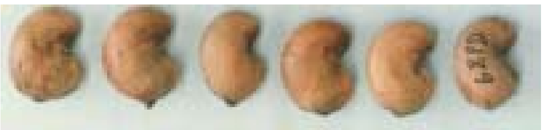

RURAL INDUSTRIES RESEARCH
& DEVELOPMENT CORPORATION

Assessment and Selection of New Cashew Hybrids

A report for the Rural Industries Research and Development Corporation

by Sam Blaikie, Pat O'Farrell, Warren Müller, Xianming Wei, Nigel Scott, Stephen Sykes and Elias Chacko (dec.)

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Foreword

During the 1980's cashew began to attract increasing attention from researchers and prospective growers as a crop with potential for tropical Australia. Since then, collaborative projects supported by CSIRO, Queensland Department of Primary Industries, Northern Territory Department of Primary Industry and Fisheries and RIRDC have tackled a suite of issues aiming to generate the technology upon which an Australian cashew industry can be founded.

Australia imports $50 m of cashew annually and, together with a projected increase in world demand, this represents both import replacement and export opportunities for prospective Australian growers. To be competitive on world markets locally grown cashew must be farmed intensively, with low labour inputs. The trees must be high yielding and consistently produce nuts of excellent quality.

This document describes the key outcomes from the final phase of a crop improvement program conducted at two sites - Wildman River, Northern Territory and Dimbulah, north Queensland. The improvement program commenced in 1988 and produced over 4000 new hybrids of which 590 of the most promising were intensively assessed during 1998 and 1999 and reported here. Following phenotypic and genetic analyses of hybrids grown at each site, the highest yielding hybrids and parents for further breeding were identified.

This project was jointly funded by CSIRO Plant Industry, Queensland Department of Primary Industries and from RIRDC Core Funds which are provided by the Federal Government.

This report, a new addition to RIRDC's diverse range of over 700 research publications, forms part of our New Plant Products R&D program, which aims to facilitate the development of new industries based on plants or plant products that have commercial potential for Australia.

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Peter Core
Managing Director
Rural Industries Research and Development Corporation

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About the Authors

Dr Sam Blaikie is a Senior Research Scientist in CSIRO Plant Industry at their Darwin laboratories. His particular interest is in tropical and sub-tropical crops and he has been involved in studies of the agronomic management and genetic improvement of cashews for the past seven years. Sam has taken the responsibility for interacting with Cashews NT where the original experiment was established.

Mr Patrick O'Farrell is a Senior Experimentalist (Horticulture) at the Centre for Tropical Agriculture of the Queensland Department of Primary Industries at Mareeba. He has worked in horticultural research and development for over thirty years in a number of crops including banana, mango, lychee, macadamia and cashew. In the latter years of the project Pat has borne the responsibility for interacting with the Cashews Australia site at Dimbulah where much of the experimental material has been planted.

Mr Warren Müller is a project leader in the CSIRO Division of Mathematics & Information Science and has provided the vital statistical advice in the design of the experiments and the analysis of the performance of hybrids reported during this project.

Dr Xianming Wei and **Dr Stephen Sykes** are geneticists with particular skills and interests in the genetics of vegetatively propagated horticultural crops and have provided specialist advice and genetic analyses for data in this report which provides foundations for any further breeding activities in cashews.

Dr Nigel Scott is Deputy Chief of CSIRO Plant Industry with a long-standing interest in both formal and molecular genetics. He led the planning and management of the project following the death of **Dr Elias Chacko**, who was the Senior Scientist in charge of CSIRO's Plant Industry, Darwin laboratory and with his expertise in cashews initiated this project in Australia.

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Executive Summary

Introduction

Since the late 1980's RIRDC has been working with CSIRO, QDPI and NTDPIF to provide improved varieties and the management technologies to support an Australian cashew industry that can compete profitably on the world market. While current world production exceeds 1,000,000 tonnes it is projected that demand will increase. A characteristic of cashew production in other parts of the world is that production systems are often extensive, with few inputs and relying on cheap labour costs to offset the low yields per hectare (0.5-1.0 t nut-in-shell). In contrast, the Australian cashew industry is envisaged as being intensively managed, with many inputs and consistently producing high yields of excellent quality nuts.

This project (CSP-6A) represents the final tranche in a long-term research investment. During 1998 – 2001 some of the most promising hybrids, generated and planted at Cashews NT (near Darwin NT) and Cashews Australia (near Cairns Qld) in the early 1990's, were intensively assessed and evaluated. To meet both productivity and quality targets, these hybrids were assessed in terms of yield, nut size and kernel recovery (the proportion of kernel in the whole nut-in-shell).

Objectives

As would be expected with such a large and long-term project, significant organisational and structural changes occurred during the life of the cashew crop improvement program. Two significant events occurred at the outset of CSP-6A. Firstly, the Principal Investigator (Dr E Chacko) passed away and secondly, a review commissioned by RIRDC identified the need to conduct genetic analyses to properly characterise the hybrid material. These events occurred early in the life of CSP-6A and it was possible to adjust the Objectives accordingly. A novel 'team approach' to management of the project was implemented in which representatives of all collaborators (including growers) met regularly (approx monthly) to ensure up-to-date exchange of information and to collectively resolve issues as they arose. All parties were satisfied with this approach and revision of the Objectives was one of the most important tasks carried out by the team.

The main Objectives were:-

1. Nominate appropriate hybrids for detailed assessment from within plantings at Cashews NT and Cashews Australia.
2. Measure yield and productivity during 1998 and 1999; compare performance (GxE) between sites.
3. Identify most productive hybrids for immediate release to industry.
4. Conduct genetic analyses to provide breeding values of hybrids; identify second generation parents.
5. Finalise commercial arrangements with existing and new growers to allow large-scale multiplication and commercial planting of selected hybrids.
6. Establish plantings of selected hybrids and their parents at CSIRO, Darwin and QDPI, Southedge.

Materials and Methods

The hybrids came from crosses made in 1991 and 1992 and were randomly planted during 1991 and 1993, respectively. Families with at least five hybrids were selected for detailed assessment. Some families were represented at each site and, within these, some hybrids were duplicated between sites since they had been multiplied by grafting to seedling rootstocks. Agronomic inputs were provided by farm mangers at each site, in line with overall plantation management strategies.

Assessments of tree productivity were carried out in 1998 and 1999 and included total nut-in-shell yield per tree, average nut weight, average kernel weight and canopy surface area. Derived variables included canopy productivity (g nut-in-shell/m^2 canopy surface area), kernel recovery (g kernel/g nut-in-shell) and economic value ($ / 100 m^2 canopy surface area), which integrated important yield traits and expressed tree productivity in terms of an expected return ($AUS) if the crop was sold as kernel. The economic value, referred to subsequently as ***value,*** was the principal basis for making selections among hybrids.

Results

Separate selections were made from within both the 1991 and 1992 hybrid sets. At the NT site there were no significant differences among families in the 1991 hybrid set but of the 1992 hybrid set, 5-14-4 x GUNTUR was clearly the most productive in 1998. At the QLD site, six families of the 1991 hybrid set were in a group with highest ***value*** in 1999 and of the 1992 hybrid set, 1-3-4 x GUNTUR had the highest ***value*** in each year. At each site, individual trees within these families were selected for release to commercial cashew operations if their productivity exceeded the minimum standards of ***value*** ($40/100 m^2 canopy surface area), kernel recovery (at least 25 %) and kernel weight (at least 1.5 g). Of the 1991 hybrids, four were selected from the Cashews NT population and two from the Cashews Australia population. Four of the 1992 hybrids were selected from the Cashews NT population and one hybrid was selected from the Cashews Australia population.

Genetic analyses indicated that the traits studied had relatively high heritabilities suggesting considerable scope for further improvement by breeding. After ranking all hybrids on the basis of the estimated breeding values (EBV) for ***value***, ten trees were selected from each group of hybrids at each site as second generation parents.

Implications

Eleven new cashew hybrids have been identified for further development by the Australian Industry. The productivity of the best 1991 and 1992 hybrids was similar, and in many cases superior, to the best performing selections reported elsewhere. Assuming the standard planting density of 200 trees per hectare, these levels of production equate to yields of 2-3 t / ha (cf world average yield of 0.5-1.0 t / ha).

Analysis of families that were in common to both sites suggested that their performance was strongly influenced by local conditions. Within these families, analysis of hybrids in common (ie scions duplicated at each site) provided further evidence of a strong environmental effect on performance. It was therefore not surprising that none of the hybrids selected for outstanding performance were common to each site. Prospective growers from areas with different environmental characteristics to those at Cashews NT and Cashews Australia should exercise caution when planting these selections, using small preliminary plantings to verify superior performance in each new environment.

The genetic analyses are the first for Australian cashew and, with the moderate to high heritabilities of measured traits, indicated that there is considerable potential for improving them by breeding. Of the eleven hybrids selected for release to industry, all but one were nominated as potential parents based on estimated breeding value (EBV) for ***value***. However, ranking of hybrids on the basis of EBV for ***value*** also identified potential parents that had not previously been selected. To avoid the possibilities of inbreeding, such a widening of the genetic base is useful. When planning future breeding strategies it would also be prudent to use genotypes possessing useful traits from other diverse origins to ensure genetic diversity.

Commercialisation and Industry Significance

Arrangements have been put in place to encourage potential growers to make use of the new material while maintaining an appropriate advantage to all stakeholders who have equity in the development of the new trees.

Commercial arrangements

Agreement to the principles governing the propagation of planting material and the royalty returns that might be expected when a successful plantation came into bearing was reached following negotiations between RIRDC, the research agencies and the principal commercial collaborator Mr Peter Shearer through Cashews Australia.

Propagation of cashew selections. In order to ease the cost of establishing a cashew plantation it was agreed there should be no royalty or licence fees applicable for the sale of cashew propagules derived from the material identified in this project. The agencies involved in the project did not themselves have the capacity to produce propagules for commercial use and it was agreed that a commercial nursery or nurseries should be licensed for the production of propagules.

Royalty on harvested nut-in-shell. A condition of the licence is that the nursery arranges with each grower to sign a non-propagation and royalty agreement which commits the grower to paying a royalty at the rate of 2.5% of the gross selling price per ton of harvested nut in shell from the selections. The royalties will be shared between RIRDC, the research agencies and Mr Peter Shearer in proportion to their financial inputs into the overall cost of the project.

NuCashew Commercial Arrangements

Subsequent to the agreement of the above principles, commercial arrangements for propagation and recouping of royalties were reached with NuPlant Ltd. This company in turn has an agreement with its subsidiary NuCashew Ltd which has published a prosectus seeking investment to commercialize new cashew plantations using hybrids from this project. This proposal is outlined in Appendix 1.

Hybrid germplasm maintenance

A ‘core’ collection has been established in each location (NT and north QLD) so that the new hybrids and their parents are secured. These collections will also serve as a source of material for new plantings. CSIRO and QDPI have taken responsibility for establishing these germplasm collections at their Darwin and Southedge locations, respectively.

CSIRO and QDPI have undertaken to maintain these germplasm collections until at least 2005, after which it is anticipated that new hybrids will have begun to supercede the selections from CSP-6A.

1. Introduction

Since the late 1980's RIRDC has been working with CSIRO, QDPI and NTDPI to provide improved varieties for an Australian cashew industry. These projects have included CSH-36A (1988-92) which saw the production of over 4000 hybrids and CSH-43A (1993-96) which entailed final field planting and initial assessment of some of the hybrids. This project, CSP-6A (1998-2001), therefore represents the final tranche in a long-term research investment into cashew crop improvement. The focus of CSP-6A was on some of the most promising hybrids, generated and planted at Cashews NT (near Darwin NT) and Cashews Australia (near Cairns Qld) in the early 1990's.

As would be expected with such a large and long-term project, significant organisational and structural changes occurred during the life of the cashew crop improvement program. Two significant events occurred at the outset of CSP-6A. Firstly, the Principal Investigator (Dr E Chacko) passed away and secondly, a review by RIRDC identified the need to conduct genetic analyses to properly characterise the hybrid material. Fortunately these events occurred early in the life of CSP-6A and it was possible to adjust the Objectives accordingly. A novel 'team approach' to management of the project was implemented in which representatives of all collaborators (including growers) met regularly (approximately monthly) to ensure up-to-date exchange of information and to collectively resolve issues as they arose. All parties were satisfied with this approach and revision of the Objectives was one of the most important tasks carried out by the team.

In revising the objectives of CSP-6A it was obvious to all parties that there were insufficient resources to effectively monitor every hybrid that had been produced during the life of the crop improvement program. However, the results of the review commissioned by RIRDC indicated that if we employed the project resources in a more strategic and targeted way, there was plenty of scope to generate valuable information on both the performance and genetic characteristics of a subset of the hybrids. In deciding which hybrids to focus on, the management team sought trees that were beyond the juvenile phase and relatively well managed. The hybrids produced in 1991 and 1992 met these criteria. Within these sets genetic analysis demanded that we identify families with at least five hybrids (up to a maximum of twenty) that were planted at both the Cashews NT and Cashews Australia sites. The management team agreed that limiting data collection to two consecutive years represented a reasonable compromise between gaining knowledge about the repeatability of hybrid performance and being able to release hybrids to industry within the timeframe of the project.

Thus, the main revised Objectives were:-

1. Nominate appropriate hybrids for detailed assessment from within plantings at Cashews NT and Cashews Australia.
2. Measure yield and productivity during 1998 and 1999; compare performance (GxE) between sites.
3. Identify most productive hybrids for immediate release to industry.
4. Conduct genetic analyses to provide breeding values of hybrids; identify second generation parents.
5. Finalise commercial arrangements with existing and new growers to allow large-scale multiplication and commercial planting of selected hybrids.
6. Establish plantings of selected hybrids and their parents at CSIRO, Darwin and QDPI, Southedge.

Structure of this report

The majority of the data collected and analysed during CSP-6A has been prepared in the form of a scientific journal manuscript that has been submitted to Australian Journal of Experimental Agriculture in June 2001. This manuscript has been re-formatted to suit RIRDC guidelines and is presented below under the headings Background, Materials and methods, Results, Discussion and References. The section on Commercialisation and Industry Significance has been added for the RIRDC report and is not a part of the journal manuscript.

Background

Cashew (*Anacardium occidentale* L) is an emerging tree crop in the Darwin (NT) and Cairns (QLD) regions of northern Australia. Current world production of cashew is in excess of 1,000,000 tonnes but is below demand (Azam-Ali and Judge 2000). Australian imports of cashew are currently valued at more than US$30m 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. Cann *et al.* (1987) suggested a target yield of 5.0 t NIS/ha, but recently Hinton (1998) concluded that yields of 2.5-3.0 t NIS/ha would be viable.

As well as yield, 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. In early 2000, typical prices for 1.0 g and 2.5 g kernels were $A8.70 and $A12.90 per kg, respectively (P. Shearer, personal communication).

An appraisal of imported and locally available cashew selections in northern Australia indicated 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 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 for 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 four thousand hybrids were produced, the work reported in this paper concentrates on two 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.

2. 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 5.3-10.9 g, kernel size from 1.4-3.2 g and kernel recovery from 26-34% (Table 1).

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

Crosses were made at CSIRO Plant Industry, Darwin (12^o S, 130^o E) in the Northern Territory and at nearby plantations by controlled pollination (Chacko 1993). At maturity, nuts from crosses were harvested, sown and grown in the nursery. 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. The two hybrid sets used in the present study came from crosses made in 1991 (1991 hybrids) and 1992 (1992 hybrids) and were randomly planted during 1992 and 1993, respectively.

Site description

Hybrids were evaluated at two commercial plantations - Cashews NT , 120 km south-east of Darwin, and Cashews Australia, 100 km west of Cairns in Queensland (17^o S, 145^o E). The climate in Darwin is warm and humid throughout the year with maximum temperatures in the range 30-35^o C and minima generally 15-23^o C. At Cashews Australia the maximum temperature ranges from 25^o C in July to 31^o C in December while the minimum ranges from 14^o C in July to 22^o C in February. At Cashews Australia the lower temperatures are associated with a pause in tree growth during June-August that delays flowering and nut development by about a month compared with Darwin. Rainfall - 1360 mm at Cashews NT and 780 mm at Cashews Australia - occurs mainly during the months December to March. At both sites reproductive growth coincides with a dry season (< 100mm rainfall) from June to October.

Evaluation strategy

The numbers of individuals assessed within each hybrid family 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 sub-sample was assessed. Some families were represented at each site and within these, some hybrids were duplicated between sites since they had been multiplied by grafting to seedling rootstocks.

Cultural management

Trees were planted at 7 x 5m and 6 x 6m at Cashews NT and Cashews Australia, 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 sub-optimal at Cashews Australia during 1998 but during 1999 supplemental inputs were provided by the research team to ensure that similar problems did not recur.

Table 2: Parental combinations, family size and the number of identical accessions at Cashews NT and Cashews Australia for (a) 1991 hybrids and (b) 1992 hybrids. * not assessed at Cashews NT.

(a) 1991 hybrids				
Parents		**Family size**		
female	**male**	**Cashews NT**	**Cashews Australia**	**No. of identical accessions**
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	*	20	
K22	GUNTUR	*	10	
GUNTUR	K22	*	12	
GUNTUR	1-1-14	*	20	
GUNTUR	1-2-13	*	20	
TOTAL		**73**	**135**	**22**

(b) 1992 hybrids				
Parents		Family size		
female	male	Cashews NT	Cashews Australia	No. of identical accessions
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	*	5	
GUNTUR	KAM6	20	20	7
1-3-4	GUNTUR	*	7	
GUNTUR	1-3-4	*	12	
1-3-17	GUNTUR	*	12	
GUNTUR	1-3-17	*	19	
1-4-11	GUNTUR	*	20	
1-4-16	GUNTUR	*	19	
1-4-18	GUNTUR	*	20	
3-11-19	GUNTUR	*	16	
GUNTUR	2-11-11	*	17	
R9T14	KAM6	*	13	
TOTAL		**101**	**281**	**50**

Data collection

Assessments were carried out in 1998 and 1999, when the 1991 and 1992 hybrid sets 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.

In each year hybrids were hand harvested and assessed for:
- total nut-in-shell weight (kg NIS per tree)
- average nut weight (g per nut)
- average kernel weight (***kwt***, g per 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 due to skirting of the lower canopy for machinery access and, at Cashews NT, the close proximity of neighbouring trees, were taken into account. Expressing nut production on the basis of CSA allowed comparisons between trees of different size.

The following variables were derived from the raw data:-
- canopy productivity (***canprod***, g NIS/m^2 CSA)
- kernel recovery (***kr***, g kernel (at 5%WC)/ g NIS (at 9%WC) %)
- economic value (***value***, $ kernel value/100 m^2 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 were supplied by commercial traders representing average prices for the last 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.

Table 3. Average (1992-2000) cashew kernel price $ A /kg, FOB used in economic value calculations.

Kernel grade	Price
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

At Cashews Australia 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 and was adapted from the descriptor used by the Systematics Association Committee for Descriptive Terminology (1962) to express the form of simple symmetrical plane shapes. Thus, for tall, narrow canopies ***shape*** was relatively high, while for short, spreading canopies it was low. At Cashews NT, 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 x Environment (G x E) interactions for ***value***, ***canprod*** and ***kwt*** were investigated separately for the 1991 and 1992 hybrids, by performing 3-way analyses of variance on families common to each site. These analyses included site and year as factors, with G x E indicated by a significant family x site interaction. Similar analyses were conducted using data from hybrids common to each site. Since duplicated hybrids were not replicated within sites, year interactions were used as residuals in analyses. Correlation coefficients were calculated for each site x year combination.

Genetic analyses

Restricted maximum likelihood (REML) was used to estimate variance components of random effects (Searle et al. 1992), and best linear unbiased prediction (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 a univariate analysis was carried out based on the model:

$$\mathbf{y} = \mathbf{Xb} + \mathbf{Za} + \mathbf{W_1 s} + \mathbf{W_2 c} + \mathbf{e} \qquad \text{(eq. 1)}$$

where **y** is the vector of observations for a given trait collected from individual trees at each site over two harvesting seasons; **b** is a vector of the fixed effects of site and harvesting season; **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 two parents; **s** is a vector of random effects of parent-by-site and parent-by-harvesting-season interaction, and **X**, **Z**, $\mathbf{W}_1$ and $\mathbf{W}_2$ are incidence matrices.

Preliminary analysis based on the model (eq. 1) showed **c** was not significant by the maximum likelihood ratio test (McCullagh and Nelder, 1989) and the model was reduced to

$$\mathbf{y} = \mathbf{Xb} + \mathbf{Za} + \mathbf{W_1 s} + \mathbf{e} \qquad \text{(eq. 2)}$$

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

Narrow-sense heritability was estimated as:

$$h^2 = \frac{\sigma_a^2}{\sigma_a^2 + \sigma_{gs}^2 + \sigma_{gh}^2 + \sigma_r^2} \qquad \text{(eq. 3)}$$

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-harvesting-season interactions, and σ_r^2 is residual variance.

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

$$r = \frac{\sigma_{ij}}{\sqrt{\sigma_i^2 \sigma_j^2}} \qquad \text{(eq. 4)}$$

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

3. Results

Phenotypic performance

(i) Analysis of family performance

At each site there were differences in ***value*** and ***canprod*** of families between years (Table 4). In particular, ***canprod*** for the trees at Cashews Australia 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 compared with 1998. There were significant differences in ***shape*** between families in both sets of hybrids, with ***shape*** in 1999 ranging from 0.907 to 1.126 for the 1991 hybrids. In the 1992 hybrid set, ***shape*** ranged from 0.801 to 0.965 in 1998 and from 0.860 to 1.117 in 1999. At Cashews NT the traits were less variable between years.

1991 hybrids

At Cashews NT ***value*** did not differ significantly between families but in 1998 ranged from 13.3 to 20.0 \$/100 m^2 CSA (Table 4a). Similarly, in 1999 differences in ***value*** between families were not significant and ranged from 16.7 to 30.9 \$/100 m^2 CSA. At Cashews Australia, ***value*** in 1998 was low and did not differ significantly between families. In 1999, CJ1 x GUNTUR had the highest ***value*** of 42.9 \$/100 m^2 CSA, but GUNTUR x CJ1, GUNTUR x NDR2-1, NDR2-1 x GUNTUR, GUNTUR x 1-2-13 and GUNTUR x 1-1-14 all had ***value*** that was similar, in the range 34.7 to 40.8 \$/100 m^2 CSA. For these families with high mean ***value***, ***shape*** in 1999 was near the top of the range, at about 1.10, in all cases.

'Family x site' interactions were not significant for ***value*** and ***kwt,*** but, although the level of replication was fairly low and varied within families, the relative performance measured in terms of ***canprod*** was dependent on site. For example, CJ1 x GUNTUR was the highest ranked family for ***canprod*** (mean over two years) at Cashews NT but GUNTUR x NDR2-1 was the highest at Cashews Australia. Within families, the performance of duplicated hybrids common to each site was only weakly correlated (r for ***value*** and ***canprod*** in the range 0.25 to 0.45).

1992 hybrids

At Cashews NT ***value*** was highest in 5-14-4 x GUNTUR at 28.3 \$/100 m^2 CSA in 1998 but in 1999 there were no significant differences (Table 4b). At Cashews Australia, 1-3-4 x GUNTUR had highest ***value*** in each year, with \$20.1 /100 m^2 CSA in 1998 and \$40.0 /100 m^2 CSA in 1999. Other families with relatively high ***value*** in 1998 were GUNTUR x 1-3-4, GUNTUR x 1-6-8 and GUNTUR x 2-11-11 and, in 1999, were 1-3-17 x GUNTUR and GUNTUR x 1-3-17. In the least productive families ***value*** was in the range \$5-10 /100 m^2 CSA in 1998 and, for 1-4-16 x GUNTUR, only \$16.2 /100 m^2 CSA in 1999. For 1-3-4 x GUNTUR ***shape*** was not the highest ranked but it was similar to the mean over the entire hybrid set.

For families common to each site, there were significant G x E effects for ***value, canprod*** and ***kr*** but not for ***kwt*** (means over two years). At Cashews NT the top ranked family for both ***value*** and ***canprod*** was 5-14-4 x GUNTUR while at Cashews Australia GUNTUR x 4-5-14 was the top ranked for ***value*** and GUNTUR x 1-6-8 was top ranked for ***canprod***. For ***kr***, GUNTUR x 4-5-14 was the top ranked at Cashews NT while at Cashews Australia it was 2-6-9 x 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 weakly correlated for ***kr*** (r = 0.08 - 0.36).

Table 4. Production measured in terms of ***value*** ($ / 100 m^2 CSA), ***canprod*** and ***kwt*** in 1998 and 1999 for (a) 1991 hybrids and (b) 1992 hybrids and, for Cashews Australia, ***shape*** in 1998 and 1999. Average SED is the standard error of difference between family means assuming average replication for each family. Family x site P values were derived from analyses including both 1998 and 1999. Shading denotes families common to each site.

(a) 1991 hybrids

		Cashews NT								Cashews Australia									
female	male	*value* 98	*value* 99	*canprod* 98	*canprod* 99	*kr* 98	*kr* 99	*kwt* 98	*kwt* 99	*value* 98	*value* 99	*canprod* 98	*canprod* 99	*kr* 98	*kr* 99	*kwt* 98	*kwt* 99	*shape* 98	*shape* 99
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		ns	ns	ns	ns	ns	ns	0.001	<0.001	ns	<0.001	ns	0.001	<0.001	<0.001	<0.001	<0.001	ns	0.023
Average SED		-	-	-	-	-	-	0.10	0.10	-	5.1	-	19.0	0.6	0.8	0.12	0.12	-	0.063

P value (family x site)	ns	0.034	ns	ns

Table 4 (Continued)

(b) 1992 hybrids

		Cashews NT								Cashews Australia									
female	male	***value*** 98	***value*** 99	***canprod*** 98	***canprod*** 99	***kr*** 98	***kr*** 99	***kwt*** 98	***kwt*** 99	***value*** 98	***value*** 99	***canprod*** 98	***canprod*** 99	***kr*** 98	***kr*** 99	***kwt*** 98	***kwt*** 99	***shape*** 98	***shape*** 99
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	ns	<0.001	ns	ns	ns	ns	0.002	<0.001	<0.001	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	0.019	<0.001
Average SED		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 x site)	0.003	<0.001	0.010	ns

(ii) Selection of best trees for commercial planting

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*** ≥ $40/100 m^2 CSA, (ii) ***kr*** ≥ 25%, and (iii) ***kwt*** ≥ 1.5g. The ***value*** threshold was broadly equivalent to an annual yield of 2 t NIS/ha and about the minimum acceptable for a future Australian industry.

1991 hybrids

Four hybrids were selected for their superior performance at Cashews NT (Table 5 a). These were from NDR2-1 x GUNTUR, GUNTUR x CJ1 and respective reciprocals. In all cases the mean ***value*** was at least $40 / 100 m^2 CSA with a maximum of $ 47 / 100 m^2 CSA being achieved by one tree (ID 3022). All trees met the minimum ***kr*** and ***kwt*** standards. The nut yield of these trees, represented by ***canprod***, was high, ranging from 135 g NIS/ m^2 CSA (ID 3274) to 245 g NIS/ m^2 CSA (ID 2393) in 1999.

At Cashews Australia, two trees were selected because they met or exceeded all standards of performance (Table 5 a). These were from GUNTUR x 1-2-13 and CJ1 x GUNTUR. For each, the mean ***value*** was $ 42 / 100 m^2 CSA and the ***kr*** and ***kwt*** minima were exceeded each year. Over both years ***canprod*** ranged from about 80 g NIS/ m^2 CSA to more than 200 g NIS/ m^2 CSA during 1999. The ***shape*** of these hybrids was close to or above respective family means.

Table 5: Characteristics of best-performing (a) 1991 and (b) 1992 hybrids selected from Cashews NT and Cashews Australia, based on their production data in 1998 and 1999.

(a) 1991 hybrids

			value ($/100 m^2 CSA)			***canprod*** (g NIS/m^2 CSA)		***kr*** (%)		***kwt*** (g)		***shape***	
ID	female	male	1998	1999	mean	1998	1999	1998	1999	1998	1999	1998	1999
Cashews NT													
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	-	-
Cashews Australia													
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

(b) 1992 hybrids

ID	female	male	*value* ($/100 m² CSA) 1998	1999	mean	*canprod* (g NIS/m² CSA) 1998	1999	*kr* (%) 1998	1999	*kwt* (g) 1998	1999	*shape* 1998	1999
Cashews NT													
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	-	-
Cashews Australia													
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

1992 hybrids

The four trees selected from Cashews NT were from 2-3-10 x GUNTUR and 5-14-4 x GUNTUR (Table 5 b). One tree achieved a very high ***value*** of \$ 59 / 100 m^2 CSA (ID 4260) and all four trees had ***kr*** and ***kwt*** well in excess of minimum standards. These trees had ***canprod*** usually in the range 140-200 g NIS/ m^2 CSA.

At Cashews Australia, only one tree (ID 4428) from 1-3-4 x 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 2g, respectively, in each year. ***Canprod*** ranged from 68 g NIS/ m^2 CSA in 1998 to 191 g NIS/ m^2 CSA in 1999. The ***shape*** of this tree was similar to its family mean.

Genetic parameters

Estimates of narrow-sense heritability (h^2) indicated there is considerable scope to improve the traits studied by breeding (Table 6). The derived measures of productivity, ***canprod*** and ***value***, had h^2 in the range 0.15-0.23 for both the 1991 and 1992 hybrid sets. The direct measures of productivity, ***kwt*** and ***kr***, had higher h^2 in the range 0.32-0.50. For each of these three traits, h^2 for the 1991 hybrids was lower than for the 1992 hybrids. For ***shape,*** h^2 was high, in the range 0.83-0.85, for both groups of hybrids.

Table 6: Estimates of heritability (h^2) ± standard errors for derived and measured traits of 1991 and 1992 hybrids grown at Cashews NT and Cashews Australia in 1998 and 1999.

Trait	1991 hybrids	1992 hybrids
value	0.21 ± 0.09	0.23 ± 0.06
canprod	0.18 ± 0.09	0.15 ± 0.06
kr	0.45 ± 0.08	0.50 ± 0.06
kwt	0.32 ± 0.08	0.46 ± 0.06
shape	0.83 ± 0.04	0.85 ± 0.05

Genetic and phenotypic correlations (0.93-0.97) were strong between ***value*** and ***canprod*** for both 1991 and 1992 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). Phenotypic correlations between these traits were also very weak but the standard errors were relatively small.

Table 7: Genetic (bold type) and phenotypic correlations between derived and measured traits for 1991 and 1992 hybrids grown at Cashews NT and Cashews Australia during 1998 and 1999.

		value	***canprod***	***kr***
value	1991	-	**0.97 ±0.02**	**-0.01 ± .22**
	1992	-	**0.93 ± 0.03**	**0.25 ± 0.13**
canprod	1991	0.97 ± 0.00	-	**-0.19 ± .25**
	1992	0.94 ± 0.01	-	**-0.02 ± .16**
kr	1991	0.27 ± 0.06	0.11 ± 0.07	-
	1992	0.30 ± 0.05	0.08 ± 0.05	-

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 1991 and 1992 hybrids. EBV's for ***value*** ranged from 8.8 to 21.1 and from 3.5 to 19.6 for the 1991 and 1992 hybrids, respectively. The ten top-ranked trees based on EBV's for ***value*** from each hybrid set at each site were listed as candidates for further crosses (Table 8).

Table 8: Trees from the 1991 and 1992 hybrids selected for further crossing based on their EBV for ***value*** when grown at (a) Cashews NT and (b) Cashews Australia. Figures in parentheses are se.

(a) Cashews NT

1991 HYBRIDS			Parentage	
Rank	ID	EBV	female	male
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
1992 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

Table 8 (cont.)

(b) Cashews Australia

1991 HYBRIDS			Parentage	
Rank	ID	EBV	female	male
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
1992 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	17.0 *(3.9)*	1-3-4	GUNTUR

4. 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 comparing the productivity of the trees in this experiment with data from other reports. Although moisture contents used to standardise yield data in this experiment were considered typical of commercial practice, it is rare that other reports 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 (Sawke *et al.* 1985, Nandini and James 1985, George *et al.* 1991, Veeraraghavan *et al.* 1991) were generally less than those for the 1991 and 1992 hybrid sets at Cashews NT and Cashews Australia. Kernel weights from these hybrids were often more than 2.0 g, with kernel recovery in some cases being well above 30 % (Tables 4-5).

Comparisons of the hybrids reported here with whole tree yields reported elsewhere (eg publications cited above) are difficult because information on tree size and/or planting density is not generally 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 is significant when extrapolating the yield of a single tree to a potential 'per hectare' performance. As well as allowing a more useful comparison of productivity between trees of various canopy sizes in this and other experiments, the use of ***canprod*** could project yields of hedgerow plantings, a likely characteristic of the future Australian cashew industry. Desirable trees will have high ***canprod*** (and ***value***) but not necessarily high CSA. Although ***shape*** was not highly variable at Cashews Australia, it was important that trees selected on the basis of productivity traits had ***shape*** near the top of the range, with upright growth habit. Compared to trees with lower values for ***shape,*** we can expect that closer planting, greater interception of sunlight and, therefore, higher yields per hectare will be possible when coupled with high values for productivity traits. Tall trees should not affect harvest efficiency because nuts are swept from the ground as they drop. However, tall trees could require pruning to ensure spray coverage to the top of the canopy and light penetration to lower levels of the canopy. With ***canprod*** of the most productive families in the range 120-170 g NIS/m^2 CSA (Table 4) and of individual selections around 200 g NIS/m^2 CSA (Table 5), these levels of production equate to yields of 10-15 kg nuts per tree. In turn, this is equivalent to 2- 3 t nuts per hectare at a standard planting density of 200 trees per hectare. 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 set by Hinton (1998) and are approaching that of Cann *et al.* (1987).

While not all families were assessed at each site, analysis of families that were in common (Table 4) suggests that their performance in terms of ***value*** and ***canprod*** was strongly influenced by local conditions, although the numbers of hybrids per family were not particularly large. Within these common families, low correlation coefficients between hybrids in common (ie scions duplicated at each site) provided further evidence that cashew growth and production is strongly influenced by environment, though 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 similar trials (e.g. Brennan and Byth 1979, Hardner *et al.* 2001). It was therefore not surprising that none of the hybrids, selected for outstanding performance, was in common at each site (Table 5). Growers from areas with different environmental characteristics to those at Cashews NT and Cashews Australia should exercise caution when planting these selections. A suitable strategy would be to verify performance in preliminary plantings using a range of rootstocks before committing further resources to them.

Based on observations made in a wide range of species, it is possible that the seedling rootstocks to which the hybrids were grafted may have influenced their productivity (Hartmann *et al*. 1990). Although it was impossible to test for rootstock effects in this experiment, qualitative data based on observations of growth and bark characteristics of rootstock, scion and graft unions during 1999 suggested that in all cases the graft union was healthy. While it is impossible to discount physiological effects of seedling rootstocks, such as differential mineral nutrient uptake, which would affect productivity, there appeared to be no obvious characteristics of the rootstock, scion or graft union that were associated with the measured productivity traits. On this basis we have assumed that rootstock effects were not significant in this experiment.

Genetic parameters and prospects for future breeding

The genetic analyses presented here are the first for Australian cashews. Furthermore, although hybrid vigour is a recognised feature of cashew (Damodaran 1975), which supports mass selections from hybrid populations based on traits such as nut yield and kernel recovery (Damodaran 1977), there has been little formal analysis of such selections reported in the literature. Some new hybrids have been released in recent years, particularly in India (Sapkal *et al.* 1998, Abdul Salam *et al.* 1998), but with one exception (Sankaranarayanan and Ahmad Shah 1999), genetic analyses of hybrid populations have not been reported.

All traits were moderately to highly heritable (Table 6). Traits that were highly interdependent had similar narrow-sense heritabilities with h^2 of ***value*** and ***canprod*** being about 0.15 - 0.23, of nut quality traits (***kwt*** and ***kr***) being 0.32-0.54 and of the trait relating to tree form (***shape***) being 0.83 - 0.85. These levels of h^2 indicated that under the environmental conditions in which the measurements were made, there is considerable potential for improving this cashew population (Falconer and Mackay 1996).

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, b), which defines correlations with coefficients in the range ≥ 0.65 as very strong, 0.64-0.5 as strong, 0.49-0.30 as weak and ≤ 0.30 as very weak, the very weak genetic correlations between ***canprod*** or ***value*** and ***kr*** indicate that selecting for either of the two 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*** (Searle 1961). It was not possible to obtain correlations for ***kwt*** or ***shape*** using either the individual tree model or reduced family model (eq. 2). Although the reason for this remains unknown it may have been because (i) ***kwt*** had a relatively small variance compared with the other traits, and (ii) ***shape*** data were limited to only one site.

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

This investigation has provided predictive information to advance cashew improvement in northern Australia. Hybrids (Table 5) showing promise for release to industry as potential new varieties were selected on the basis of their phenotype for key characteristics. Their potential lies in the fact that they must be maintained as distinct genotypes by vegetative propagation. Hybrids (Table 8) were also selected as potential new parents based on EBV's. 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, only one was not nominated as a potential parent based on EBV for ***value***. From this it could be argued that parent selection at this stage of the breeding program could be based solely on phenotype. However, EBV's supported the selection of not only these hybrids as parents but also others that were not identified for release. By using the 10 best from each hybrid set at each site based on EBV's, the genetic base would be wider than if only hybrids released to industry were used as parents. Indeed to avoid the possibilities of inbreeding, it would be prudent to use hybrids with high EBV's for ***value*** along with genotypes possessing useful traits from other diverse origins to ensure a continuing wide genetic base. The results from this investigation indicated that genetic improvement in cashew hybrids is likely to be rapid and if further crosses can be made, it would be interesting to assess via progeny tests the benefits or otherwise of selecting parents based on either EBV's or phenotypes.

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6. Commercialisation and Industry Significance

The hybrids that have been identified for immediate release to the industry and those that have potential as second generation parents have been clearly specified in the previous sections. However, a further objective of CSP-6A was to put in place arrangements that would encourage potential growers to make use of the new material while ensuring an appropriate return to all stakeholders with equity in the development of the new trees.

Commercial arrangements

Agreement to the principles governing the propagation of planting material and the royalty returns that might be expected when a successful plantation came into bearing was reached following negotiations between RIRDC, the research agencies and the principal commercial collaborator Mr Peter Shearer through Cashews Australia.

Propagation of cashew selections. In order to ease the cost of establishing a cashew plantation it was agreed there should be no royalty or licence fees applicable for the sale of cashew propagules derived from the material identified in this project. The agencies involved in the project did not themselves have the capacity to produce propagules for commercial use and it was agreed that a commercial nursery or nurseries should be licensed for the production of propagules.

Royalty on harvested nut-in-shell. A condition of the licence is that the nursery arranges with each grower to sign a non-propagation and royalty agreement which commits the grower to paying a royalty at the rate of 2.5% of the gross selling price per ton of harvested nut in shell from the selections. The royalties will be shared between RIRDC, the research agencies and Mr Peter Shearer in proportion to their financial inputs into the overall cost of the project.

NuCashew Commercial Arrangements

Subsequent to the agreement of the above principles, commercial arrangements for propagation and recouping of royalties were reached with NuPlant Ltd. This company in turn has an agreement with its subsidiary NuCashew Ltd which has published a prosectus seeking investment to commercialize new cashew plantations using hybrids from this project. This proposal is outlined in Appendix 1.

Hybrid germplasm maintenance

A further objective was to ensure that a ‘core’ collection be established in each location (NT and north QLD) so that the new hybrids and their parents be secured. This collection will also serve as a source of material for growers wishing to establish the new hybrids on their plantations. CSIRO and QDPI have taken responsibility for establishing these germplasm collections at their Darwin and Southedge locations, respectively.

At each location the germplasm will comprise field plantings of each hybrid and their respective parents. In Darwin, each hybrid and parent will also be kept in pots in the greenhouse to insure against termites or other unforseen attack by pests/disease in the field. In all cases the hybrids and parents have been multiplied by grafting onto the same seedling rootstock (BLA39-4) that was used in the field evaluations reported above.

CSIRO and QDPI have undertaken to maintain these germplasm collections until at least 2005, after which it is anticipated that new hybrids will have begun to supercede the selections from CSP-6A.

7. APPENDIX 1

NuCashew Commercial Arrangements

A path to market the improved cashew hybrid selections that have been developed in this project has been established in a licence agreement with NuPlant Limited (a Company associated with Mr Peter Shearer). The ownership of the selections remains with RIRDC and with CSIRO as the lead agents for the other agencies namely Queensland Department of Primary Industries, Northern Territory Department of Primary Industry and Fisheries. Under the licence NuPlant Ltd can propagate the selections in order to sell and distribute them to other parties. This licence is exclusive for a period of five years and can be extended for three further five year periods on an exclusive basis provided that NuPlant Ltd can demonstrate that it can continue to meet industry demand. If NuPlant Ltd wishes to use the propagation facilities of a third party, such as a nursery, then this must be approved in writing by CSIRO as the lead agency. At this time the export of any propagating material and selections is prohibited.

Prior to the sale and distribution of propagation material from the selections, the purchaser must sign an agreement with NuPlant Ltd that provides for the non-propagation, non-distribution and the payment of a royalty at the rate of 2.5% of gross selling price per tonne of harvested nut-in-shell from the selections. The gross selling price is to be agreed, based on market value and will be reviewed each three years. In determining the harvested tonnage from the selections to which royalties apply, there is recognition that in the first three years from planting production from the selections will be too low to charge a royalty payment. To compensate for this, in the fourth to tenth year of production, a royalty is payable on the difference between the harvested tonnage from all cashew trees on the growers property and the harvesting tonnes from non-selection trees of the grower for the previous three years. From year ten onwards, the royalty is based on the proportional area of plantings of the selections in any one orchard.

NuPlant Ltd is responsible for collecting all royalties, accounting for them and forwarding 90% of royalty income to CSIRO for distribution to RIRDC, the Northern Territory Department of Primary Industry and Fisheries and the Queensland Department of Primary Industries.

NuPlant Ltd and its subsidiary NuCashew Ltd have issued a prospectus seeking to raise $1.9M for investment in the farming of cashew trees at Cashew NT at Wildman River in the Northern Territyory. The aim is to establish 100 hectares of cashew plantations at the Wildman River site. The investment is being sold in parcels of 1000 cashew selections on approximately 5 hectares of land. If this is successful it will contribute to the establishment of the cashew industry in the Northern Territory.

A condition of NuPlant Ltd's licence is that it also supplies cashew propagules from the selections to other growers who may be independent of NuCashew Ltd on terms no less favourable than those available to its customers in NuCashew Ltd. It is hoped that the sale of the cashew selections to other independent select growers will gain favour.

The owners of the property at La Belle Downs in the Northern Territory are also seeking a licence to grow other selections that have been planted on that property. These selections, bred in 1988, were made on individual tree performance during project CSH43A (1993–1996).