responsive to interplant competition than indeterminate black gram due to a mainly determinate growth habit, and more responsive than black gram to plant density for grain yield and yield components, and at later sowings increased plant densities compensated for reduced plant size.

The current study was designed to examine growth responses to row spacing and to plant density in a range of adzuki bean varieties including Bloodwood and Erimo that are currently grown commercially in Australia, and in a range of potential production areas. The study was aimed at examining management options of row spacing and seeding rate for commercial application, hence the emphasis on mechanised seeding rates rather than exact manually planted densities.

Materials and methods

Climate and experimental design

Three trials were sown during 1995–98, with different experimental designs and some differences in the traits measured. The climatic conditions for each trait are given in Table 1.

In trials 1 and 3 a factorial combination of 3 row spacings (71.1, 35.6 and 17.8 cm) and 3 densities (250×10^3, 500×10^3 and 750×10^3 plants/ha) were applied with 4 varieties in trial 1 [Bloodwood (Desborough 1983), Dainagon, Wase Dai Ryu and Cha Gara Wase, all varieties directly or derived from Japan], and 3 varieties in trial 3 (Bloodwood, Dainagon and Erimo). In trial 2, 4 densities (200×10^3, 400×10^3, 550×10^3 and 700×10^3 plants/ha) were used at 30 cm row spacing in a factorial design with 3 varieties (Bloodwood, Dainagon and Erimo). All 3 trials had 4 replicates. The densities chosen ranged above and below the existing recommendation of 500×10^3 plants/ha, while for row spacing there has not been a standard due to the diversity of planting equipment on farms.

The choice of varieties reflected the Australian standard Bloodwood, the Japanese standard Erimo (not available for trial 1), and a niche market in Japan for large-seeded adzuki beans represented by Dainagon and Wase Dai Ryu varieties. The latter were of strategic interest in development of a business plan for the industry (Redden *et al*. 2000).

The experimental header used for harvesting was able to directly head below the height of the lowest pods that were at least 3 cm above ground level in most cases. Harvest loss appeared to be negligible.

Table 1. Climate at three locations for the adzuki bean trial of row spacing × plant density × variety

Sowing dates for trials 1–3 were 18 January 1995, 15 December 1995 and 22 January 1998 respectively
Days to harvest for trials 1–3 were 90, 109 and 110 respectively

	Trial 1	Trial 2	Trial 3
	Mean maximum temperature		
December	—	28	—
January	31.4	29.1	30.7
February	38.3	28.8	30.6
March	29.8	26.8	31.8
April	26.3	—	25.8
May	—	—	21.9
	Mean minimum temperature		
December	—	16.3	—
January	17.5	20.4	17.4
February	18.3	17.4	17.8
March	15.5	16.3	14.7
April	10.1	—	13.8
May	—	—	7.7
	Rainfall/irrigation (mm)		
December	0	152/0	
January	135/78	268/0	88/82
February	98/122	62/0	52/167
March	70/158	87/0	22/212
April	8/83		54/119
May	0	0	29/32
Total	301/441	504/0	245/612

Trial 1. Management and data

The first adzuki bean trial was sown on a farm property near Kumbia (26°33′S, 151°50′E) in south Queensland on 18 January 1995. The design was a randomised split-plot with varieties within random combinations of row spacing × seeding rate providing 36 main plots sown side by side, with 4 subplots of varieties in each. Plot length was 8.0 m, with width varying as per treatment, 9 rows of 17.8 cm, and 5 rows of 35.6 cm or 3 rows of 71.2 cm. Due to planter error only 5 rows were correctly spaced at 17.8 cm intervals. Excluding guard rows (9 rows of 17.8 cm width) on each side, the site dimension was 32 by 54 m.

The site was a red brown clay deep loam (buffer pH 5.7) to which 200 kg/ha of Crop King 700 fertiliser (32.5% N, 9.3% P and 1.4% S) was applied in November. Standard procedures for weed and insect control were followed.

The trial was sprinkler irrigated to recharge soil moisture according to a pan evaporation measured at Kingaroy 20 km away. A light rain of about 5 mm fell immediately after sowing the trial to provide excellent conditions for germination.

Subplot measurements were: ground cover [visual percentages (Redden *et al*. 1987)] and canopy height in centimetres at 63 days after sowing (DAS), days to physiological maturity (80% of pods turned buff), and at full maturity — plant density (2 datum row sections × 1 m length), pod height index (5, lower pods touching ground; 6, lower pods clear off ground; 7, lower pod tips 2 cm above ground; 8, 5 cm above ground; 9, >5 cm above ground), and lodging percentage. Direct mechanical harvest at 90 DAS provided grain yield data (kg/ha) for subplot datum rows trimmed at each end to 6 m length, with 1 central datum row at 71.2 cm spacing, 3 central datum rows at 35.4 and 17.8 cm spacings. For each subplot grain was sampled for measurement of 100-seed weight on whole grains at about 10% moisture content.

Trial 2. Management and data

The second adzuki bean trial was sown at Grafton Agricultural Research and Advisory Station, New South Wales (29°37′S, 152°57′E), on 15 December 1995 into a fertile river alluvial soil. The trial was sown no-tilled on 30 cm row spacing into winter cereal residue. Fertiliser was applied at sowing in each row at 22.5 kg N/ha and 25 kg P/ha. Herbicides imazethapyr at 400 mL/ha and glyphosate at 1.5 L/ha were applied post-sowing, pre-emergence to the soil surface, with rain falling within 5 days of application. Insecticide was applied in early and mid March. Each plot was 8 by 8 m, and the design was factorial with 4 replicates.

Data recorded were: plant density 17 DAS (mean of 10 counts per plot), plant height from 10 measurements per plot (to attachment point of uppermost pod on stalk), seed yield (109 DAS) using direct mechanical harvester from 9 m^2 area, with mass adjusted to 10% moisture and seed size (g/100 seed) adjusted to 10% moisture with 2 samples per plot. Although height was measured at maturity in this trial, the data are comparable with the canopy height at mid pod fill measured in the other trials, due to the very determinate and low level of branching of lines utilised, which were all derived from Japan.

Trial 3. Management and data

The third adzuki bean trial was sown at Hermitage Research Station (28°13′S, 152°2′E), on 22 January 1998. The design was factorial with 3 row spacings × 3 plant densities × 3 varieties with 4 randomised, complete-block replicates. Plot length was 10 m with width varying as per treatment, 9 rows of 17.8 cm spacing, 5 rows of 35.6 cm spacing and 3 rows of 71.1 cm spacing.

The site had an Elphinstone depositional medium to heavy grey clay soil with pH 9.0 (McKeown 1978). Fertiliser was applied at 91 kg N/ha, 26 kg P/ha and 3.9 kg K/ha.

Post emergence weed control at day 26 with Bentazone resulted in burning and dehiscence of upper leaves, however, growth was again vigorous 1 week later. Only 2 applications of insecticide were necessary, at 48 and 79 DAS.

Irrigation was from trickle tapes at 30 cm depth in lines 60 cm apart at 90° to the direction of planting. A total of 687 mm was supplied with 11 irrigations between sowing and harvest at 110 DAS.

All plots were planted with 10% above the required plant density, and then thinned back to the required level at 30 DAS. Very little thinning was required, with 4 plots having either uneven stands [Bloodwood 35 cm × (750 × 10^3) replicate 1, Erimo 17.5 cm × (250 × 10^3) replicate 1] or plant density 20% below target [Erimo 35 cm × (250 × 10^3) replicate 1, Bloodwood 17.5 cm × (750 × 10^3) replicate 2]. The Dainagon 17.5 cm × (750 × 10^3) treatment had one missing plot for all data plus a second missing for total dry weight.

Plot data recorded as in experiment 1 were: ground cover at 62 DAS, canopy height (cm) at 72 DAS, physiological maturity and 100-seed weight. Additional data recorded on a plot basis were: DAS to first flower, total dry weight of shoots at 73 DAS from samples of 1 m length in 7, 3 and 1 datum rows respectively at 17.8, 35.6 and 71.1 cm row spacings, while grain yield was obtained by machine harvest from the same datum rows, after trimming plot ends to about 6 m length at 110 DAS.

Results

Trial 1

Due to diagonal gradients for yield across the trial, spatial analyses were applied (Cullis and Gilmour 1995) to correct for environmental within-site trends not accounted for by estimation of replicate effects.

The error in planting 17.8 cm row spacing treatments necessitated a reduced harvest area in these plots, with 3.1 m^2 for 17.8 cm row spacing, 6.4 m^2 for 35.6 cm row spacing and 4.2 m^2 for 71.2 cm row spacing. Although precautions were taken to exclude buffer areas around each sample harvested, there is some possibility that an upward bias may be introduced with smaller areas.

A significant 25.8% yield increase occurred for narrow (17.8 cm) versus wide (71.2 cm) rows, and a 30.8% yield increase for high versus low plant density (Table 2). An interaction occurred between seeding rate and row spacing such that yield was significantly greater for high and medium versus low seeding rates in narrow rows, whereas there was no corresponding advantage in wide rows (Table 3).

Overall varietal differences were confined to a consistent low yield potential shown by Cha Gara Wase (Table 2). Varieties responded differentially to row spacing with significant yield increases in narrow rows shown by varieties Dainagon (64%) and Wase Dai Ryu (26%) (Table 3), whereas Bloodwood had a non-significantly low yield of 1.66 t/ha in 71.1 cm rows and similar yields of about 2 t/ha in both 35.6 and 17.8 cm rows. No significant yield responses to row spacing occurred with Cha Gara Wase.

Canopy height (Table 2) was increased for both narrow versus wide row (11%) and for increased plant density (27%). These canopy height responses were positively associated with increased pod height only for high versus low plant density (8% gain). For canopy and pod height the variety Cha Gara Wase was less vigorous, consistent with its low yield (Table 2).

Although lodging was affected only by plant density and not row spacing, being less at high (8.5%) versus low (11.5%) plant density, for direct harvesting levels below 40% lodging are not of concern.

Seed weight increased by 5.7% as row widths narrowed to 17.8 cm and by 4.9% with plant density increase from 250 × 10^3 to 750 × 10^3 plants/ha (Table 2). The large seed sizes of Dainagon and Wase Dai Ryu were confirmed, being over one-third larger than for Bloodwood. For the large-seeded varieties interactions occurred with row spacing, Dainagon maximising seed size in 35.6 cm rows and Wase Dai Ryu in 17.8 cm rows (Table 4). The seed weight responses in these 2 varieties were small in comparison with the yield increases from wide to narrow rows, but did not correspond with yield gains from wide to narrow rows at 35.6 cm spacing.

Ground cover was notably less at both the low seeding rate and in wide rows, being only 60% of complete ground

Table 2. Grain yield and agronomic responses of adzuki bean in trial 1 to row spacing, seeding rate and variety

	Grain yield (kg/ha)	Canopy height (cm)	Pod height index	Maturity (days)	100-seed weight (g)	Ground cover (%)	No. plants at harvest ($\times 10^3$/ha)
Row spacing (cm)							
71.2	1610	39.5	7.8	77.7	12.3	68.8	358
35.6	1741	40.2	7.7	78.0	12.6	88.4	443
17.8	2026	43.8	7.9	77.6	13.0	94.3	545.5
l.s.d. ($P = 0.05$)	386	2.76	n.s.	n.s.	0.32	3.4	58.8
Density (plants/ha)							
250×10^3	1534	36.5	7.5	78.2	12.2	76.8	285
500×10^3	1838	40.8	7.8	77.6	12.8	84.5	439
750×10^3	2006	46.3	8.1	77.4	12.8	89.9	622.5
l.s.d. ($P = 0.05$)	386	2.76	0.4	0.4	0.32	3.4	58.8
Variety							
Bloodwood	1877	48.0	8.0	77.5	11.0	88.3	508
Dainagon	1993	39.2	8.1	71.0	14.7	84.8	425.5
Wase Dai Ryu	1989	42.3	8.1	79.0	15.2	87.6	449
Cha Gara Wase	1312	35.2	7.0	75.5	9.4	74.6	412.5
l.s.d. ($P = 0.05$)	218	2.8	0.3	0.5	0.56	3.6	86.0

cover for the 250×10^3 plants/ha density in 71.2 cm rows (Table 4), but over 67% at the intermediate plant density and 79% at the high plant density in 71.2 cm rows, and over 82% in intermediate and narrow rows at low plant density. Row spacing and plant density interacted for effects on ground cover with the combination of medium–high seeding rates and narrow rows approaching 100% ground cover and with little difference between 35.6 and 17.8 cm rows at high seeding rates (Table 4). Ground cover was affected also by the interaction between variety and row spacing, being greater than 90% at 17.8 cm and 35.6 cm row spacings for all varieties except the less vigorous Cha Gara Wase (Table 4) at 35.6 cm row spacing.

The harvest plant density was not significantly different from the sowing rate at low seeding rates, but 12% less at 500×10^3 plants/ha and 17% less at 750×10^3 plants/ha (Table 2). The latter suggests that inter-plant competition leading to mortality increased with seeding rates. Even more pronounced were the reduced harvest densities 28% below the mean sowing rate (500×10^3 plants/ha) in 71.2 cm rows (Table 2). Within-row mortality was exacerbated as mean density/m increased from 8.9 plants (11.2 cm spacing) in narrow rows to 35.6 plants (2.8 cm spacing) in wide rows. Across varieties plant density at harvest was lowest for Cha Gara Wase which appeared to be less vigorous. Seed for all varieties was from the same source, harvested in Grafton, December 1994, and had close to 100% germination. No interactions between row spacing, plant density or variety were detected for harvest densities.

Table 3. Trial 1. Treatment interactions for grain yield

	Row spacing (cm) 71.2	35.6	17.8	l.s.d. ($P = 0.05$)
Row spacing × plant density interaction				
250×10^3 plants/ha	1545	1611	1444	668
500×10^3 plants/ha	1654	1662	2200	
750×10^3 plants/ha	1633	1951	2435	
Variety × row spacing interaction				
Bloodwood	1665	2007	1978	490
Dainagon	1580	1772	2584	
Wase Dai Ryu	1824	2095	2316	
Cha Gara Wase	1344	1162	1512	

Table 4. Trial 1. Interaction of variety and row spacing upon 100-seed weight (g) and interactions amongst row spacing, seeding rate and variety on percentage ground cover

	Row spacing (cm) 71.2	35.6	17.8	l.s.d. ($P = 0.05$)
100-seed weight (g)				
Bloodwood	11.0	10.7	11.2	0.94
Dainagon	14.2	15.7	14.9	
Wase Dai Ryu	14.8	14.5	16.2	
Cha Gara Wase	9.1	9.5	9.6	
Percentage ground cover				
250×10^3/ha	59.6	82.9	87.9	5.93
500×10^3/ha	67.7	89.4	97.4	
750×10^3/ha	79.2	92.9	97.5	
Percentage ground cover				
Bloodwood	80.0	91.1	93.9	6.33
Dainagon	64.4	94.4	95.5	
Wase Dai Ryu	75.6	91.1	96.1	
Cha Gara Wase	55.0	77.0	91.7	

Table 5. Trial 2. Response to plant density at Grafton

Density (plants/ha) or variety	Mean yield (kg/ha)	100-seed wt (g)	Density (plants/m^2)	Height (mm)
Bloodwood				
200×10^3	2989	11.8	23.2	464
400×10^3	3077	12.3	37.1	450
550×10^3	3185	12.4	50.3	417
700×10^3	3517	12.2	65.8	403
Erimo				
200×10^3	2790	12.1	23.6	400
400×10^3	3456	12.1	38.8	466
550×10^3	3430	12.1	48.3	396
700×10^3	3669	11.7	66.7	483
Dainagon				
200×10^3	2472	15.9	22.1	355
400×10^3	2819	15.8	34.3	312
550×10^3	2869	15.7	51.3	302
700×10^3	2594	14.8	65.3	268
Plant density means				
200×10^3	2750	13.3	22.9	406
400×10^3	3117	13.4	36.8	409
550×10^3	3161	13.4	50.0	372
700×10^3	3260	12.9	65.9	384
Variety means				
Bloodwood	3192	12.2	44.1	433
Erimo	3336	12.0	44.4	436
Dainagon	2688	15.5	43.2	309
l.s.d. ($P = 0.05$)				
Plant density	308	0.4	3.2	41
Variety	267	0.4	2.8	36
Plant density × variety	533	0.7	5.5	71

Trial 2

Growing conditions at Grafton were very favourable, with mean yields above 3 t/ha, 71% higher than in trial 1.

Plant densities achieved were close to the targeted levels, with 14% higher levels at 200 plants/ha and 8, 9 and 6% lower at 400, 550 and 700 plants/ha respectively (Table 5). All varieties achieved a similar plant density at each sowing rate. At low plant density, mean yield over varieties was reduced, while there was a reduction in seed weight at the highest plant density. Plant height was reduced at the intermediate plant density of 550 × 103 plants/ha in comparison with 750×10^3 plants/ha, and it was reduced for Dainagon at 700×10^3 compared with 200×10^3 plants/ha.

The variety Dainagon produced lower yields than either Bloodwood or Erimo when averaged over all plant densities. There was no significant effect of plant density on yield in Dainagon but there was an almost significant yield increase at the highest plant density with Bloodwood, and a significant yield reduction in Erimo at the lowest plant density compared with the other 3 plant densities.

Seed weight and mature height were lowest at the highest plant density for Dainagon, but there was no significant (P>0.05) effect on seed weight in Bloodwood. Dainagon had 28% higher seed weight than the other varieties. Significant but opposite height responses to plant density increase were measured in Erimo (positive) and Dainagon (negative). There was no lodging in any treatment.

Trial 3

Grain yield with a mean of 1580 kg/ha was lower than for trials 1 and 2. Significant yield increases of 19% from wide to narrow rows, and of 22% from low to high plant density

Table 6. Trial 3. Grain and agronomic responses of adzuki to row spacing seeding rate and variety

	Grain yield (kg/ha)	Total DW (kg/ha)	Days to flowering	Days to maturity	Canopy height (cm)	100-seed wt (g)	Ground cover (%)	Harvest index
Row spacing (cm)								
70	1423	4424	44.6	93.9	36.7	13.7	76.4	0.33
35	1619	5152	45.2	94.6	33.7	13.8	92.1	0.32
17.5	1698	4998	45.6	94.5	33.0	13.9	93.5	0.37
l.s.d. ($P = 0.05$)	111	412	0.5	—	1.4	—	2.8	—
Density (plants/ha)								
250×10^3	1409	4719	45.5	94.9	32.9	13.2	80.7	0.31
500×10^3	1607	4911	45.0	93.9	34.4	14.1	89.6	0.34
750×10^3	1724	4944	45.0	94.2	36.1	14.2	91.7	0.36
l.s.d. ($P = 0.05$)	111	—	0.5	0.6	1.4	0.6	2.8	0.045
Variety								
Bloodwood	1685	5002	45.4	92.8	39.9	12.1	90.1	0.35
Dainagon	1381	4451	44.3	99.0	26.8	17.3	81.9	0.33
Erimo	1674	5121	45.7	91.3	36.7	12.1	89.9	0.34
l.s.d. ($P = 0.05$)	111	412	0.5	0.6	1.4	0.4	2.8	—

Table 7. Trial 3. Row spacing × variety interaction for total dry weight and row spacing × plant density interaction for canopy height

	Row spacing (cm)			l.s.d. (P = 0.05)
	70	35	17.5	
	Total dry weight (kg/ha)			
Bloodwood	4661	5385	4960	685
Dainagon	3762	4947	4643	
Erimo	4850	5125	5390	
	Canopy height (cm)			
250×10^3	34.1	31.8	32.7	2.5
500×10^3	38.5	33.7	31.6	
750×10^3	38.6	35.6	34.7	

were observed (Table 6). There was no significant interaction between row spacing and plant density with a maximum yield of 1916 kg/ha at 17.8 cm row spacing and 750×10^3 plants/ha showing a largely additive increment of 47% over 1306 kg/ha at 71.1 cm row spacing and 250×10^3 plants/ha.

The varieties Bloodwood and Erimo were similar for yield, total dry weight, seed weight, flowering and ground xcover, with only small differences in canopy height and maturity, whereas Dainagon, as it was in trial 2 and in contrast to trial 1, was lower yielding than Bloodwood (Table 6). The reduced yield of Dainagon in this trial was also reflected in lower shoot weight, height and ground cover plus later maturity than Bloodwood (contrasting with earlier maturity in trial 1).

Total dry weight was measured at about peak growth as dehiscence of older leaves began. Total dry weight was reduced only at wide spacing and low plant density, with equivalence between 17.8 and 35.6 cm row spacings and between densities of 500×10^3 and 700×10^3 plants/ha (Table 6). The only interaction was between variety and row spacing. No significant response was shown by Erimo, but Bloodwood and Dainagon had reduced total dry weights in 71.2 cm row spacing, with maximum values expressed at 35.6 cm row spacing but not significantly above those for 17.8 cm row spacing (Table 7).

Phenology effects were relatively slight, with flowering earlier in wide than in intermediate and narrow rows, and both flowering and maturity later in low than in intermediate and high plant densities.

Canopy height was increased in 70 cm rows and positively responded to each increment in plant density. The resultant interaction (Table 7) displayed significantly greater height at both 500×10^3 and 750×10^3 plants/ha at 71.1 cm spacing compared with the other row spacings in all 3 densities, as well as the lowest plant density at 71.2 cm spacing.

Ground cover was dramatically less in wide, 71.1 cm, rows with no difference between 35.6 and 17.8 cm row spacings, and ground cover was also less at 250×10^3 plants/ha with a non-significant gain at high over intermediate plant density (Table 6). Extensive interactions for percentage ground cover (Table 8) occurred amongst spacing, plant density and variety. Ground cover was least at 71.1 cm row spacing and at 250×10^3 plants/ha, and Dainagon responded more than the other varieties for an increased ground cover from 500×10^3 to 750×10^3 plants/ha. Row spacing × plant density interactions for ground cover principally involved a marked minimum value for the 71.2 cm × 250×10^3 plants/ha treatment.

Table 9. Trial 3. Variety × plant density interaction for harvest index

Variety	Density (plants/ha)			l.s.d.
	250×10^3	500×10^3	750×10^3	(P = 0.05)
Bloodwood	0.32	0.39	0.34	0.079
Dainagon	0.28	0.29	0.41	
Erimo	0.34	0.34	0.34	

Table 8. Trial 3. Treatment interactions for ground cover percentage

	Row spacing (cm)			l.s.d.	Density (plants/ha)			l.s.d.
	17.5	35.6	70.0	(P = 0.05)	250×10^3	500×10^3	750×10^3	(P = 0.05)
				Row spacing × variety interaction				
Bloodwood	95.8	93.3	81.3	4.9				
Dainagon	87.1	89.2	66.3					
Erimo	93.8	93.8	82.1					
				Row spacing × variety interaction				
Bloodwood					85.8	91.3	93.3	1.75
Dainagon					71.7	85.8	88.3	
Erimo					84.6	91.7	93.3	
				Row spacing × plant density interaction				
17.5 cm					84.6	96.3	99.5	3.5
35 cm					85.0	94.2	97.1	
70 cm					72.5	78.3	78.3	

Seed weight was affected by plant density but not row spacing, with seed weight reduced by 8% at the low plant density. Dainagon had 43% larger seed than Bloodwood and Erimo. Harvest index response was significant only for high over low plant density, due mainly to the variety Dainagon which displayed a significant variety × plant density interaction (Table 9).

Discussion

Plant density

In all 3 trials, there was a yield increase of 18.5–31.0% for plant density increases in the 200×10^3–750×10^3 plants/ha range. This occurred over a 2-fold difference in site mean yield, which could be expected to influence inter-plant competition in the row spacing and plant density treatments. The consistency of the studies is further shown by comparing the respective plant density yield increases at 35.6 cm spacing in trials 1 and 3 with the yield increase at 30 cm spacing in trial 2: being 21, 22 and 18.5% respectively. Varietal × plant density interaction for yield only occurred in trial 2, with no response for Dainagon, a significant and positive response to increased plant density for Erimo, and an almost significant positive response for Bloodwood with increasing plant density.

Seed weight responses to plant densities were inconsistent. In trials 1 and 3, seed weight increased from the low to the intermediate plant density, but declined marginally between intermediate and high plant density in trial 2. The latter result was due to plant density × line interaction and a negative response only for the large-seeded variety Dainagon. In the other trials no plant density × variety interaction occurred for seed size. Dainagon was the only large-seeded variety in trials 2 and 3.

Dainagon was included in all 3 trials. The comparable height measurements indicate a height decline with increasing plant density in trial 2, but the reverse trend in trials 1 and 3. These results suggest that within-row competition between plants spaced at 4.76 cm within rows for 700×10^3 plants/ha in trial 2 was increased at nearly twice the yield level of the other trials. Thus the optimal plant density for Dainagon in a high yielding environment was 400×10^3– 550×10^3 plants/ha but 750×10^3 plants/ha in low yielding environments, whereas 700×10^3–750×10^3 plants/ha maximised yield for Bloodwood in all trials. Bloodwood and Erimo, both with medium seed size, may be capable of further yield responses to densities above 750×10^3 plants/ha even in high yielding environments, provided that row spacings are 35 cm or less.

Row spacing

Yield. Row spacing, investigated in trials 1 and 3, had yield responses of 19–26% from 71 to 18 cm rows. Lawn (1983) found a partially linear 71% yield response in adzuki bean from 100 to 25 cm row widths with a January sowing in south Queensland, but with density/ha confounded with row spacing due to a constant 20 plants/m within rows. In the current studies number of plants/m at harvest were 15.7 for the wide row–low seeding rate treatment and 12.7 for the narrow row–high seeding rate treatment, with a yield gain of 58% in the latter. For earlier sowing dates with greater vegetative growth, Lawn (1983) found grain yield to be either depressed in narrow rows or to plateau at 50 cm row spacing in combination with full light interception during reproductive growth.

In trials 1 and 3 the yield responses to both plant density and row spacing were mainly additive, although in trial 1 an interaction occurred with little response to plant density in wide rows, but a 69% response in narrow rows. A similar interaction had been observed in navy beans (Redden *et al.* 1987), a summer legume of similar duration though less determinate habit. A varietal interaction with row spacing occurred in trial 1. The 2 large-seeded varieties Dainagon and Wase Dai Ryu demonstrated continuous and large yield responses to narrowing of rows, but there was an absence of responses for Bloodwood and Cha Gara Wase. The latter had the lowest yield potential, lowest height and least ground cover, this apparent non-adaptation may be relevant to its lack of response to row spacing. Bloodwood, however, did show a positive yield response to narrower rows in trial 3. Varietal interaction with environment was also demonstrated by the yields of Dainagon being significantly lower than Bloodwood in trials 2 and 3, but not significantly greater than Bloodwood in trial 1. Factors which might contribute to variety × site interaction for yield include soil type, climate, rainfall–irrigation with possible under watering in trial 1 and over watering in trial 3, and relative humidity. Genetic adaptation may be site specific in certain cases, for example, Dainagon with high yield, ground cover and moderate height at Kingaroy, but relatively lower than Bloodwood and Erimo in these expressions at other locations. Yield of adzuki bean has been found to be more sensitive to row width than for other *Vigna* spp. (Lawn 1983).

Seed weight. A positive seed weight response of 57% to narrow rows was significant in trial 1 only, a similar but reduced response in trial 3 was non-significant. However, in trial 1 varietal interaction with row spacing showed absence of response for Bloodwood and Cha Gara Wase, and differential row spacings for maximum expression of seed weight in 35.8 cm rows for Dainagon and 17.8 cm rows for Wase Dai Ryu. Thus Bloodwood was consistent with no seed weight response to row spacing in both trials, whereas Dainagon appeared to show specific adaptation to environments.

Maturity. A very small delay in maturity of less than 1 day at low plant density occurred in trials 1 and 3. In trial 3 flowering was delayed by 0.5 days at the lowest plant density compared with intermediate and high plant densities, but shortened by 1 day in wide rows in comparison with other row spacings. No row spacing × plant density interactions were found for either time to flower or for maturity. These phenologic responses are unlikely to be biologically significant in most field situations.

Height. Height responses to row spacing were inconsistent, maximised in narrow rows in trial 1, but in wide rows in trial 3. In the absence of significant interactions, no conclusions can be drawn from these results.

Ground cover. Ground cover was 19 and 25% less in wide rows than narrow rows in trials 3 and 1 respectively. The differences between 35 and 17.8 cm rows was either small or non-significant. There were also responses at a lower level to increased plant density in both trials, especially from the 250×10^3 to 500×10^3 plants/ha treatments.

Interactions between row spacing, plant density and variety were a feature of both trials. In wide rows the ground cover increases with plant density were 20% in trial 1 but 6% in trial 3; corresponding responses in narrow rows were 10% in trial 1 and 15% in trial 3. In both trials there was nearly full ground cover in the narrow row, high plant density treatment. The depressed adzuki bean yields in wide rows observed by Lawn (1983), was ascribed to incomplete interception of solar radiation, with leaf area index least for January rather than November and December sowings in southern Queensland.

Plant stands were comparable with 20 plants/m (Lawn 1983) at the high seeding rate in 35.6 cm rows with 19.1 plants/m. However, ground cover data in the current study are inadequate to account for the physiology of yield responses, especially as total biomass was only measured in trial 3. Ground cover percentage had correlations of $R^2 = 0.64$ (n = 27) with grain yield and R^2 = 0.38 with biomass in trial 3.

Varietal interactions with row spacing for ground cover displayed the largest differences in wide rows with non-significant and small differences in ground cover in narrow rows. In both trials 1 and 3 Dainagon had less ground cover than Bloodwood in the wide rows. Bloodwood and Erimo were very similar in ground cover responses to spacing in trial 3. A varietal interaction with plant density occurred in trial 3 only, where Dainagon had particularly low ground cover at low plant densities. Thus Dainagon had less capacity to achieve ground cover unless rectangularity was reduced and plant densities increased.

Biomass. Total dry weight was recorded in trial 3 only, and was less responsive than grain yield with significant response to row spacing but not plant density. Harvest index, yield/total dry weight, therefore showed the converse with no response to row spacing but a significant reduction at low plant density. However, Dainagon showed a varietal interaction with plant density, with a dramatic increase in harvest index at high plant density. For total dry weight significant varietal interaction occurred with row spacing, with a reduction in wide rows, and maximum expressions in 35 cm rows for Bloodwood and Dainagon.

Although a correlation of 0.92 was found between total dry weight and harvest index over varieties and row spacing, this association was weaker at r = 0.65 with the omission of the wide row spacing treatment. Broadly the results are suggestive of a direct relationship between solar interception and total dry weight as indicated by ground cover. However, Dainagon responded differently from other varieties.

Conclusions

Benefits are suggested for improved yield, harvest ability, establishment and seed size with the planting of adzuki beans in narrow rows with high plant densities. The Japanese standard Erimo is equivalent to Bloodwood in yield and agronomy and appears suitable for commercial use in Australia with similar crop recommendations. The large-seeded variety Dainagon appears to be more sensitive to density and row spacing and may have reduced yield. This study is part of a larger integrated project involving extension, food, economic and marketing research (Redden and Desborough 1996) and final recommendations will depend on these complementary studies. The Japanese standard variety Erimo performed similarly to Bloodwood for yield and seed weight at different plant densities and row spacings, but the large-seeded variety Dainagon was inconsistent in responses with comparable high yield in the narrow row treatment at only one site. In general, larger seed is desirable in export markets and the current extension ‘Agnote’ on adzuki bean (Falconer and Desborough 1983) already recommends narrow rows (18 cm) and densities of 500×10^3 to 600×10^3 plants/ha. This study supports these recommendations with the question of seeding rate to be further examined on practical and economic criteria.

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