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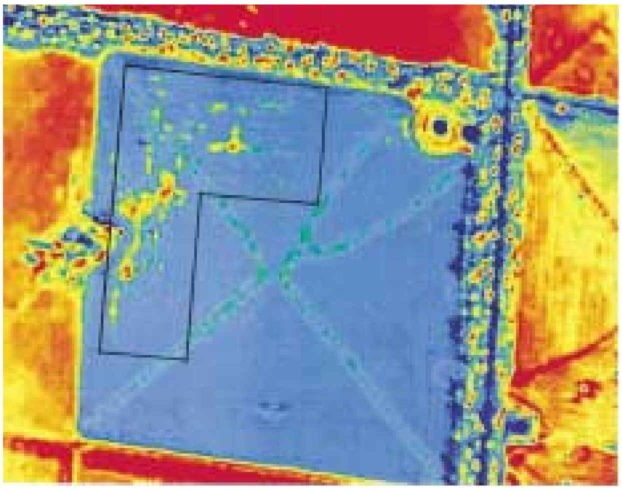

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Assessment and selection of new hybrids from the Australian cashew breeding program

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Abstract. Cashew (*Anacardium occidentale* L.) is an emerging crop suited to tropical regions of Australia. To be viable on world markets, Australian cashews must be more productive and of higher quality than competing products. Since these characteristics are not exhibited consistently by existing varieties, an improvement program was initiated. This paper reports on the evaluation of 2 sets of hybrids produced in 1991 and 1992, which were planted on commercial cashew orchards in the Northern Territory and Queensland and were assessed in terms of yield and quality during 1998 and 1999.

Large differences in performance were measured between families. Depending on the site and hybrid set, the best family yielded 2–5 times more than the least-productive family. Also, kernel weight and kernel recovery, key characteristics of quality, varied significantly between families. Comparison between sites indicated a genotype by environment interaction, necessitating separate selections for each of the sites.

Eleven individual trees that exceeded minimum productivity standards were selected from the best-performing families at each site which were NDR2-1 × GUNTUR, GUNTUR × CJ1, CJ1 × GUNTUR, GUNTUR × 1-2-13, 2-3-10 × GUNTUR, 5-14-4 × GUNTUR and 1-3-4 × GUNTUR. The economic value of these trees was 1–1.5 times higher than the minimum threshold and was a reflection of the high yield and quality of the nuts they produced.

Genetic analyses indicated that the traits studied had relatively high heritabilities, suggesting considerable scope for further improvement by breeding. To facilitate this, 10 trees were selected from each set of hybrids at each site for use as second-generation parents.

Introduction

Cashew (*Anacardium occidentale* L.) is an emerging tree crop in northern Australia. Current world production of cashew is in excess of 1 million tonnes, but is below demand (Azam-Ali and Judge 2000). Australian imports of cashew are currently valued at about US$30 million per year. To be competitive on world markets, Australian cashew trees must produce higher yields of better quality nuts than traditional cashew producers in Asia, Africa and South America.

In contrast to most other cashew-growing regions of the world, Australian cashew production is intensive. To offset associated costs, yields must be greater than the world average of 0.5–1.0 t nut-in-shell (NIS) per hectare. Oliver *et al.* (1992) suggested a target NIS yield of about 4.0 t/ha, but recently Hinton (1998) concluded that NIS yields of 2.5–3.0 t/ha would be viable. Cashew is noted for its precocity and in Australia begins bearing within 2 or 3 years of planting. Peak yields are usually achieved by about 6 years (Grundon *et al.* 1999), with an expectation that these levels of productivity would be maintained for at least 15 years.

As well as yield, the economic value of cashew is determined by kernel characteristics. Commercial kernel size (weight) is influenced by nut size and kernel recovery, the latter being the proportion (%) by weight of kernel in the whole nut. Kernel size is known to vary from less than 1.0 g to more than 2.5 g (at standard moisture content of 5% w/w) and the value increases progressively with size (Malorgio 1994). In early 2000, typical prices for 1.0 g and 2.5 g kernels were A$8.70 and A$12.90 per kilogram, respectively (P. Shearer pers. comm.).

An appraisal of imported and locally available cashew selections in northern Australia indicated that they were unlikely to meet productivity criteria (Chacko *et al.* 1990) and a crop improvement program was started to develop superior varieties tailored for the Australian industry. Hybrids were bred using parents from India, Brazil and

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within Australia. Indian research (Nair *et al.* 1979) had demonstrated large yield improvements in hybrids bred from parents of diverse geographic origin, compared with parents from local populations. Similar large improvements were anticipated from the Australian program. The aim was to identify high-yielding hybrids with nuts of at least 6–10 g and kernel recovery of at least 25–30% to attract premium prices. An additional aim was to develop varieties with erect growth habit suited to high planting densities (Chacko *et al.* 1990).

Although more than 4000 hybrids were produced, the work reported in this paper concentrates on 2 subsets of several hundred hybrids produced in 1991 and 1992. These hybrids featured the Indian variety Guntur as the predominant parent (female or male), which had the desired growth habit (Chacko 1993). Data were collected and analysed to identify hybrids suitable for release to industry and for second-generation parents for further breeding. Selections based on genetic analyses, the first for Australian cashew, were compared with those based on phenotypic data.

Materials and methods

Production of hybrids

Parents were selected on the basis of pre-existing productivity and quality data for which nut size ranged from 5.3 to 10.9 g, kernel size from 1.4 to 3.2 g and kernel recovery from 26 to 34% (Table 1).

Crosses were made by controlled pollination at cashew plantations in the Northern Territory (NT) (Chacko 1993). At maturity, nuts from crosses were harvested and sown. Several months after germination, each hybrid was multiplied by grafting onto seedling rootstocks and then planted in the field for evaluation. Seedling rootstocks were from a common mother source tree (BLA39-4), which had produced trees of uniform growth habit in previous work (E. K. Chacko unpublished data). The 2 hybrid sets used in the present study came from crosses made in 1991 (91 hybrids) and 1992 (92 hybrids).

Description of sites

Hybrids were evaluated at 2 commercial plantations: Cashews NT (13°S, 132°E), 120 km south-east of Darwin (NT site), and Cashews Australia (17°S, 145°E), 100 km west of Cairns (Qld site). At the NT site the maximum temperature typically ranges from 36°C in October to 30°C in June and the minimum temperature from 12°C in July to 24°C in November. At the Qld site, the maximum temperature ranges from 25°C in July to 31°C in December, while the minimum ranges from 14°C in July to 22°C in February. At the Qld site, a pause in tree growth is associated with the lower temperatures during June–August which delay flowering and nut development by about a month compared with the NT site (Grundon *et al.* 1999). Rainfall — 1360 mm at the NT site and 780 mm at the Qld site — occurs mainly during the months December–March. At both sites, reproductive growth coincides with a dry season (<100 mm rainfall) from June to October. The soil at the NT site is a red earth, Gn2.11, and at the Qld site is a haplic, mesotprophic, red chromosol, Dr4.62 (Northcote 1979).

Field layout

The 91 and 92 hybrids were planted in 1992 and 1993, respectively. At each site, the 91 and 92 hybrids were planted within separate but adjacent areas. Within each area the location of hybrids was randomised.

Evaluation strategy

The numbers of individuals assessed within each family and, within each family, the number that were clonally propagated are shown in Table 2. Only families with at least 5 hybrids were selected for detailed assessment. Where there were more than 20 individuals within a family at a site, a randomly selected subsample of 20 was assessed. Some families were represented at both sites and, within these, some hybrids were duplicated between sites since they had been multiplied by grafting to seedling rootstocks. In all cases, a single replicate of each hybrid was assessed.

Table 1. Key characteristics of the parents of hybrids generated in 1991 and 1992 (Chacko 1993)

Parent	Country of origin	Nut-in-shell weight (g)	Kernel size (g)	Kernel recovery (%)	Comments
GUNTUR	India	5.6	1.5	27	Ideal growth habit
NDR2-1	India	6.9	2.0	29	High yield in India, spreading habit
H3-13	India	5.3	1.4	26	Upright habit
Ullal	India	6.0	1.7	28	High fruit set, heavy-bearing
K22	India	5.9	1.6	30	High-yielding, upright habit
1-1-14	Brazil	7.9	2.2	29	—
1-2-13	Brazil	8.3	2.5	30	—
1-3-4	Brazil	7.5	2.0	27	—
1-3-17	Brazil	10.9	3.2	30	—
1-4-11	Brazil	6.4	2.0	31	—
1-4-16	Brazil	6.1	2.0	32	—
1-4-18	Brazil	7.0	2.4	34	—
1-6-8	Brazil	9.3	2.4	26	—
2-3-10	Brazil	9.4	2.9	31	—
2-6-9	Brazil	6.3	2.0	31	—
2-11-11	Brazil	7.7	2.1	28	—
3-11-19	Brazil	6.6	1.8	28	—
4-5-14	Brazil	9.8	3.0	30	—
5-14-4	Brazil	7.3	2.0	27	—
CJ1	Brazil	9.3	2.9	31	—
R9T14	Australia	6.2	1.7	33	High yield in Darwin
KAM6	Australia	6.0	1.5	33	High yield in Queensland

Cultural management

Trees were planted at 7 by 5 m and 6 by 6 m at the NT and Qld sites, respectively. At each site, agronomic inputs (pesticides, fertilisers and irrigation) were provided by the managers in line with the overall plantation management strategy. These inputs were suboptimal at the Qld site during 1998, but during 1999 supplemental inputs were provided by the research team.

Data collection

Assessments were carried out in 1998 and 1999, when the 91 and 92 hybrids had been growing in the field for 5–7 and 4.5–6 years, respectively. At this age, trees were considered to have completed their juvenile phase and developed the seasonal pattern of growth that is characteristic of mature trees. Limiting data collection to 2 consecutive years represented a compromise between gaining knowledge about the repeatability of hybrid performance and being able to release hybrids to industry within time and budgetary limitations.

In each year, hybrids were hand-harvested and (i) assessed for total NIS weight (kg/tree), and a 25-nut subsample randomly selected to determine, (ii) average nut weight (g/nut), and (iii) average kernel weight (*kwt*, g/kernel).

For comparison with commercial yields, NIS weight was based on a minimum commercial nut size (≥25 mm in length) expressed at 9% water content (WC), the threshold recommended for safe storage of nuts in India (Russell 1969) and Brazil (Franca 1988). Kernel weight was expressed at 5% WC, the maximum specified by the International Organisation for Standardisation for packaging following nut processing (ISO 1982).

The canopy surface area (CSA) of each tree was calculated from tree height and diameter, assuming a spherical shape. Losses of CSA because of skirting of the lower canopy for machinery access and, at the NT site, the close proximity of neighbouring trees, were taken into account. Typically, CSA of mature cashew in Australian plantations is 75–100 m^2 and, because cashew is a terminal bearing species, represents a measure of the potential productivity of the tree. Expressing nut production on the basis of CSA allowed comparisons between trees of different size.

The following variables were derived from the raw data: (i) canopy productivity [*canprod*, NIS (g) per CSA (m^2)], (ii) kernel recovery [*kr*, percentage kernels (g, at 5%WC) per NIS (g, at 9%WC)], and (iii) economic value [*value*, kernel value (in A$) per100 m^2 of CSA].

To calculate *value*, each hybrid's kernel yield (g/m^2 CSA) was multiplied by the kernel price corresponding to the particular kernel grade specified by the ISO (1988) for the average kernel weight of the hybrid. Prices, supplied by commercial traders, were averages for the previous 8 years (Table 3). *Value* integrated important yield traits of *canprod*, *kwt* and *kr* to rank individuals and families. *Value* was the principal basis for comparing performance and making selections among hybrids.

At the Qld site the trees grew unpruned, except for skirting, as 'spaced trees'. To make comparisons of growth habit, an index of canopy form, *shape*, expressed canopy height as a proportion of the canopy mean diameter measured along and across the row. Thus, for tall, narrow canopies, *shape* was relatively high, while for short, spreading canopies it was low. At the NT site, regular pruning was required to minimise competition between trees and for this reason, *shape* was not calculated at this site.

Statistical analyses

Phenotypic analyses. Separate univariate analyses of variance were performed on all response variables for each site and each year of harvest to test for differences between hybrids. Examination of residuals showed that none of the variables required transformation.

Genotype × Environment (G × E) interactions for *value*, *canprod*, *kr* and *kwt* were investigated separately for the 91 and 92 hybrids, by performing 3-way analyses of variance on families common to each site. These analyses included site and year as factors, with G × E indicated by a significant family × site interaction. The relative performances at each site of the families selected for evaluation was of primary importance, so family was a fixed effect in the analyses.

Table 2. Parental combinations, family size and the number of identical accessions at Northern Territory (NT) and Queensland (Qld) sites for 91 and 92 hybrids

Parents		Family size		No. of identical
Female	Male	NT site	Qld site	accessions
		91 hybrids		
CJ1	GUNTUR	11	8	6
GUNTUR	CJ1	14	6	1
NDR2-1	GUNTUR	18	8	4
GUNTUR	NDR2-1	16	19	7
ULLAL	GUNTUR	7	7	3
GUNTUR	ULLAL	7	5	1
H3-13	GUNTUR	n.a.	20	
K22	GUNTUR	n.a.	10	
GUNTUR	K22	n.a.	12	
GUNTUR	1-1-14	n.a.	20	
GUNTUR	1-2-13	n.a.	20	
Total		73	135	22
		92 hybrids		
2-3-10	GUNTUR	20	20	12
2-6-9	GUNTUR	13	20	9
5-14-4	GUNTUR	20	21	6
GUNTUR	1-6-8	20	20	11
GUNTUR	4-5-14	8	20	5
4-5-14	GUNTUR	n.a.	5	
GUNTUR	KAM6	20	20	7
1-3-4	GUNTUR	n.a.	7	
GUNTUR	1-3-4	n.a.	12	
1-3-17	GUNTUR	n.a.	12	
GUNTUR	1-3-17	n.a.	19	
1-4-11	GUNTUR	n.a.	20	
1-4-16	GUNTUR	n.a.	19	
1-4-18	GUNTUR	n.a.	20	
3-11-19	GUNTUR	n.a.	16	
GUNTUR	2-11-11	n.a.	17	
R9T14	KAM6	n.a.	13	
Total		101	281	50

n.a., not assessed.

Table 3. Average (1992–2000) cashew kernel price (A$/kg), FOB used in economic value calculations (Pankaj N. Sampat, pers. comm.)

FOB, 'free on board' includes costs of loading kernels for dispatch

Kernel grade	Price (A$)
W180 (kernels >2.53 g)	$12.91
W210 (kernels 2.15–2.52 g)	$11.79
W240 (kernels 1.89–2.14 g)	$9.99
W320 (kernels 1.42–1.88 g)	$9.12
W450 (kernels 1.01–1.41 g)	$8.69

Similar analyses were conducted using data from individual accessions common to each site (Table 2). Since duplicated hybrids were not replicated within sites, year interactions were used as residuals in analyses. Correlation coefficients comparing the phenotypic performance of duplicated hybrids between sites were calculated for each year.

Genetic analyses. Restricted maximum likelihood (REML) was used to estimate variance components for random effects (Searle *et al.* 1992), and best linear unbiased predictors (BLUP) to obtain estimated breeding values (EBV) (White and Hodge 1989). Analyses were performed using the ASREML program (Gilmour *et al.* 2000). Separate analyses were performed for the 1991 and 1992 hybrid sets.

For each variable, an analysis was carried out based on the model:

$$y = Xb + Za + W_1 s + W_2 c + e \quad (1)$$

where y is the vector of observations for a given trait collected from individual trees at each site over 2 years, b is a vector of the fixed effects of site and year, a is a vector of random additive genetic effects of individual trees, c is a vector of random effects of specific combining ability between the 2 parents, s is a vector of random effects of parent-by-site and parent-by-year interaction, and X, Z, W_1 and W_2 are incidence matrices. In this model, the inclusion of parent as a random effect to determine breeding values contrasted with family as a fixed effect in the phenotypic analyses.

Preliminary analysis based on the model (equation 1) showed that c was not significant by the maximum likelihood ratio test (Gilmour *et al.* 2000) and the model was reduced to

$$y = Xb + Za + W_1 s + e \quad (2)$$

The model terms for the bivariate analyses to determine genetic and phenotypic correlations were the same as in this model (equation 2).

Narrow-sense heritability was estimated as:

$$h^2 = \sigma_a^2/(\sigma_a^2 + \sigma_{gs}^2 + \sigma_{gh}^2 + \sigma_r^2) \quad (3)$$

where σ_a^2 is variance due to additive genetic effects, σ_{gs}^2 is variance due to parent-by-site interactions, σ_{gh}^2 is variance due to parent-by-year interactions, and σ_r^2 is residual variance.

Genetic (r_g) and phenotypic correlations (r_p) were calculated as:

$$r = \sigma_{ij}/(\sqrt{\sigma_i^2\ \sigma_j^2}) \quad (4)$$

where σ_{ij} is covariance between ith and jth traits, and σ_i^2 variance for ith trait and σ_j^2 for jth trait. Variance components were referred to as genetic or phenotypic, respectively, depending on whether r_g or r_p was estimated.

Results

Phenotypic performance

Family performance — overall. Significant differences in family performance were detected at both sites (Table 4). Also, there were differences between years, particularly at the Qld site where *canprod* was up to 10 times greater in 1999 than in 1998. This large increase in productivity was associated with a mean *kwt* that was 30% lower in 1999 than in 1998.

Family performance — 91 hybrids. A wide range of *value* was observed between families, although the differences were only significant at the Qld site in 1999. In this case, CJ1 × GUNTUR had the highest *value* of \$42.9/100 m^2 CSA, but GUNTUR × CJ1, GUNTUR × NDR2-1, NDR2-1 × GUNTUR, GUNTUR × 1-2-13 and GUNTUR × 1-1-14 all had *value* that was similar, in the range \$34.7–40.8/100 m^2 CSA. For these families with high *value*, *shape* in 1999 was near the top of the range, at about 1.10.

Although the level of replication was fairly low and varied within families, 'family × site' interactions indicated that *canprod* was dependent on site but that *value* and *kwt* were not. For example, CJ1 × GUNTUR was the highest-ranked family for *canprod* (mean over 2 years) at the NT site, but GUNTUR × NDR2-1 was the highest at the Qld site. Within families, the performance of duplicated hybrids common to each site was only weakly correlated (r for *value* and *canprod* in the range of 0.25–0.45).

Family performance — 92 hybrids. At the NT site, *value* ranged from \$9.4 to \$28.3/100 m^2 CSA, with 5-14-4 × GUNTUR being significantly higher than any other in 1998 (Table 4). At the Qld site, 1-3-4 × GUNTUR had the highest *value* in each year, with \$20.1/100 m^2 CSA in 1998 and \$40.0/100 m^2 CSA in 1999, but had *shape* that was ranked near the middle of the range. Other families with relatively high *value* in 1998 were GUNTUR × 1-3-4, GUNTUR × 1-6-8 and GUNTUR × 2-11-11 and in 1999, 1-3-17 × GUNTUR and GUNTUR × 1-3-17.

For families common to each site, there were significant G × E effects for *value*, *canprod* and *kr* but not for *kwt*. Based on means over 2 years, the top ranked family for both *value* and *canprod* was 5-14-4 × GUNTUR at the NT site, while at the Qld site, GUNTUR × 4-5-14 was top-ranked for *value* and GUNTUR × 1-6-8 for *canprod*. For *kr*, GUNTUR × 4-5-14 was top-ranked at the NT site, while at the Qld site the top-ranked was 2-6-9 × GUNTUR. Within families, the performance of duplicated hybrids common to each site was not correlated for *value* and *canprod* (r = 0.05–0.11) and was weakly correlated for *kr* (r = 0.08–0.36).

Selection of best trees for commercial planting — overall. Trees identified for release to the Australian cashew industry were selected according to the following conditions. The first was that trees belonged to one of the highly ranked families identified in Table 4. The second was that they met standards over both years of (i) mean (1998 and 1999) *value* of ≥\$40/100 m^2 CSA, (ii) *kr* ≥25%, and (iii) *kwt* ≥1.5 g. The *value* threshold was broadly equivalent to an annual NIS yield of 2 t/ha and approaching the minimum acceptable for a future Australian industry.

Selection of best trees for commercial planting — 91 hybrids. Four hybrids were selected for their superior performance at the NT site (Table 5). These were from NDR2-1 × GUNTUR, GUNTUR × CJ1 and respective reciprocals. The maximum mean *value* of \$47/100 m^2 CSA was achieved by 1 tree (ID 3022). For these trees, *kr* ranged from 25.4 to 34.7% and *kwt* ranged from 1.5 to 2.5 g. The nut yield of these trees, represented by *canprod*, was high, NIS/CSA ranging from 135 g/m^2 (ID 3274) to 245 g/m^2 (ID 2393) in 1999.

At the Qld site, 2 trees were selected (Table 5). These were from GUNTUR × 1-2-13 and CJ1 × GUNTUR. For each, the mean *value* was \$42/100 m^2 CSA and the *kr* and *kwt* ranged from 26.3 to 32.4% and from 1.6 to 2.3 g, respectively. Over both years *canprod* ranged from about 80 g/m^2 (NIS/CSA) to more than 200 g/m^2 during 1999. The *shape* of these hybrids was close to or above respective family means.

Selection of best trees for commercial planting — 92 hybrids. Two trees each were selected from 2-3-10 × GUNTUR and 5-14-4 × GUNTUR at the NT site (Table 5). One tree achieved a very high *value* of \$59/100 m^2 CSA (ID 4260) and all 4 trees had *kr* and *kwt* well in excess of minimum standards. These trees had *canprod* usually in the range 140–200 g/m^2 (NIS/CSA) .

At the Qld site, only 1 tree (ID 4428) from 1-3-4 × GUNTUR met all performance standards (Table 5*b*). For this tree *value* was \$44/100 m^2 CSA, with *kr* and *kwt* exceeding 31% and 2 g, respectively, in each year. *Canprod* ranged from 68 g/m^2 (NIS/CSA) in 1998 to 191 g/m^2 in 1999. The *shape* of this tree was similar to its family mean.

Genetic parameters

Variance components were estimated for the random effects of parent × site and parent × year interactions but were non-significant as shown by a likelihood ratio test (Gilmour *et al.* 2000). This contrasts with significant family × site interactions found in the phenotypic analyses for some response variables for both 91 and 92 hybrids. Thus, different ranking of the performance of the families at the 2 sites was not due to different ranking of the parent lines (averaged over all the families derived from them) at the 2 sites.

Estimates of narrow-sense heritability (h^2) indicated that there is considerable scope to improve the traits studied by breeding (Table 6). The derived measures of productivity,

Table 4. Performance of families measured in terms of economic *value* (A\$/100 m^2 CSA), canopy productivity (*canprod*), kernel recovery (*kr*), and average kernel weight (*kwt*) in 1998 and 1999 for 91 and 92 hybrids and, for the Queensland site, *shape* in 1998 and 1999

Average s.e.d. is the standard error of difference between family means, assuming average replication for each family. Family × site *P*-values were derived from analyses including both 1998 and 1999. Bold type denotes families common to each site

Female	Male	Northern Territory site								Queensland site									
		value 1998	*value* 1999	*canprod* 1998	*canprod* 1999	*kr* 1998	*kr* 1999	*kwt* 1998	*kwt* 1999	*value* 1998	*value* 1999	*canprod* 1998	*canprod* 1999	*kr* 1998	*kr* 1999	*kwt* 1998	*kwt* 1999	*shape* 1998	*shape* 1999
									91 hybrids										
CJ1	**GUNTUR**	**20.0**	**29.7**	**73.8**	**113.9**	**27.9**	**27.8**	**1.92**	**1.96**	**8.8**	**42.9**	**31.5**	**167.2**	**26.4**	**28.2**	**2.01**	**1.64**	**0.909**	**1.126**
GUNTUR	**CJ1**	**15.2**	**30.9**	**57.1**	**114.3**	**27.4**	**28.0**	**1.85**	**1.91**	**11.0**	**35.8**	**36.9**	**149.3**	**28.7**	**26.6**	**1.84**	**1.32**	**0.910**	**1.101**
NDR2-1	**GUNTUR**	**14.9**	**26.5**	**51.7**	**91.9**	**28.0**	**29.0**	**1.90**	**1.94**	**9.5**	**34.7**	**33.6**	**128.2**	**29.9**	**30.6**	**1.80**	**1.20**	**0.894**	**1.105**
GUNTUR	**NDR2-1**	**13.3**	**20.1**	**47.3**	**64.5**	**28.6**	**29.0**	**1.97**	**2.01**	**14.2**	**40.7**	**50.7**	**152.5**	**30.3**	**29.9**	**1.89**	**1.23**	**0.931**	**1.083**
ULLAL	**GUNTUR**	**16.3**	**16.7**	**62.1**	**69.2**	**28.6**	**26.5**	**1.64**	**1.59**	**9.7**	**23.1**	**39.7**	**100.7**	**27.5**	**26.6**	**1.48**	**0.86**	**0.860**	**0.927**
GUNTUR	**ULLAL**	**16.9**	**20.5**	**65.9**	**84.8**	**28.7**	**26.9**	**1.51**	**1.55**	**5.1**	**29.0**	**19.5**	**111.6**	**28.5**	**29.5**	**1.83**	**1.01**	**0.803**	**0.907**
GUNTUR	K22	—	—	—	—	—	—	—	—	14.9	26.1	54.1	99.4	30.4	30.4	1.61	1.06	0.879	0.970
K22	GUNTUR	—	—	—	—	—	—	—	—	12.1	24.1	43.9	92.0	30.2	29.9	1.63	0.94	0.857	0.968
GUNTUR	1-2-13	—	—	—	—	—	—	—	—	11.3	40.8	38.2	154.4	28.5	29.3	1.93	1.49	0.884	1.088
GUNTUR	1-1-14	—	—	—	—	—	—	—	—	14.1	35.0	46.4	128.9	31.6	30.4	1.86	1.30	0.919	1.098
H3-13	GUNTUR	—	—	—	—	—	—	—	—	7.6	30.7	28.1	122.7	29.7	28.3	1.54	0.90	0.929	1.063
P-value		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.001	<0.001	n.s.	<0.001	n.s.	0.001	<0.001	<0.001	<0.001	<0.001	n.s.	0.023
Average s.e.d.		—	—	—	—	—	—	0.10	0.10	—	5.1	—	19.0	0.6	0.8	0.12	0.12	—	0.063
P-value (family × site)		n.s.		0.034		n.s.		n.s.											
									92 hybrids										
1-3-4	GUNTUR	—	—	—	—	—	—	—	—	20.1	40.0	52.8	117.5	30.4	31.6	2.58	2.17	0.832	0.955
GUNTUR	1-3-4	—	—	—	—	—	—	—	—	19.0	27.0	53.2	98.2	30.8	30.1	2.41	1.49	0.912	0.953
1-3-17	GUNTUR	—	—	—	—	—	—	—	—	8.0	33.4	24.0	108.8	29.6	29.7	2.27	1.99	0.825	0.933
GUNTUR	1-3-17	—	—	—	—	—	—	—	—	4.1	38.5	12.8	135.6	28.5	30.4	2.18	1.80	0.880	0.979
4-5-14	GUNTUR	—	—	—	—	—	—	—	—	9.1	30.0	29.3	120.6	28.4	28.3	2.20	1.41	0.962	1.026
GUNTUR	**4-5-14**	**9.4**	**23.1**	**29.2**	**75.8**	**29.4**	**29.6**	**2.19**	**1.99**	**6.9**	**32.7**	**23.1**	**127.9**	**27.8**	**28.5**	**2.14**	**1.50**	**0.965**	**1.096**
1-4-11	GUNTUR	—	—	—	—	—	—	—	—	8.1	29.2	27.6	105.9	29.9	30.7	1.73	1.29	0.801	0.860
1-4-16	GUNTUR	—	—	—	—	—	—	—	—	6.1	16.2	22.0	60.2	28.8	28.8	1.90	1.64	0.934	1.117
1-4-18	GUNTUR	—	—	—	—	—	—	—	—	7.7	31.1	25.2	113.2	30.4	31.0	1.97	1.46	0.836	0.904
2-3-10	**GUNTUR**	**19.7**	**22.7**	**62.4**	**72.6**	**29.5**	**28.8**	**2.14**	**2.07**	**5.5**	**28.7**	**19.5**	**109.2**	**28.3**	**29.1**	**1.81**	**1.48**	**0.868**	**0.947**
2-6-9	**GUNTUR**	**16.2**	**19.1**	**66.5**	**72.9**	**27.1**	**28.0**	**1.69**	**1.74**	**4.8**	**29.2**	**19.2**	**111.0**	**29.7**	**29.5**	**1.68**	**1.32**	**0.840**	**0.919**
3-11-19	GUNTUR	—	—	—	—	—	—	—	—	12.1	20.6	47.2	85.6	27.8	26.7	1.53	1.39	0.828	0.862
5-14-4	**GUNTUR**	**28.3**	**24.9**	**109.1**	**93.4**	**27.3**	**27.9**	**1.66**	**1.75**	**13.5**	**25.3**	**50.0**	**106.5**	**27.5**	**25.9**	**1.67**	**1.23**	**0.832**	**0.916**
GUNTUR	**1-6-8**	**17.4**	**18.2**	**63.9**	**67.8**	**27.8**	**27.5**	**1.84**	**1.89**	**15.2**	**24.3**	**56.1**	**106.5**	**28.5**	**25.7**	**1.77**	**1.19**	**0.837**	**0.962**
GUNTUR	2-11-11	—	—	—	—	—	—	—	—	16.8	25.2	59.9	106.5	29.0	27.2	1.86	1.23	0.865	0.961
GUNTUR	**KAM6**	**14.6**	**17.7**	**57.1**	**63.7**	**27.4**	**29.0**	**1.67**	**1.88**	**7.8**	**31.0**	**28.7**	**130.0**	**28.4**	**27.1**	**1.83**	**1.08**	**0.834**	**0.913**
R9T14	KAM6	—	—	—	—	—	—	—	—	12.6	26.6	46.1	114.7	28.4	26.8	1.69	1.10	0.838	0.998
P-value		<0.001	n.s.	<0.001	n.s.	n.s.	n.s.	n.s.	0.002	<0.001	<0.001	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	0.019	<0.001
Average s.e.d.		3.7	—	13.1	—	—	—	—	0.09	2.9	3.4	10.8	12.3	0.8	0.9	0.12	0.13	0.048	0.053
P-value (family × site)		0.003		<0.001		0.010		n.s.											

Table 5. Phenotypic characteristics of best-performing 91 and 92 hybrids selected from the Northern Territory (NT) and Queensland (Qld) sites, based on their production data in 1998 and 1999

Shape, index of canopy form (see Materials and methods)

ID	Female	Male	Economic value ($A\$/100\ m^2$ CSA)			Canopy productivity (NIS/CSA)(g/m^2)		Kernel recovery (%)		Average kernel weight (g)		Shape	
			1998	1999	Mean	1998	1999	1998	1999	1998	1999	1998	1999
						Northern Territory site, 91 hybrids							
3022	NDR2-1	GUNTUR	37.1	57.0	47.1	103.7	171.0	30.4	28.3	2.4	2.2	—	—
2393	GUNTUR	CJ1	21.7	61.8	41.8	81.2	244.6	29.4	27.7	1.9	1.7	—	—
3072	CJ1	GUNTUR	42.5	39.9	41.2	58.3	172.1	31.6	25.4	1.8	1.5	—	—
3411	NDR2-1	GUNTUR	24.8	55.8	40.3	104.5	136.2	26.0	34.7	1.8	2.5	—	—
						Queensland site, 91 hybrids							
3336	GUNTUR	1-2-13	31.3	52.2	41.8	82.0	178.6	32.4	32.1	2.2	1.6	0.91	1.07
3106	CJ1	GUNTUR	25.2	57.7	41.5	81.2	207.9	26.3	30.4	2.3	1.8	1.16	1.46
						Northern Territory site, 92 hybrids							
4260	2-3-10	GUNTUR	50.8	67.2	59.0	140.0	198.4	30.8	28.7	2.3	2.4	—	—
4386	5-14-4	GUNTUR	46.6	44.6	45.6	115.6	178.9	34.2	27.3	2.2	1.9	—	—
4379	5-14-4	GUNTUR	41.7	46.9	44.3	168.3	163.1	27.2	31.5	1.7	1.8	—	—
4242	2-3-10	GUNTUR	26.6	54.2	40.4	75.9	148.7	29.7	30.9	2.4	2.5	—	—
						Queensland site, 92 hybrids							
4428	1-3-4	GUNTUR	25.1	61.8	43.5	68.1	191.3	31.3	32.3	2.3	2.0	0.68	0.97

canprod and *value*, had h^2 in the range 0.15–0.23 for both the 91 and 92 hybrids. The direct measures of productivity, *kwt* and *kr*, had higher h^2 in the range 0.32–0.50. For each of these 3 traits, h^2 for the 91 hybrids was lower than for the 92 hybrids. For *shape*, h^2 was high, in the range 0.83–0.85, for both groups of hybrids.

Genetic and phenotypic correlations (0.93–0.97) were strong between *value* and *canprod* for both 91 and 92 hybrid sets (Table 7). Genetic correlations between *value* or *canprod* and *kr* were very weak, but the standard errors were high (0.13–0.25). Also phenotypic correlations between these traits were very weak but the standard errors were relatively small.

Selection of trees for further crossing

Estimated breeding values (EBV) for the derived trait *value* were calculated from genetic parameters and ranked for each of the 91 and 92 hybrids. EBV's for *value* ranged from 8.8 to 21.1 and from 3.5 to 19.6 for the 91 and 92 hybrids, respectively. The 10 top-ranked trees based on EBVs for *value* from each hybrid set at each site were listed as candidates for further crosses (Table 8).

Table 6. Calculated estimates of heritability (h^2) ± standard errors for derived and measured traits of 91 and 92 hybrids grown at the Northern Territory and Queensland sites in 1998 and 1999

Shape, index of canopy form (see Materials and methods)

Trait	91 hybrids	92 hybrids
Economic value ($\$/100\ m^2$ CSA)	0.21 ± 0.09	0.23 ± 0.06
Canopy productivity (NIS/CSA, g/m^2)	0.18 ± 0.09	0.15 ± 0.06
Kernel recovery (%)	0.45 ± 0.08	0.50 ± 0.06
Average kernel weight (g)	0.32 ± 0.08	0.46 ± 0.06
Shape	0.83 ± 0.04	0.85 ± 0.05

Discussion

Comparative productivity of selected hybrids

Eleven new cashew hybrids have been identified with potential for further development by the Australian industry. Their selection was based primarily on the novel parameters *value* and *canprod* which expressed tree productivity in terms of yield of saleable product (kernel), with the confounding effects of variation in tree (canopy) size and nut moisture content removed. These parameters were devised to standardise the way in which trees and their productivity were compared. In doing so, however, the need to exercise caution was highlighted when the productivity of the trees in this experiment was compared with data from other reports. Although moisture contents used to standardise yield data in this experiment were considered typical of commercial practice, other reports rarely specify moisture contents at which yields are determined. However, assuming similar moisture contents, nut size and kernel recovery for the hybrids in this experiment were similar and, in many cases, superior to the best-performing selections reported elsewhere. For example, the highest values for kernel weight (1.4–2.8 g) and kernel recovery (22–31%) reported overseas (Nandini and James 1985; Sawke *et al.* 1985; George *et al.* 1991; Veeraraghavan *et al.* 1991) were generally less than those for the 91 and 92 hybrids at the NT and Qld sites. Kernel weights from these hybrids were often more than

2.0 g, with kernel recovery in some cases well above 30% (Tables 4 and 5).

Comparisons of the hybrids reported here with whole tree yields reported elsewhere (e.g. publications cited above) are difficult because information on tree size and/or planting density is generally not provided. A high-yielding tree may have a very large canopy or an average canopy with high nut production per unit canopy area. The implications of distinguishing between these possibilities are significant when projecting likely planting densities. Although *shape* was not highly variable at the Qld site, the trees selected on the basis of productivity traits had *shape* near the top of the range, suggesting that they may be suited to close planting. With *canprod* of the most productive families in the range of 120–170 g/m^2 (NIS/CSA) (Table 4) and that of individual selections about 200 g/m^2 (Table 5), these levels of production equate to nut yields of 10–15 kg/tree. If similar yields per tree were achieved at the standard planting density of 200 trees per hectare, this would equate to nut yields of 2–3 t/ha. It is notable that in what has been a relatively short breeding, evaluation and selection cycle for a tree crop, these hybrids have the potential to meet the economic threshold of 2.5–3.0 t/ha set by Hinton (1998) and are approaching the threshold of about 4.0 t/ha established by Oliver *et al.* (1992).

The analysis of families that were in common to both sites (Table 4) suggested that their performance in terms of *value* and *canprod* was strongly influenced by local conditions. Within these common families, low correlation coefficients between hybrids in common (i.e. scions duplicated at each site) provided further evidence that cashew growth and production were strongly influenced by environment, although trees were propagated to seedling rootstocks, which may have influenced the results to a greater or lesser degree. Such environmental effects have been common in other agronomic trials (e.g. Brennan and Byth 1979; Hardner *et al.* 2001). It was therefore not surprising that a different group of hybrids was selected for outstanding performance at each site (Table 5). Growers from areas with different environmental characteristics to those at the NT or Qld sites should exercise caution when planting these selections. Also, it is possible that the seedling rootstocks to which the hybrids were grafted may have influenced their productivity (Hartmann *et al.* 1990). Since it was not feasible to test for rootstock effects in this experiment, a suitable strategy for prospective growers would be to verify the performance of selections in preliminary plantings, using a range of rootstocks, before committing further resources to them.

Genetic parameters and prospects for future breeding

The genetic analyses presented here are the first for Australian cashews. While other reports (Damodaran 1975, 1977; Abdul Salam *et al.* 1998; Sapkal *et al.* 1998; Sankaranarayanan and Ahmad Shah 1999) have demonstrated that wide segregation of key characteristics can occur in hybrid progenies and that hybrids can be selected for release as new varieties, there has been little formal genetic analyses reported elsewhere in the literature.

All traits were moderately to highly heritable (Table 6), with these levels of h^2 indicating that under the environmental conditions in which the measurements were made, there is considerable potential for improving this cashew population (Falconer and Mackay 1996). Similarly, in a study of seedling cashews, Faluyi (1987) defined broad-sense heritabilities for nut and kernel weight of about 55% and recognised the opportunity for improving these traits by selection.

It was not surprising that *canprod* and its derivative trait *value* showed a high level of additive genetic and phenotypic correlation (Table 7), with selection for one of these necessarily leading to an improvement in the other. Using the arbitrary scale of de Souza *et al.* (1998*a*, 1998*b*), the very weak genetic correlations between *canprod* or *value* and *kr* indicate that selecting for either of the 2 former traits is unlikely to influence *kr*. The corresponding phenotypic correlations were also very weak indicating that environmental influences made a large contribution to phenotypic variation in *kr*. The bivariate analyses in ASREML did not provide satisfactory estimates for most of the correlations involving *kwt* or *shape*, using either the full individual tree model (equation 1) or reduced family model (equation 2). This may have been because (i) *kwt* had a relatively small variance compared with the other traits, and (ii) *shape* data were limited to only 1 site.

Table 7. Genetic (bold type) and phenotypic correlations between derived and measured traits for 91 and 92 hybrids grown at the Northern Territory and Queensland sites during 1998 and 1999

	Hybrid set	Economic value ($/100 m^2 CSA)	Canopy productivity (NIS/CSA) (g/m^2)	Kernel recovery (%)
Economic value ($/100 m^2 CSA)	91	—	**0.97 ± 0.02**	**–0.01 ± 0.22**
	92	—	**0.93 ± 0.03**	**0.25 ± 0.13**
Canopy productivity (NIS/CSA, g/m^2)	91	0.97 ± 0.00	—	**–0.19 ± 0.25**
	92	0.94 ± 0.01	—	**–0.02 ± 0.16**
Kernel recovery (%)	91	0.27 ± 0.06	0.11 ± 0.07	—
	92	0.30 ± 0.05	0.08 ± 0.05	—

As with the selection of best-performing hybrids (Table 5), parent selection for future breeding may require separate groups of trees to be identified, depending on whether the breeding is to be conducted in the Northern Territory or northern Queensland (Table 8). Although there was evidence for G × E effects on *value* and *canprod* from the phenotypic analyses, it is impossible to determine the repeatability of the G × E or the degree to which it was caused by non-repeatable, random, non-genetic (environmental and management) variation between sites. Hardner *et al.* (2001), working with macadamia, reached a similar conclusion when there was no replication of plantings across sites. If possible, hybrids should be replicated several times in at least 2 sites for future breeding and selection work, based on production traits such as *value* and *canprod*.

Table 8. Trees from the 91 and 92 hybrids selected for further crossing based on their estimated breeding values (EBV) for *value* when grown at the Northern Territory and Queensland sites

s.e. is shown in parentheses

Rank	ID	EBV	Female parent	Male parent
		Northern Territory, 91 hybrids		
1	2393	21.1 (*5.2*)	GUNTUR	CJ1
2	3182	21.0 (*5.2*)	CJ1	GUNTUR
3	3072	21.0 (*5.2*)	CJ1	GUNTUR
4	3022	20.8 (*5.2*)	NDR2-1	GUNTUR
5	2953	19.4 (*5.2*)	GUNTUR	CJ1
6	3411	19.3 (*5.2*)	NDR2-1	GUNTUR
7	2946	19.2 (*5.2*)	GUNTUR	CJ1
8	3274	19.2 (*5.2*)	GUNTUR	NDR2-1
9	2743	18.9 (*5.2*)	GUNTUR	CJ1
10	2836	18.4 (*5.2*)	CJ1	GUNTUR
		Queensland, 91 hybrids		
1	3071	20.4 (*5.2*)	CJ1	GUNTUR
2	2810	20.4 (*5.2*)	GUNTUR	CJ1
3	3106	20.3 (*5.2*)	CJ1	GUNTUR
4	3336	20.0 (*5.2*)	GUNTUR	1-2-13
5	3095	19.7 (*5.2*)	GUNTUR	1-2-13
6	3242	19.4 (*5.1*)	NDR2-1	GUNTUR
7	3326	19.0 (*5.1*)	GUNTUR	NDR2-1
8	3419	18.6 (*5.2*)	CJ1	GUNTUR
9	2923	18.4 (*5.1*)	GUNTUR	NDR2-1
10	3406	18.2 (*5.1*)	GUNTUR	NDR2-1
		Northern Territory, 92 hybrids		
1	4386	18.7 (*3.8*)	5–14–4	GUNTUR
2	4260	18.7 (*3.8*)	2–3–10	GUNTUR
3	4379	18.5 (*3.8*)	5–14–4	GUNTUR
4	4314	17.5 (*3.8*)	5–14–4	GUNTUR
5	4048	17.1 (*3.8*)	5–14–4	GUNTUR
6	4382	16.9 (*3.8*)	5–14–4	GUNTUR
7	4030	16.4 (*3.8*)	5–14–4	GUNTUR
8	4376	16.3 (*3.8*)	5–14–4	GUNTUR
9	4013	16.1 (*3.8*)	5–14–4	GUNTUR
10	4045	16.1 (*3.8*)	5–14–4	GUNTUR
		Queensland, 92 hybrids		
1	4428	19.6 (*3.9*)	1-3-4	GUNTUR
2	4138	18.6 (*3.9*)	1-3-4	GUNTUR
3	4830	18.2 (*3.9*)	1-3-4	GUNTUR
4	4848	18.0 (*3.9*)	GUNTUR	1-3-4
5	4776	17.7 (*3.9*)	GUNTUR	1-3-4
6	4030	17.6 (*3.8*)	5-14-4	GUNTUR
7	4874	17.3 (*3.9*)	GUNTUR	1-3-4
8	4025	17.3 (*3.9*)	1-3-4	GUNTUR
9	4938	17.1 (*3.9*)	GUNTUR	1-3-4
10	4429	7.0 (*3.9*)	1-3-4	GUNTUR

This investigation has resulted in the selection of 2 groups of hybrids that can now be used to advance cashew improvement in northern Australia. A similar evaluation of the remaining hybrids planted at each site will be contingent on the availability of appropriate resources. The hybrids listed in Table 5 were selected on the basis of their phenotype for key characteristics. These hybrids have the potential to provide superior planting material for the Australian cashew industry, providing they are maintained as distinct genotypes by vegetative propagation. The hybrids listed in Table 8 were selected as potential new breeding parents based on EBVs. Their potential rests with a predicted ability to pass on genes to improve the *value* trait in the next generation. It was interesting to note that of the 11 hybrids selected for release as potential varieties, all but 1 (ID 4242) were also selected as potential parents. From this, it could be argued that parent selection could have been based solely on phenotype. However, there were hybrids not considered for release as potential varieties, e.g. 3071 and 2810 (Table 8), that were ranked more highly as parents than others that were also identified for propagation and distribution to industry (e.g. 3336 and 3106). Thus, while this investigation has indicated that genetic improvement in cashew hybrids is likely to be rapid, it would be interesting at this early stage of a cashew breeding program to assess via progeny tests the benefits or otherwise of selecting parents based on either EBV's or phenotypes.

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