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Proceedings—Full Papers

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***Domesticating African mahogany (*Khaya senegalensis*) in northern Australia - underpinning investment in plantations***

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**Abstract**

African mahogany (*Khaya senegalensis*), Ks, is a high-value hardwood species native to a seasonally-dry belt from Senegal-Guinea to Sudan-Uganda. It is well known in global markets although timber supplies from Africa are diminishing rapidly. In the Northern Territory (NT), Queensland (Qld) and Western Australia (WA), widespread Ks plantings of various kinds have been made since the 1960s. The largest plantations are in the Douglas-Daly region, NT where more than 14 000 ha have been planted since 2006, and new plantings averaged more than 1700 ha y<sup>-1</sup> in recent years. A vast tract of northern Australia is climatically suitable for Ks plantations. Australian Ks plantation trees produce wood suited to specialty purpose and appearance grade sawn timber and veneer products. Furniture crafted from sawn plantation timber has won state and national awards. Prices are expected to be high for final crop logs and veneer billets.

Results of the diverse trials and commercial plantings indicate that Ks needs improvement in bole length and straightness at least to enhance merchantable yield of plantations, and that it has many desirable attributes. These include adaptability to a range of climatically-suitable environments, responsiveness to silvicultural management, tolerance of potential pests, capacity to grow relatively fast while producing high quality wood products, great variation in traits of economic importance and amenability to genetic improvement. The main potential risks to be factored into grower deployment strategy are fire, frost, severe cyclones in coastal areas, drought and possible emergence of serious pests and diseases.

The NT and Qld governments began domesticating Ks in 2001. Above average trees were selected within about seven hectares of government provenance trials and other stands planted in the NT by the forestry research unit of the then Commonwealth Forestry and Timber Bureau in the 1960s–1970s. These stands comprised more than 23 provenances from 11 of the 20 African countries where Ks occurs naturally. The selected trees were grafted and planted in small clonal seed orchards (CSOs) in the NT (98 clones initially, 44 added later) and Qld (a 68-clone subset) in 2001 and 2003 respectively. Seed from some of the selected NT trees and others at Weipa, Qld provided plants for establishment of a hedge garden planted at the Berrimah Research Farm (NT) in 2004. Cuttings from a large sub-set of the NT hedges were established as potted hedges in Qld in 2005. Rooted cuttings were produced for clone trials planted in the NT and Qld during 2005–2012. The CSOs and other sources provided seed to plant progeny trials in the NT and Qld during 2009–2012. Early results of clone, progeny and provenance trials, the latter in Australia and Sri Lanka, indicate genetic variation exists for traits of economic importance.

Beginning in the mid-2000s, large amounts of Ks seed were imported from Africa annually to support industrial plantings under Managed Investment Schemes. This seed included many provenances and trials were planted on company land in the NT during 2006–2013 and in Qld in 2006 and 2008, several via collaboration between industry and the Qld government. Additionally, many African provenances and families were planted privately in Qld in 2008. The total genetic base of the species in Australia now comprises more than 100 provenances from 17 African countries, and landraces, and is the widest outside Africa.

A second phase of domestication began recently in the NT and Qld, led by the private sector. It will be based primarily on trees selected in newer provenance and progeny trials and plantations established since 2008, and older landrace plantings.

Taken together with the comparative advantages Australia holds for extending Ks plantations, the attributes of the species and its domestication status indicate it is worthy of ongoing domestication in Australia, and of consideration for further plantation development in and beyond the Douglas-Daly hub. Long-term R&D will be essential to underpin a potentially-new, sustainable industry in northern Australia.

## Introduction

African mahogany (*Khaya senegalensis*), referred to as Ks in this paper, is a high-value tropical hardwood species occurring naturally in a seasonally-dry belt from Senegal-Guinea in the west to Sudan-Uganda in the east (Dickinson *et al.* in prep, Sexton 2013). Ks is well known in global markets although timber supplies from Africa are diminishing rapidly.

Widespread plantings of Ks have been made in northern Australia since its introduction 1959. These include various trials in the NT in the 1960s and 1970s; mined site rehabilitation at Weipa, Qld during the 1960s to 1985; woodlots and trials in north-east Qld during the late 1980s to 2008; trials in the Ord River Irrigation Area, near Kununurra, Western Australia (WA) in the 1980s and 1990s; trials in the NT during 1999 and 2000; and industrial plantations in Qld, the NT and WA between 2005 and the present. The largest plantations are in the Douglas-Daly region of the NT where some 14 000 ha have been planted since 2006 with ongoing annual plantings that have averaged more than 1700 ha in recent years (F. Miller, African Mahogany Australia, 2014, pers. comm.).

Ks is among the highest-value species in large, commercial timber plantations in Australia. Dried dressed Medium Feature to Select Grade timber sawn from 30-y-old plantation trees was judged in an industry survey in 2004 to retail for between A\$3000 and A\$5500 m<sup>-3</sup> on the domestic market (Armstrong *et al.* 2007). Furniture crafted from it won state and national awards (Nikles *et al.* 2008). Twenty-year-old plantation trees produced wood well suited to specialty purpose and appearance grade sawn timber and veneer products (Zbonak *et al.* 2010). While future domestic and export market prices for clear-fall and



**Figure 1. Senegal provenance trees (age 6.5 y) in the Douglas-Daly, NT. Central tree DBH 13.2 cm. Note the variation between individual trees in height of unbranched bole, growth, form and branch characteristics. Photo: J. Stone.**

thinnings logs from Australian plantations are uncertain, they are expected to be high for final crop logs and veneer billets.

Initiation and progress of the domestication of Ks that began, in Australia, in 2001 has been widely reported (Bevege *et al.* 2004, 2006; Dickinson *et al.* 2011; Nikles 2006; Nikles *et al.* 2004, 2008, 2012; Reilly *et al.* 2007, 2009). It was first undertaken jointly by the NT and Qld governments via tree selection in experimental plantings made by CSIRO near Darwin from the late 1960s to the early 1970s including a series of three provenance trials planted in 1971–1973. This base was augmented later with seedlings from trees selected at Weipa and other areas in Qld. The facilities established and R&D outcomes of this program, which was curtailed in 2011–2012 due to changes in government funding priorities, are summarised in this paper.

Experience gained from these diverse activities in many locations over many years in northern Australia indicates Ks, though requiring improvement in stem and branch form, has a number of desirable attributes. These include a vast homoclimate; wide adaptability to soils, pH and drought; a useful level of windfirmness; responsiveness to silvicultural management; high tolerance of or resistance to potential pests when grown on suitable sites; capacity to grow relatively fast and produce wood products of high quality and value; and genetic and/or phenotypic variation in many economic traits. As well, Australia holds many comparative advantages for developing a new, African mahogany-based industry in northern Australia.

A second phase of domestication, led by the private sector, began recently in Qld (Sexton 2013) and the NT [R. Fremlin, African Mahogany Genetics (AMG) 2014, pers. comm.]. It will be based primarily on trees selected in newer provenance and progeny trials and plantations established since 2008 and landrace plantings. Drivers for this phase include excellent phenotypes observed (Fig. 1) and results of genetic studies presented in this paper indicating that all traits of economic importance assessed are heritable.

These factors indicate Ks is worthy of ongoing domestication in northern Australia, and of consideration for further commercial deployment in and beyond the Douglas-Daly hub. Additional hubs might be identified broadly via results of existing plantings (where available), the homoclimate boundaries (Arnold *et al.* 2004), local climate (including cyclone history) and soils, and land availability (constrained by vegetation management regulations).

This paper updates the domestication of Ks in northern Australia, provides evidence of genetic or phenotypic variation for traits of economic importance in growing Ks plantations commercially, discusses prospects for genetic improvement and encourages extension of plantations. Sustained R&D suggested will be essential to underpin a potentially-new, sustainable industry in northern Australia.

### **Initial genetic base, tree selection and facilities established during 2001–2004**

The initial genetic base, tree selection for conservation and improvement and clonal seed orchards (CSOs) and hedge gardens that were established under the NT and Qld Governments during 2001–04 were described in Nikles *et al.* 2008. The base comprised three adjacent provenance trials planted near Darwin in 1971–1973 and other local stands including 26 provenances in all from 11 African countries and New Caledonia. Within these stands, totalling c. seven ha, 98 above-average trees were selected and established in two NT CSOs near Darwin in 2001 (1.3 ha and 0.6 ha). A 68-clone sub-set of the 98, NT clones was planted

in a CSO in Qld in 2003 (0.7 ha). A further 44 NT selections were added to the NT CSOs later, as were several local selections to the Qld CSO, increasing diversity. A provenance seedling seed orchard (PSSO) (Nanson 1972) of 0.8 ha was developed from a trial of five Burkina Faso provenances planted in 2001 near Mareeba, Qld.

An in-ground hedge garden was planted at the Berrimah Research Farm (NT) in 2004. Seedlings (528) from selected trees (11 from the NT and an unknown number from Weipa (Qld)) and wildlings from the NT, were included initially and supplemented by 40 rooted cuttings (RCs) from select-tree-stump coppice (31 RCs, nine clones) and other sources. A sub-set of >200 clones from the NT hedges and a local clone were established in pots in Qld (Pomroy and Lee 2006). Management to maintain hedge vigour while delaying onset of physiological ageing was undertaken by irrigation, fertilising and topping as required both in the NT and Qld.

### **Seed orchards – outcomes**

Details of the sites and composition of the CSOs in the NT and Qld are given in Dickinson *et al.* 2012a. Seed production occurred first in the NT orchards when they were 5.5 y old. Only 60% of clones have flowered in the NT (90% in Qld) and less than half have produced viable seed (Dickinson *et al.* 2012a). The highest yield (c. 3 kg ha<sup>-1</sup>) was obtained in 2010 from the larger NT CSO (Nikles *et al.* 2012). The PSSO has produced little seed. In both NT and Qld CSOs most seed came from few clones (Dickinson *et al.* 2012a). However, sufficient seed was obtained to enable establishment of second-generation progeny trials from 31 clones (see Section ‘Progeny trials’ below). Flowering in the NT CSOs is between July and November, and between November and February in Qld. Within CSOs, flowering of the clones from their diverse origins across central Africa is highly synchronous and should facilitate production of genetically-diverse seed crops. The CSOs were also used to identify and describe male and female flowers and flowering patterns and for research on control of pollination and flower induction (Dickinson *et al.* 2012a). Further research required on flowering and seed production is outlined in the Section ‘R&D to support genetic improvement’ below.

### **Genetic trials established by the public and private sectors**

#### ***Clone trials***

The hedges provided rooted cuttings for numerous clone trials and a demonstration area planted between 2005 and 2012 in the NT and Qld, either on government or private land with more than 400 clones included (Nikles *et al.* 2012, R. Fremlin, AMG, 2012, pers. comm.). The number of clones per trial ranges from 21 to 320 (Reilly and Robertson 2006, Reilly *et al.* 2011). However, problems associated with most trials have generally constrained procurement of definitive results. Due to the low multiplication rate from early hedges, most clones in early trials had only two or three replications. Three trials planted on Melville Island could not be followed up. One trial at the Douglas-Daly Research Farm sustained considerable mortality due to animal predation on roots. A trial near Ingham, Qld was severely damaged by Tropical Cyclone Yasi. In some trials numerous trees forked below or just above breast height compromising assessment. Additionally, the limited resources available from governments did not permit optimal silvicultural management of the trials, and changes in government funding priorities since 2011 have curtailed trial assessment and analysis. Results for a few trials are outlined below.

### ***Trial planted in March 2007 in the Douglas-Daly, NT***

This collaborative trial of government clones was planted on company land at approximately 14°04'S, 131°27'E, 90 m a.s.l. The mean annual rainfall (MAR) is 1182 mm and the soil type is a Red Kandosol. A randomised incomplete block (RICB), single-tree-plot design was used with five replications of 240 trees per replication. Initial stocking was 1000 s ha<sup>-1</sup>. Entries comprised 197 clones as rooted-cuttings (ramets) from a sample of the Berrimah Farm seedling hedges. The number of ramets per clone varied from three to five. The Control was a bulk of seedlings from Darwin street trees. The trial was measured at ages 1.5 y (height) and 4.2 y (height, DBH and merchantable bole length and scored for straightness (scale 1–6, 6 = best). Survival was >95%. There were highly significant differences for the four quantitative traits ( $P < 0.001$ , unpublished results) showing there was genetic variation at the clone level. Clone median scores for the ordinal data of straightness ranged from two to five and significant differences were inferred. Preliminary estimates of clonal heritabilities at age 4.2 y were high – 0.524, 0.666, 0.651 and 0.748 (standard errors not available) for the four quantitative traits respectively. For each trait, many clones surpassed the Control. However, only one clone was among the top 10% of clones for all four quantitative traits and among the top 14% of clones with a median straightness score of five illustrating the rarity of clones combining a high expression of several desirable traits. This is not surprising given the early stage of domestication and large number of traits of interest. Applying a notional, integrative index of clone 'worth' calculated as mean DBH<sup>2</sup> × bole length × median straightness, the top 5% of clones (10) had an average index value of 3294 (4256 for the best clone) compared to 1572 for the Control. The best individual Control seedling of 148 in the trial had an index value of 3591 illustrating the potential for selection in such populations.

### ***Trial planted in May 2008 near Ingham, Qld***

This collaborative trial of government clones was planted on company land at approximately 18°28'S, 145°58'E, 80 m a.s.l., MAR 1583 mm on a Brown Kandosol soil. Initial stocking was 1250 s ha<sup>-1</sup>. A randomised complete block (RCB) design was used with 11 replications of 80-tree blocks and non-contiguous single- or multiple-tree plots to cope with variable numbers of ramets per clone (2–31); those with >11 ramets had >1 ramet in some or all replications. Entries included 56 rooted-cuttings (ramets) clones comprising 55 from a sample of the clonal hedges established in Qld from cuttings transferred from the NT hedge garden, and a single Qld clone derived from basal coppice on a 'plus' tree of outstanding height, good diameter and above-average straightness selected at age 3 y in a stand in coastal north Qld. Controls were Burkina Faso and Darwin seedlings; each had 10 or more seedlings per replicate. The trial was measured at age 2.3 y for DBH and height and scored for straightness (1–6, 6 = best). The trial was strongly impacted by Tropical Cyclone (TC) Yasi at age 2.7 y. The strength of the winds at the site exceeded 163 km hr<sup>-1</sup> (Category 2–3). At age 3.0 y the trial was re-assessed for the above traits and also for apical persistence (a surrogate for 'merchantable height' on a scale 1–6, 6 = best) and 'lean' (1–5, 1 = best). The 2.3-y assessment of straightness was considered the more reliable. There were statistically significant differences for



**Figure 2. A rooted-cutting tree (ramet) (age 22 m) of Queensland Clone 1 in a replicated, single-tree-plot trial of 56 clones near Ingham, Queensland. Clone 1 (nine ramets, mean height 6.3 m at age 3 y) was the tallest in the trial. Photo: G. Dickinson**

3.0-y DBH and height ( $P < 0.001$ ) and the ordinal data for the scored traits were also considered to indicate genetic differences among clones. Of the Controls, Burkina Faso was superior to Darwin in all traits and its 3.0-y DBH mean exceeded the 'all clones' mean (7.9 cm vs 7.3 cm). However, several individual clones exceeded Burkina Faso in some traits. For example, clone 311, derived from a seedling of Darwin select tree 166, was superior to Burkina Faso for DBH, height, straightness and axis persistence but was poorer in lean. Clone means for lean ranged widely (1.32–4.36) several being better than Burkina Faso (mean 2.08). The Qld Clone 1 (Fig. 2) ranked well: at 3.0 y, first for height, fifth for DBH, fifth for apical persistence; and at 2.3-y, fifteenth for straightness. However, at 3.0 y it ranked 44th for lean, perhaps because of its great height and consequent exposure. No clone combined low lean (good windfirmness) with high growth, straightness and axis persistence under the extreme-wind conditions of the trial. The likely potential of the clones without the effect of such extreme winds was assessed by combining individual clone values in an index calculated as  $3\text{-y DBH}^2 \times \text{axis persistence score} \times 2.3\text{-y straightness score}$ . This gave wide-ranging index values. The top-ranking five clones (c. 9%), had index values ranging from 1069 to 2733 (mean 1680) while that for the better control (Burkina Faso) was 1062, a difference of 58%. Results indicate genetic variation among clones many having potential in areas not prone to extremely strong winds; and superiority of best clones over a natural-stand Control for an integrated index.

#### ***Trial of clones and families planted in June 2009 near Mareeba, Qld***

This collaborative trial is on private land at approximately 17°01'S, 145°19'E, 550 m a.s.l., with a MAR 920 mm and on a Yellow Kandosol/Chromosol soil. Initial stocking was 1250 s ha<sup>-1</sup>. Entries comprise 48 hedge garden clones, seedlings of 10 CSO and two Qld-select-tree families and a seedling Control (Tiefora, Burkina Faso). Each block of the RCB design of 12 replications has 100 trees randomly allocated as single-tree plots of a) clones – 48, b) families – 12 of three seedlings each (discussed under 'Progeny trials' below) and c) 16 Control seedlings. The trial was measured for DBH and height at age 3.1 y and a volume index [ $1/3 \text{ height} \times (\text{DBH}/200)^2$ ] was calculated for each entry. Survival at 3.1 y ranged from 83 to 100% with almost all clones recording > 90% and Control 97%. Control seedlings averaged 4.3 cm in DBH, 2.5 m in height and 0.0015 in volume index. Most clones surpassed the Control seedlings in DBH (83% of the clones), height (92%) and volume index (83%). The mean of the top 10 clones (c. 20%) in volume index exceeded that of the control by 93% (0.0029 vs 0.0015).

#### ***Clone demonstration area planted in January 2011 near Mareeba, Qld***

This collaborative planting is on private land at approximately 16°58'S, 145°19'E, 400 m a.s.l., with a MAR 920 mm and on a Yellow/Brown Chromosol soil. Initial stocking was 833 s ha<sup>-1</sup>. There are 54 clones and a Control established as single-row plots, the Control comprising a mixture of seedlings from >10 CSO families. Though a statistical design was not employed, several clones had repeated rows. Although no measurements have been made, observations suggest that the DBH, height, bole length, stem straightness and branch configuration vary considerably at age 2 y suggesting differences between clones for these traits. Relative within-clone uniformity contrasted with the high variation among seedlings.

Despite the problems associated with several clone trials, results indicate there is genetic variation among clones with the best being superior to the Controls. Across the older trials, 10 clones combining superiority for most commercial traits have been nominated; some of



these clones appear to show adaptability across diverse sites. These are worthy of further testing and inclusion in new grafted seed orchards and breeding populations. Some of the existing trials could be considered for conversion to CSOs in the future.

### **Progeny trials**

Progeny trials have been established by the public and private sectors, several collaboratively. Eight trials were planted between 2008 and 2012. Some trials include families from wild trees in Africa. A milestone was reached in 2009 when the first trial that included second-generation families from seed of the NT CSOs was planted. To our knowledge these are the first progeny trials of Ks from CSO seed in the world.

#### ***Trials planted in October 2008 near Cooktown and Ingham, Qld***

These trials, planted on private land, mainly comprise ‘families-within-provenances’ and included more than 300 African seedlots (families and bulks) most collected by G. Sexton in 2007 from several western African countries (Sexton 2013). Seedlots were obtained from several additional African countries subsequently. For the 2008 planting near Ingham, a RICB design with six replications of four-tree line plots of families was used. These trials were damaged, variously at the two locations, by cattle, fire, flood and cyclone. The trial near Ingham was impacted by TC Yasi at age 2.3 y with heavy rains and winds  $>200 \text{ km hr}^{-1}$ . More than 60% of the trees were pushed over to varying degrees. However, provenance and family variation (genetic) and individual tree variation (phenotypic) in tree responses were exhibited and several superior trees for pre-cyclone growth and post-cyclone relative windfirmness were selected and established in a seed orchard (Sexton 2013; G. Sexton, Designer Timbers, 2014, pers. comm.).

#### ***Trial planted in June 2009 near Mareeba, Qld***

This trial is incorporated within the clone-progeny trial of the same year, location and stocking as described above under ‘Clone trials’. Family Entries include 10 CSO families and two Qld-select-tree families each of 36 trees (12 replications of three-tree, non-contiguous plots). The Control is provenance Tiefora, Burkina Faso. The trial was measured for DBH and height at age 3.1 y and a volume index  $[1/3 \text{ height} \times (\text{DBH}/200)^2]$  was calculated for each family and the Control. Survival exceeded 90% for all families and the Control. CSO family means for DBH, height and volume index averaged 5.0 cm, 3.2 m and 0.0024 respectively, exceeding the respective Control values of 4.3 cm, 2.5 m and 0.0015 by 17%, 25% and 60% respectively. The two Qld families were relatively poor in volume index (0.0020 and 0.0014). The CSO families ranged in volume index 0.0019–0.0029 with a family from a Senegal seed parent (9-096) ranking first and from two Ugandan seed parents (9-094, 9-116) ranking equal second. This top 30% of families averaged 0.00283 in volume index exceeding the Control by 89%. The poorest CSO families were from two Ugandan and one Senegal seed parents. These observations indicate likely significant differences in growth between families and between the best families and the African control.

#### ***Trial planted in February 2010 at the Katherine Research Station, NT***

This trial is on state land near Katherine, NT located at 14°28'S, 132°16'E, 108 m a.s.l., with a MAR 970 mm. Soil type is ‘Tippera red earth’, a deep clay loam textured Red Kandosol. Entries comprise 38 families from seed of the Darwin CSO representing 30 clones (eight clones had families from two or three grafts). The Controls are two African bulks (Tiefora,

Burkina Faso and Favako, Mali) and a landrace bulk (Katherine, NT). A RICB design with 11 replications of four-tree line plots was used. Initial stocking was 797 s ha<sup>-1</sup> in replicates 1–6 and 870 s ha<sup>-1</sup> in replicates 7–11. Drip irrigation was applied in the first few years. Survival three months after planting exceeded 95%. The trial was measured for DBH and bole length and scored for straightness (1–6, 6 = best) at age 3.5 y. Survival remained high (>95%). However, a very large number of trees exhibited forking below breast height preventing standard DBH measurement and compromising measurement of bole length, the scoring of straightness and statistical analysis. Inspection of the data showed that one family (Togo seed parent 9-078) excelled in having the most trees combining good DBH ( $\geq 11.0$  cm), bole length ( $\geq 3.0$  m) and straightness score ( $\geq 4.0$ ), *viz.* nine of its full complement of 44 trees present. A few other families each had four or five trees meeting the criterion; their CSO seed parents were from Nigeria, New Caledonia, Senegal and Uganda provenances. Senegal was represented in the trial by five families all of which had some trees meeting the criterion, but no family was outstanding. The Australian landrace performed relatively well having five trees that met the criterion. Of the African Controls, Tiefora, Burkina Faso and especially the Favako, Mali had few trees meeting the criterion, *viz.* three and one respectively. Results indicate likely significant differences between families with the best surpassing the African Controls in numbers of superior trees.

#### ***Trial planted in May 2010 at the Ayr Research Station, Qld***

This trial is on state land at 19° 37' S, 147°23'E, <10 m asl., MAR (Ayr) 1054 mm. The site is mapped as the Katoora unit mainly with the soil, possibly a Stratic Rudosol, being highly variable with upper layers (to 80 cm) of light clay with 80–100 cm of sandy loam below. Initial stocking was 1000 s ha<sup>-1</sup>. Entries comprise 42 families (41 from seed of the Darwin CSO representing 30 clones since nine clones had families from two or three grafts), one family of a Qld select tree and two Controls—an African bulk (Tiefora, Burkina Faso) and a landrace bulk (Katherine, NT). A RICB design with seven replications of three-tree line plots was used, with the African Control having two lines in each replicate. TC Yasi, classed as Category 1 to 2 when it passed over the trial at age seven months, caused variable degrees of tree lean though more than 90% of trees were judged unaffected. In April 2014, TC Ita passed over the trial at age 3.9 y; the maximum wind gust speed was 61 km hr<sup>-1</sup> and little damage occurred.

The trial was measured at age 3.3 y for DBH, total height and ‘height to a utilisation-limiting defect’ (HTULD), and scored for straightness (1–6, 6 = best). Survival was almost 100%. Examination of trait means for the 30 clonal families, from pooling of results where there were 2–3 families per clone, the single Qld family and the two Controls gave the following observations. Family means varied widely for each trait ranging 3.5–5.4 m for total height, 5.4–8.0 cm for DBH, 2.8–4.5 m for HTULD and 2.2–4.2 for straightness score. Respective trait means and standard deviations for the 30 CSO families were 4.5±0.34 m, 7.0±0.46 cm, 3.6±0.35 m and 3.10±1.14. One family (9-077) surpassed the mean plus two standard deviations for height and HTULD (and surpassed the 30-family mean for DBH and straightness). On the same criterion, family 9-027 was superior for DBH and surpassed the 30-family means for total height, HTULD and straightness. Means for the Tiefora, Burkina Faso Control were 4.3 m, 7.1 cm, 3.1 m and 3.3 (with standard deviations similar to those for the families), *i. e.* poorer than CSO families in total height and HTULD but better in straightness and marginally better in DBH. The landrace population was similar to Burkina Faso in height and HTULD but poorer in DBH (6.5 cm) and straightness (2.8).

To facilitate preliminary comparisons of CSO families and Controls for three important traits, a simple index combining DBH, HTULD and straightness was calculated as  $DBH^2 \times HTULD \times \text{straightness}$ . For the better six CSO families (20%) the following list shows the family name, the country source of the CSO seed parent and index values respectively: 9-077, Senegal, 926; 9-027, Nigeria, 909; 9-008, New Caledonia, 892; 9-033, Ivory Coast, 815; 9-050, Senegal, 690; 9-104, Uganda, 604. Index values for both Controls were considerably less: Tiefert, Burkina Faso, 513 and Katherine landrace, 391 indicating superiority of the better six CSO families, the seed parents of which were of diverse original provenance.

As a simple approach to gauging the distribution of trait-wide, superior trees within families and Controls, trees combining  $DBH \geq 8.8$  cm,  $HTULD \geq 4$  m and a straightness score  $\geq 4$  were noted. (These limits were approximately 20% above overall means and take no account of site variation). It was found that 20 families had one or two trees meeting the criterion, with four families (9-027, Nigeria; 9-065, Nigeria; 9-083, Central African Republic; and 9-104, Uganda) each having two trees meeting the criterion, while the Controls had none. Thus several families and individual trees in this young trial may be promising for future breeding.

### ***Trial planted in January 2011 in the Douglas-Daly, NT***

This trial was established by AMG on company land with location and environmental details similar to those given for other trials in the Douglas-Daly. Initial stocking was  $1263 \text{ s ha}^{-1}$ . This trial is of special interest as the Entries include families from two South Sudan provenances (7 and 10 families) giving the first opportunity (along with a 2011 provenance trial described below) since the trials of the 1970s to assess the potential of far eastern sources. Controls comprise bulks of a Mali provenance and an Australian landrace (Kununurra, WA) giving a total of 19 entries (R. Fremlin, AMG, 2014, pers. comm.). The basic design is RCB with 36 replications of single-tree plots. The trial was measured for DBH, height, height to crown break and scored for 'acceptability', branch habit and straightness at age 2.3 y. High score values were best for all traits. Family and Control means were provided by R. Fremlin. Across all Entries, means for the respective traits were 4.9 cm, 3.5 m, 3.0 m, 2.7, 4.5 and 3.6. For DBH, provenance means were: South Sudan 1 – 4.7 cm, South Sudan 2 – 4.9 cm, Mali – 5.1 cm and Kununurra – 5.0 cm. The Controls appeared to have slightly better 'acceptability' than the South Sudan material. South Sudan provenances 1 and 2 and Controls had similar means for the other traits. Among the families, South Sudan 1 had one family exceeding an arbitrary 5.0 cm in DBH, i.e. 14% of its families, while Sudan 2 had three (30%). In the provenance trial planted in the Douglas-Daly in 2008, the particular Mali provenance used as a Control here was poor in DBH relative to most other Mali provenances and markedly so relative to all provenances from Burkina Faso, Cameroon, Guinea and Senegal (see below under 'Provenance trials'). This suggests South Sudan provenances may exhibit relatively poor growth. However, the means for all traits of one family of South Sudan 2 were high or higher than those of all other families and the Controls, indicating there is the possibility of finding good breeding material in South Sudan provenances in the future when additional biotic and abiotic factors may impact the populations available for selective breeding.

Early results of the progeny trials reviewed here indicate variation between families, many being superior to the Controls. The trials will enable forward and backward selection in the future breeding cycle and could be considered for conversion into SSOs in the future. Parents in the CSOs with superior families could be targeted for special seed collections, e.g. for

vegetative multiplication. This highlights the need to maintain these valuable trials (and CSOs wherein some clones have not yet produced seed).

### Provenance trials

During 2006–13, nine trials were established by growers, several in conjunction with the Qld government: in the NT (seven in the Douglas-Daly, one on Melville Is.) and another near Ingham in coastal north Qld. Also planted near Ingham, and Cooktown, Qld in 2008 were family-in-provenance trials established on private land; those near Ingham were reviewed in the Section ‘Progeny trials’ above. Several of these trials are reviewed below.

#### *Trials planted in January 2008 in the Douglas-Daly and in April 2008 near Ingham, Qld*



**Figure 3. African provenance trees (age 2.8 y) near Ingham, Queensland after being impacted by Tropical Cyclone Yasi (Category 2–3). Note the erect central tree, exhibiting no stem damage in the midst of damaged cohorts. Photo: G. Dickinson.**

and b) central ( $0^{\circ}$  to  $20^{\circ}$  E), *viz.* Cameroon (5); and varying numbers of Australian landraces (Darwin, one or two; and Kununurra, WA, two or three in the respective trials). Initial stocking was  $1250 \text{ s ha}^{-1}$  in both trials. RCIB designs with four replications of 60-tree, multi-row plots were used. The Qld trial was impacted by TC Yasi at age 2.8 y in February 2011 and was damaged severely (Fig. 3). The trials were assessed at age 3 y for several traits – height, DBH and straightness at both sites; branch thickness in the NT only; and axis persistence, lean and diseased trees in Qld only (Dickinson *et al.* in prep.). Both country of origin and provenance had statistically significant effects for all traits assessed at each site:  $P < 0.001$  for both country and provenance at both sites for height and DBH, and for provenance straightness and diseased trees at the Ingham site; and  $P < 0.01$  or  $P < 0.05$  for all other trait combinations with country and provenance. Quoting from Dickinson *et al.* in prep, ‘Senegal and Guinea provenances performed best overall, with good height and diameter growth, straightness,

Locations and environmental details for these trials on company land, established in collaboration with the Qld government, are similar to those given for the clone trials planted in the Douglas-Daly, NT in 2007 and near Ingham, Qld in 2008 respectively (Dickinson *et al.* in prep.). These trials included 38 provenances from five African countries of two broad regions across the natural range: a) western (west of longitude  $0^{\circ}$ ), including Senegal (four provenances), Guinea (1), Mali (22) and western Burkina Faso (6);



**Figure 4. Cameroon provenance trees (age 6.5 y) in the Douglas-Daly, NT. Central tree DBH 13.5 cm (estimated). Note the variation between individual trees in height of unbranched bole, growth, form and branch characteristics. Photo: J. Stone.**

axis persistence, thinner branches and good tolerance of pink disease (*Erythricium salomonicolor*). However, their average windfirmness was intermediate; this may be due to increased susceptibility to wind damage caused by their greater height. Cameroon trees had very good DBH, intermediate height and outstanding disease tolerance, but poorer straightness, axis persistence and larger branches. Burkina Faso trees had intermediate to good height, DBH and straightness, but often branches were larger and disease tolerance was poorer. Mali trees generally had good straightness, axis persistence and windfirmness, but often had poorest height, DBH and disease tolerance. Australian landraces varied greatly in height, diameter and axis persistence, but generally were of poorer straightness and windfirmness and had thicker branches. Individual provenances from Senegal (3), Guinea (1) and Mali (2) performed very well for most traits at both sites'. At both sites individual trees with a good combination of all traits (candidate 'plus' trees) were observed in most provenances (Figs 1, 3–4). Hence, it should be possible to develop diverse breeding populations by selection in these trials.

### ***Trial planted in February 2009 in the Douglas-Daly, NT***

Location and environmental details for this trial on company land, established in collaboration with the Qld government, are similar to those given above for other trials in the Douglas-Daly. Initial stocking was 1250 s ha<sup>-1</sup>. The trial included 71 provenances, many common to the 2008 trials, viz. Burkina Faso (4 provenances), Cameroon (5), Mali (19) and Senegal (4). New provenances from common countries were: Burkina Faso (4), Mali (20) and Senegal (5), while new countries were: Benin (4) and Niger (6) – both (along with Cameroon) of the central region defined for provenances of the 2008 trials described above. A RICB design with three replications of 60-tree, multi-row plots was used. The trial was measured by AMG at age 4.3 y for DBH and scored for 'tree value index' (TVI), a subjective rating of individual trees on a combination of relative growth, straightness, branching and apical dominance using a scale of 1–9, 9 = best. Data were analysed and results provided by AMG (R. Fremlin, AMG, 2014, pers. comm.; M. and S. Carson, Forest Genetics Ltd NZ, 2014, pers. comm.). Survival was high (92%) and there were highly significant differences between provenances for both DBH ( $P < 0.0001$ ) and TVI ( $P < 0.0002$ ). Diameter means ranged from 6.0 cm for a Niger provenance to 8.6 cm for a Burkina Faso provenance from the Central-South Region of that country. Country means for Burkina Faso, Cameroon and Senegal were similar and best (c. 7.3 to 7.4 cm), as in the 2008 trial, while Niger and Benin (c. 6.4 and 6.5 cm respectively) were poorest, with Mali provenances intermediate (6.8 cm). Inspection of the ranked means for DBH showed Mali provenances dominated in an arbitrary top 20% (14) of places with seven provenances in this cohort. However, when expressed as a percentage of the number of Mali provenances in the 'top 14' relative to the number in the trial, viz. seven of the 39 provenances, the proportion was only 18%. This compared to 38% for Burkina Faso provenances, 33% for Senegal, 20% for Cameroon and zero for both Benin and Niger provenances. Similar treatment of the TVI results showed the following percentages: Senegal 44%, Burkina Faso 25%, Mali 21% and zero for both Benin and Niger. Based on a combination of the traits as a more critical criterion of country-source potential, in this case the proportions of provenances combining 'top 20% for DBH and TVI score >3.5', the following results were found: Burkina Faso 25%, Mali 13%, Senegal 11% and zero for both Benin and Niger. The extremely poor performances for both traits of all the Benin and Niger provenances, which were clustered geographically in a relatively very localised, low elevation region in the far north of Benin and far south west of Niger (records of the 2008 Ks seed collections for the then Great Southern Limited (GSL) company per R. Fremlin, 2008, pers. comm.) may indicate inbreeding or long-term natural or heavy dysgenic selection

pressure in the sampled area of Benin-Niger. Unfortunately, this trial has been lost to land re-development.

The results for growth and tree quality lend support to the findings of the 2007 and 2008 trials, *viz.* that many provenances from the western region are the more promising at young ages.

### ***Trial planted in 2011 in the Douglas-Daly, NT***

This trial was established on company land by AMG and is located similarly to other trials in the Douglas-Daly. There are 12 African provenances – Burkina Faso (1 provenance), Mali (7) and South Sudan (4); and an Australian landrace (Kununurra) as Control. Five provenances are common to either the 2008 or 2009 trials. One of the South Sudan provenances was established as nine individual families. Initial stocking was 1263 s ha<sup>-1</sup>. A RCB design with up to six replications of multi-row plots was used. The trial was measured at age 2.5 y for DBH and scored for TVI (1–9, 9 = best) by AMG. Provenance means were provided by AMG (R. Fremlin, AMG, 2014, pers. comm.). The provenance means for DBH and TVI ranged 5.6–6.5 cm and 3.9–5.1 for the respective traits. Simple arithmetic rankings of the provenance means for DBH by country were: South Sudan — 1st, 6th, 9th, 11th; Mali – 2nd, two at 3rd, 8th, 10th, 11th; Burkina Faso — 7th; Australia — 3rd. Though a South Sudan provenance ranked first for DBH (6.5 cm), narrowly surpassing two Mali provenances at ranks 2nd (6.4 cm), and 3rd (6.3 cm) respectively, these Mali provenances performed very poorly or poorly for DBH in either the 2008 or 2009 trials in the Douglas-Daly. Similarly, in the progeny trial planted in the Douglas-Daly in 2011 (see ‘Progeny trials’ section above), both provenances of South Sudan were slightly poorer in DBH at age 2.3 y than the known-poor Mali provenances. Unless these South Sudan provenances are inbred relative to the Controls, one may infer that even the high-growth South Sudan provenance might prove to be inferior in growth to Senegal and some other western provenances that have been demonstrated to be more vigorous than many Mali provenances in earlier trials mentioned above. The most promising provenances, *i.e.* those ranking highest for both traits, comprised three of the Mali provenances and the Australian landrace. Although a South Sudan provenance ranked 1st for DBH, it ranked 11th for TVI exhibiting a tendency observed in most trials and more generally, *i.e.* a negative phenotypic relationship of DBH and tree quality (TVI here) for many provenances. The other South Sudan provenances ranked poorly for TVI – 8th, 12th and 13th.

Of interest is that one South Sudan family is currently the most promising material in the trial having a mean DBH of 7.3 cm and TVI mean score of 4.8. Hence, some useful breeding material might be found in South Sudan accessions, of which there is now a substantial amount in the Douglas-Daly (R. Fremlin, AMG, 2014, pers. comm.), as it would add diversity to breeding populations.

In general, therefore, early results of several trials of provenances from across the tri-regional range in Africa indicate that provenances from the western region are the more promising. However, at older age when additional biotic and abiotic factors may have impacted the populations available for selective breeding, this may change. Field observations show that superior individual trees occur in populations of all three regions. It would be wise to sample a wide range of provenances for future conservation and breeding material.

## Prospects for genetic improvement under <20-25-y rotations

Achieving genetic improvement requires a well-defined objective; knowledge of heritable traits, their correlations and relative economic importance; genetic resources with variability for these traits; and means to identify, capture and deploy superior material. The objective of Ks plantations in northern Australia is the production of high-value specialty purpose and appearance grade sawn timber and veneer products that attract high prices (Bevege 2004). For high recovery in processing young hardwoods from both thinnings and final crop logs, veneering is attractive relative to sawing (McGavin et al. 2014, Zbonak et al. 2014). Logs for veneering should have high small end diameter under bark with minimal sweep, taper, knots and out of roundness (McGavin et al. 2014). These qualities also apply to logs for sawing. Harvesting costs have a large impact on plantation profitability (M. Brown, University of the Sunshine Coast, 2014, pers. comm.) so growing fewer trees ha<sup>-1</sup> could be more economical. Genetically-improved planting stock allows for the economy of lower initial stockings. A further challenge in Ks plantation management on short rotations is producing logs with early development and a high proportion of desirable deep red heartwood colour. Best results in a Ks plantation enterprise will come from integrating genetic and cultural approaches to improvement of crops.



**Figure 5. A private woodlot (age 8.5 y) at Moongobulla, south of Ingham, Queensland. The central, superior tree was selected for conservation and breeding. Photo: Kevin Harding**

These factors provide a basis for choosing tree and log characteristics to target for genetic improvement. Breeding would need to develop genotypes with attributes that maximise recovery of high-value products and are adapted to optimal plantation management. Tree selection traits would include DBH, merchantable bole length, stem straightness, branching, knots, log taper, sweep, roundness and heartwood. Improved windfirmness, responsiveness to silvicultural management and tolerance or resistance to pests would contribute to higher stand yields. Prospects for genetically improving many of these characteristics for Ks plantations are considered broadly in the following sections.

### Variation in economic traits

Results of the genetic trials reviewed in sections of this paper above indicated variation in Ks at the levels of provenance, family and clone, and large ranges in means at these levels, for a number of economic traits. These include DBH, height, merchantable bole length, stem straightness, branch thickness, windfirmness, heartwood proportion and tolerance of pink disease and shoot borer. Figures 1 and 3–5 illustrate the great tree-to-tree variation in Ks for several of these traits. Preliminary estimates of clonal heritabilities for several traits are favourable. For log taper, roundness and sweep, knots, heartwood, windfirmness, and pests and diseases additional information is presented below.

#### *Log sweep, roundness and taper*

Minimal sweep, out of roundness and taper, calculated as the ratio of small end to large end diameter expressed as a percent (highest = best), will result in higher recovery in sawing and

veneering (Mc Gavin *et al.* 2014). There is wide variation in taper among Ks trees. For example, in stands established at c. 1100 s ha<sup>-1</sup> near Darwin, among thirty eight, above-average trees harvested at age 30 y for a sawing study, 10 logs of comparable length (3.8–4.2 m) had taper ranging from 57 to 90% (Armstrong *et al.* 2007). Zbonak *et al.* 2010 reported on a sawing study of younger Qld and NT trees. For the sample of 20, 18-y-old trees grown from establishment at 130 s ha<sup>-1</sup> near Homehill, Qld, the ranges in taper for 3 m and 3.6 m logs (eight of each) were 61% to 80% and 57% to 80% respectively. For 14-y-old trees established at c. 1100 s ha<sup>-1</sup> near Katherine, NT, taper of 26, 3 m logs ranged from 61% to 97%. Sweep also ranged widely among trees: 10–100 mm and 2–70 mm in the Qld and NT samples respectively (Zbonak *et al.* 2010). Data on roundness were not recorded but a wide range can be seen in photos in Armstrong *et al.* 2007 and Zbonak *et al.* 2010.

Taper of Ks may be heritable as it can be observed to vary among trees in close proximity (Fig. 1, 3–5). These observations and the data above on logs from three locations indicate that billets with little taper are extant in trees of Ks plantations. Taper, sweep and roundness may respond to selection.

### ***Knots***

Knots can cause defect in veneers and sawn timber and are often a cause of low grade in Ks boards (Armstrong *et al.* 2007). Minimising this defect can be controlled by pruning, at additional cost. Depending on the length of clean bole desired, however, it may not be required, or its extent reduced, as a non-branched state can persist in Ks to a height of several metres (Fig. 1, 3–5). In such trees, development of the first branch or cluster is delayed, the foliage below having been or being comprised of compound leaves which are shed progressively leaving only scars that are soon overgrown with knot-free wood depending on the occlusion quality and time. Ks trees with this habit seem often to subtend a single, first branch, or very few branches per first cluster, and may exhibit good diameter, straightness, taper and axis persistence (Fig. 1, 3–4), rendering them potential candidate plus trees. ‘Height of non-branched stem’, not specifically assessed in the clone, progeny and provenance trials described in sections above, should be considered for study of its genetic variation and relative economic value in a selection index (Cotterill and Dean 1990).

### ***Heartwood***

Early development and high heartwood proportion of a deep red heartwood colour are expected to enhance the value of Ks grown on the short rotations likely for Australian plantations (perhaps <20–25 y). Armstrong *et al.* 2007 noted that many timber merchants may only pay a premium for ‘solid coloured’ heartwood boards and, since sapwood of Ks is lyctus susceptible, its volume will influence treatment costs. In 18- and 20-y-old trees grown at 130 and 157 s ha<sup>-1</sup> respectively near Homehill, Qld, there was no clear distinction between heartwood and sapwood zones; a transition zone was recognised also and visual assessment of these three zones was made (Zbonak *et al.* 2010). These zones are illustrated in Fig. 6 for a typical 15-y-old tree grown near Kununurra, WA (R. Fremlin, AMG, 2014, pers. comm.).

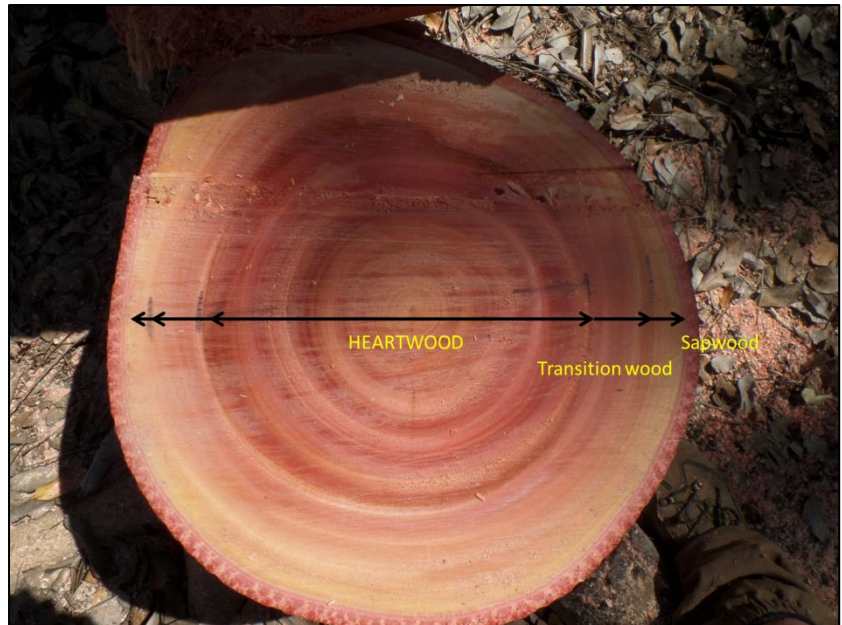
Genetic variation in heartwood % at the provenance, family and clonal levels is indicated by results reported by Lee *et al.* 2012 of a preliminary study of cores from:



a) five Burkina Faso provenances sampled at age 9.5 y in a trial planted in 2001 near Mareeba, Qld (5–7 trees per provenance for a total of 28 trees). Provenance means ranged 32–68%.

b) nine, 5.5-y-old clones (33 trees) and seedlings (59 trees) from the same nine NT parent trees grown together near Darwin after planting in 2005. Heartwood % for the seedling families ranged 22–43% and for the clones 30–47%.

Assessment of heartwood colour of the cores showed variation in both lightness and richness among family seedlings and clones, though it was lower among the provenances. Some clones and seedling families were notable for desirable colour and illustrate the possibility to enhance desirable colour through selection and breeding.



**Figure 6. Heartwood, transition wood and sapwood in a cross section of a tree (age 15 y) grown in the Ord River Irrigation Area near Kununurra, Western Australia. Photo: R. Fremlin.**

A number of studies have shown wide phenotypic variation in heartwood proportion among individual plantation trees. Armstrong *et al.* 2007 reported a mean of 50.3% and range of 30.5–81.1% across 38, 30–32-y-old trees harvested in plantations near Darwin, NT. This range was the same for a sub-sample of 10 trees in the same large-end-diameter class of 450–550 cm. Zbonak *et al.* 2010 found the means and ranges for the central, dark coloured zone of trees grown near Homehill, Qld were: for 11, 18-y-old trees, 30.7% and 13.7–52.8%; and for 21, 20-y-old trees, 35.7% and 26.7–50.8%. Corresponding values for 27, 15-y-old ‘plus’ trees grown near Kununurra, WA were 41.8%, and 20.8–62.5% (R. Fremlin, AMG, 2014, pers. comm.).

These results of the preliminary genetic study and of the three reports of phenotypic variation of heartwood % indicate a potential to usefully include this trait in selecting trees for breeding and conservation. This could apply among trees even less than age 10 y, provided a suitable method of non-destructive sampling was available.

### **Windfirmness**

Wind damage to plantation trees may take the form of lean (that may extend to blow down), stem curvature (that may extend to breakage at some height), or some loss of crown, all of which may result in financial loss. Some tropical tree species exhibit genetic variation in ‘relative windfirmness’, i.e. a degree of resistance to wind damage. For example, Luo *et al.* 2006 found statistically significant variation among provenances and families of *Eucalyptus pellita* in a trial in the Leizhou Peninsula subjected to winds associated with a typhoon with maximum wind speeds exceeding 160 km h<sup>-1</sup> (Category 2–3, Australian Bureau of

Meteorology website). Within-provenance heritabilities for 3-y 'lean' and 'break' were  $0.36\pm 0.05$  and  $0.34\pm 0.06$  respectively. The genetic variation among and within provenances of *Pinus caribaea* var. *hondurensis* (PCH) in Qld enabled effective selection for improved windfirmness (Anon.1981). PCH was much more severely damaged than *P. caribaea* var. *caribaea* in the Cardwell area of north Qld by TC Yasi (Category 4) in February 2011 (I. Last, HQPlantation Pty Ltd, 2011, pers. comm.). While most or all trees in a plantation may be destroyed by extremely strong winds, losses under less severe conditions may be reduced where planting stock of improved windfirmness is deployed.

Ks trees as single specimens or groups in amenity plantings are prone to damage by very strong winds, e.g. by TC Tracey in Darwin in 1974 and TC Yasi in north Qld in 2011 (Lindsay and Dickinson 2012). However, damage to plantation trees is variable and may provide opportunity to improve windfirmness by selective breeding.

Evidence of genetic variation among Ks provenances was provided by results of lean assessment in the trial planted near Ingham in April 2008, described under 'Provenance trials' above, after being subjected to severe TC Yasi at age 2.3 y. Analysis of 3-y data for lean (scored on a 1–5 scale, 1 = best) showed significant differences among country means ( $P < 0.006$ ) and between the 43 African and Australian provenances ( $P < 0.05$ ) (Dickinson *et al.* in prep.). Across the trial, several superior trees were observed that combined high phenotypic values in all traits assessed (e.g., Fig. 3), demonstrating that superior individual-tree 'windfirmness' does not have to come at the expense of high expression of other desirable traits.

The private planting of African families-in-provenance in October 2008 near Ingham, Qld described under 'Progeny trials' above that was impacted by TC Yasi at age 2.3 y, exhibited genetic variation at the provenance and family levels and individual tree variation in windfirmness (Sexton 2013; G. Sexton, 2014, pers. comm.).

Genetic variation in windfirmness was observed in a trial of 56 clones planted in May 2008 near Ingham, Qld as described under 'Clone trials' above. Clone means for lean score (1–5 scale, 1 = best) ranged widely (1.32–4.36) some clones ranking better (lower mean) than the better Control (Burkina Faso, mean of 2.08).

Individual tree variation in windfirmness has been observed in older Ks stands of generally unknown provenance in north Qld which have been impacted by one or more cyclones. Yield plots were established in more than 52 stands or plantations by staff of QDAFF Forestry Science ranging in years of planting from 1972 (some of the Weipa plots) to 2006. A Report on the results of the trial plot measures (ranging from 2003 to 2012), including remarks on cyclone effects, has been drafted (Dickinson *et al.* 2012b). One of the most exposed plantations is that at Balgal Beach, c. 50 km north of Townsville, on a Grey Sodosol, planted in 2002 and 2003. When measured in August 2011 a comment made in the Report was: "The stand suffered remarkably little damage during T C Yasi, which is believed to have generated Category 2 strength winds here in February 2011". A superior tree [the parent of Clone 1 (Fig. 1) in the clone trial planted in 2008 near Ingham], selected in 2006 in the area planted in 2003, sustained no damage from TC Yasi despite its great height and consequent exposure.

Other examples of Ks stands in Qld having a degree of windfirmness include: 9-y-old stands on Red and Yellow Kandosols at Moongabulla (c. 10 km north-west of Balgal Beach) sustained only low damage from TC Yasi (Lindsay and Dickinson 2012); stands 15 km south

of Townsville planted in 1997 sustained only minor damage from TC Yasi; and at Murray Upper in the Cardwell region a stand planted in 2004 ‘withstood the full force of TC Yasi in 2011’ (Dickinson *et al.* 2012b). At Elderslie c. 40 km north of Cooktown, 7-, 8- and 9-y-old Ks plantations were impacted by TC Ita in April 2014. Lindsay and Knobel 2014 reported (p 1): ‘TC Ita was estimated to be a Category 5 system, with maximum wind speeds in excess of 250 km per hour near the centre, prior to crossing the coast. TC Ita crossed the coast near Cape Flattery, 25 km north-east of Elderslie....passing directly over the plantation’. ‘It seems likely that the cyclone was less intense than Category 5....’ and ‘was the strongest to affect the Cooktown region in over 50 years’. ‘Broadly speaking, the vast majority of the African mahogany trees at Elderslie showed little or no signs of wind damage. Most damaged trees were restricted to the edge of the plantation, with only isolated trees inside the plantation having broken branches, leaning over or (very occasionally), snapped stems. Damage levels were much higher in recently thinned areas’. ‘There was little rain immediately before TC Ita, but a very great amount afterwards, resulting in ..., and saturation of the soil profile after the strongest winds had passed’.

This summary of genetic and phenotypic variation of windfirmness in Ks suggests that it would be a legitimate selection criterion in breeding Ks, for deployment in sub-coastal regions where severe cyclones are rare, in order to reduce the risk of damage and economic losses. Indirect selection for windfirmness may be feasible via intuitively surrogate traits such as narrow crown with minimal, thin and steep branching; and superior stem straightness. Availability of superior germplasm incorporating a useful level of windfirmness might encourage establishment of Ks plantations in new suitable areas beyond the current, main plantations hub of the Douglas-Daly, NT.

### ***Pests and diseases***

The status of pests and diseases of Ks in Australia was described in Nikles *et al.* 2008. Among pests known then, knowledge of the shoot borer (*Hypsipyla robusta*), potentially an economically important pest, was reviewed and they stated that it “currently poses minimal threat to Ks in northern Australia” (p 41). The present authors understand this is still the case. There are indications of genetic variation in resistance to *Hypsipyla* for several Meliaceae species including *K. ivorensis* and Ks in Africa (Nikles *et al.* 2008) and Ks in Australia (Peng 2011). The very broad germplasm base of many provenances and families of Ks, which has been assembled in Australia, provides a potential hedge against possible future, stronger adaptation of *H. robusta* to Ks in Australia, and any inadvertent introduction of African *Hypsipyla* species, through potential opportunity to breed for tolerance if the need arises. Another tactic to use is: Avoid ‘off-site’ planting.

Giant termite (*Mastotermes darwiniensis*) occurs across the monsoonal tropics of Australia but it is not currently considered a serious threat to plantations. Recently two unidentified species of case moth (Lepidoptera: Psychidae) of unknown importance have been found in some Douglas-Daly plantations (R. Peng, Charles Darwin University, 2011, pers. comm.).

Few diseases have been recorded for Ks (Nikles *et al.* 2008). More recently, pink disease (*Erythricium salomnicolor*), was noted in a provenance trial at a site in Qld; it was assessed and genetic differences between provenances were found (Dickinson *et al.* in prep.) allowing for the possibility to select for tolerance. Similar cankerous symptoms have been exhibited in trees in far north Qld and the Douglas-Daly, NT (G. Pegg, H & FS, Qld DAFF, 2013, pers. comm.).

This overview indicates there are no serious pests or diseases associated with Ks plantings in appropriate locations and sites in Australia at present. Means for dealing with those having potential to become important economically are potentially available via the experienced teams of scientists in the public sector and the possibilities to select for tolerance in the broad genetic base available. However, continuous monitoring of plantations and surveillance of entry ports by biosecurity authorities should be maintained.

### **Genetic resources**

The broad genetic resources established in NT and Qld stands of the 1960s and early 1970s that formed the base of the conservation and improvement program of the NT and Qld governments that began in 2001 were described by Nikles *et al.* 2008. By 2001, 32 provenances from 11 African countries had been established in plantings including those in the NT and at Weipa and near Mareeba, Qld. These have been supplemented by numerous subsequent introductions (Dickinson *et al.* 2009; Sexton 2013; R. Fremlin, AMG, 2014, pers. comm.).

Since 2004, large amounts of Ks seed have been imported to Australia from Africa for industrial plantation establishment that began in Qld in 2005 (355 ha planted during 2005–2007) and in the NT in 2006. The ongoing annual plantings in the NT have accumulated around 14 000 ha of plantations with an average of 1700 ha being planted in recent years. Seeds were kept separate by provenance initially (and by parent tree in some cases) enabling many provenance and progeny trials to be established as summarised above. Most of the provenances are also represented as mixtures in the vast industrial plantations. The total genetic base of Ks established in northern Australia comprises more than 100 provenances from 17 of the 20 African countries in which Ks occurs naturally, and landraces. It is the broadest in the world outside Africa. However, some considerable areas of known, unique provenances have been lost to land re-development in the NT; this highlights an urgent need to conserve the most promising trees of remaining provenances which is done best through breeding programs (Dvorak 2012).

### **Next phase of domestication**

The first phase of domestication of Ks in Australia began in 2001. It was undertaken by the NT and Qld governments primarily to conserve the broad genetic base of germplasm in provenance trials established near Darwin, NT in 1971–1973 and in other stands that were under threat (Nikles *et al.* 2004). In line with the conservation imperative, the strategy adopted was “mild selection of trees with ‘acceptable’ relative vigour, straightness, bole length and branching” (Nikles *et al.* 2004, p 1) to ensure sampling of all provenances. Across c. seven ha of stands, 142 trees were selected, grafted and planted in both a ‘conservation clone bank’ and a ‘gene recombination orchard’ (both referred to as CSOs in this paper) near Darwin and a sub-set of 68 clones in a CSO near Mareeba, Qld. A hedge garden with a broad range of seedling and rooted cuttings sources was also established for tree improvement as described above in the Section ‘Initial genetic base ...’. This phase, that included establishment of clone and progeny trials, several in collaboration with private growers, also as described above, continued until 2011 when a change of governments’ priorities led to a gradual curtailment of the program.

Seed production by the small government seed orchards, and from the clone and progeny trials that might be converted to seed sources, will not sustain large plantation establishment

programs. Because commercial supplies of seed from Africa are now unreliable, Nikles *et al.* 2012 suggested establishment of a range of local, seed-producing facilities beginning with plantation ‘seed tree’ and ‘seed production areas’ (SPA) systems and then new seed orchards. Large areas of plantations have reached or exceed seed-bearing age (c. 8 y) in the NT (R. Fremlin, AMG, 2014, pers. comm.) and Qld making these approaches applicable. Plant requirements might be augmented in the future by macro- and/or micro-propagation from seed of superior families (see ‘R&D’ section below).

A second phase of domestication led by the private sector has commenced. New seed orchard establishment began in Qld in 2008 (Sexton 2013). Penfold *et al.* 2011 outlined the program of tree improvement planned by AMG in the Douglas-Daly based on extensive provenance trials planted in 2008, 2009 and 2011. In 2014, AMG selected 28, 15-y-old trees in plantations near Kununurra, WA and grafting for a CSO was undertaken (R. Fremlin, AMG, 2014, pers. comm.). AMG is also planning to select superior trees in genetic trials and plantations in the Douglas-Daly for CSO establishment and progeny testing. Other components of the company program include: maintaining their provenance, progeny and clone trials; studying seed production and procurement locally; research on vegetative propagation; and assessing variation in heartwood properties (R. Fremlin, AMG, 2014, pers. comm.).

### **R&D to support genetic improvement**

Pending the establishment and maturation of new CSOs and/or SSOs in perhaps 10 y, methods available for procuring seed locally include mass selection (seed trees), seed production areas (SPAs) and PSSOs within stands at or above the age when viable seeds are produced (Nikles *et al.* 2012). Potentially, some of the clone, progeny and provenance trials could be considered for conversion to CSOs, SSOs and PSSOs respectively. There may be a need to undertake research to determine: optimal dates for pod collection relative to ages, seasonal conditions, sites and provenances; how to ripen pods collected prematurely; and how to store seed locally.

The CSOs and PSSO have produced little seed and from only about one half of the clones; this may be due to sub-optimal locations (environments). Hence research to identify locations conducive to early and heavy seed bearing of Ks is suggested. Extension of the preliminary research on the effect of paclobutrazol (Dickinson *et al.* 2012a) needs to be followed up. Since existing progeny trials will enable identification of superior parents and individual trees (Section above ‘Progeny trials’), refinement of the technique for controlling pollination (Dickinson *et al.* 2012a) is desirable so that superior seedlots for multiplication (see next paragraph) could be produced.

Maximum gains from tree breeding are realised through commercial deployment of superior clones. This strategy is almost universal in industrial plantations of several eucalypt hybrids. It has also been widely adopted commercially with teak (*Tectona grandis*) following pioneering research by Goh and Monteuuis (1997) that led to feasible mass production of clones by rooted cuttings, *in vitro* microcuttings and meristem culture of trees of any age (Goh and Monteuuis 2012). Macro-propagation from juvenile hedges of Ks is feasible (Pomroy and Lee 2006; Reilly and Robertson, 2006) but it is constrained for large-scale commercial operations by the low, initial multiplication rate from hedges and current low availability of genetically-superior seedlings. An option that might be applicable to Ks commercially is micro-propagation of shoot tips from newly germinated seeds with

encapsulation as so-called ‘synthetic seeds’ that has a very high multiplication rate from Ks seed (Hung and Trueman 2011, 2012). *In vitro* storage of Ks clones from shoots of newly germinated seeds delays maturation relative to storage as *ex vitro* stock plants in a nursery and provides an effective method for clonal archiving while enabling production of planting stock with juvenile characteristics required for plantation establishment (McMahon et al. 2013). Hence it is suggested that the field performance of Ks plants from ‘synthetic seeds’ and stored shoots be investigated.

Availability of technology enabling mass propagation of ‘selection-age’ Ks trees (perhaps around age 6–8 y), would provide a useful tool for genetic research and, if commercially viable, for plantation establishment. For example, clone testing of superior phenotypes would open a way to clonal forestry, some clone trials could be converted to clonal breeding orchards and options for breeding strategy broadened. Callister 2013 proposed a strategy for rapid improvement of teak through integration of seedling and cloned progeny trials that would deliver superior clones for deployment within 15 y. Application to Ks would require capacity to mass propagate superior, selection-age trees on their own roots and that grew as required. Thus research on propagation of selection age trees of Ks is suggested to determine whether a similar approach is feasible with this species.

Earliness of heartwood formation and a high proportion of heartwood are likely to be among key factors in enhancing the profitability of plantations grown on relatively short rotations of c. <20–25 y. Similarly, genetic variation in log taper, knottiness and windfirmness are traits that need to be studied further for possible incorporation among tree selection criteria.

Although genetic gains have been realised in many forest tree species without the aid of a selection index that is based on knowledge of genetic parameters and relative economic values of traits affecting product value, long-term success depends on development and use of an appropriate selection index (Cotterill and Dean 1990, Hardner and Peace 2009). Research towards development of a selection index for Ks is suggested.

Ks has a vast homoclimate across northern Australia (Arnold et al. 2004) yet large-scale industrial planting is currently confined to the Douglas-Daly, NT. Although smaller-scale, commercial plantings have been made near Weipa and north of Cooktown, Qld and in the Ord River Irrigation Area near Kununurra, WA, expansion is precluded by limited availability of cleared land or, in the case of Weipa, policy regarding mine site rehabilitation and other considerations. A large amount of information exists on the performance of Ks in many other areas of northern Australia, e. g. Dickinson *et al.* 2012b, and could be supplemented by updating for use in determining locations of new areas where the species might be planted commercially. Possible additional plantation hubs might be identified broadly via research on results of existing plantings (where available), the homoclimate boundaries (Arnold et al. 2004), local climate (including cyclone history) and soils, and land availability (constrained by vegetation management regulations). Such research is recommended.

## **Discussion**

Significant genetic differences among provenances, families and clones for several economic traits, which can influence stand productivity, have been demonstrated across several genetic trials in the NT and Qld reviewed in this paper. These traits include DBH, height, merchantable bole length, stem straightness, branch thickness, windfirmness, heartwood

proportion and tolerance of pink disease and shoot borer. While log roundness, sweep, taper and knottiness have not yet been assessed in genetic trials, it has been shown here that there is considerable phenotypic variation in these traits that are important for high recoveries of high grade products from sawing and veneering. Hence, selection for most economic traits should be effective in developing breeding populations, and propagation and deployment of the most promising material should secure genetic gains. This conclusion was also reached from results of a trial of 21 provenances from four West African countries and Niger established in Sri Lanka and assessed recently at 3.5 y of age (Kangane Mudiyansele, 2014).

Results from several provenance trials in northern Australia suggest a broad pattern of regional variation in growth with sources in western Africa generally the more promising. However, considering other economic traits as well, good provenances can be found among a wider sample of provenances. Moreover, the oldest of these trials is only seven years of age, and present indications may change in the future when additional biotic and abiotic factors may impact the populations available for conservation and selective breeding. Hence, these trials should be maintained.

The species has a number of favourable biological attributes. It can be grafted easily and the CSOs already planted have produced moderate amounts of viable seed within eight years. This is about the same age that seedling trees have produced seed. Hence, SSOs may be a good option, especially since they may be developed from progeny trials which are an integral component of breeding strategy. Cuttings from hedged seedlings root readily, and micro-propagation from seed is feasible. Although there appears to be a negative relationship between growth and tree quality traits, there are rare 'correlation breakers' among individual trees that will provide material for breeding and conservation. These attributes offer a range of opportunities for evolving seed improvement activities and for choosing among breeding methods.

Many issues remain to be targeted by R&D, e.g most advantageous locations and how to manage seed orchards, and whether 'selection-age' trees can be propagated commercially opening the option to practice clonal forestry.

A very wide genetic base has been accumulated in Australia in provenance, progeny and clone trials, industrial plantations and woodlots across more than 15 000 ha of plantings. As well, the first stage of domestication via the NT and Qld governments' program, begun in 2001, has provided an opportunity for a second round of seed orchard establishment via: forward selection of superior clones in trials, of superior trees within progeny trials, and for 'backwards selection' of the best, first-generation parents in the CSOs based on progeny trials. Similar trials and large plantations established by companies, especially in the NT, provide a new opportunity to advance the domestication of the species, preferably in collaboration (Dickinson 2011, Nikles *et al.* 2012). Of concern is the fact that 39 new provenances planted in 2009 have been lost to land re-development in the NT; this highlights an urgent need to conserve the most promising trees in remaining provenance trials and other stands.

Demonstrated genetic and phenotypic variation of windfirmness in Ks indicates that windfirmness would be a legitimate selection criterion in breeding Ks, for deployment in sub-coastal regions where severe cyclones are rare. Indirect selection for windfirmness may be feasible via potential surrogate traits. Availability of superior germplasm incorporating a

useful level of windfirmness could encourage establishment of Ks plantations in new suitable areas beyond the current, main plantations hub of the Douglas-Daly, NT.

A second phase of domestication has commenced in the NT and Qld led by the private sector founded on a very broad base of germplasm and with knowledge that there is genetic variation to capture at the levels of provenance, family, clone and individual tree. This augurs well for ongoing conservation and improvement of the species.

Progress on the domestication and deployment of Ks in northern Australia outlined in this paper allows a strong case to be made for capitalising on the many comparative advantages that Australia currently holds for further commercial deployment in the Douglas-Daly regional hub of the NT, and extension to new hubs within the vast homoclimate of the species in northern Australia. Such a development, if underpinned by adequate R&D such as outlined for genetic improvement in this paper, could realise a new, sustainable primary, processing and manufacturing industry in northern Australia benefitting the whole value chain.

## **Conclusions**

Prospects for genetic improvement of Ks in northern Australia are excellent—there is genetic variation in all traits of economic importance that have been assessed and high individual-tree variation in others that may have a genetic component; and a very wide genetic base of >100 provenances from 17 African countries has been accumulated across the NT and Qld. However, of concern is the fact that 39 new provenances planted in 2009 have been lost to land re-development; this highlights an urgent need to conserve the most promising trees of remaining provenances which is done best through breeding programs (Dvorak 2012). The private sector programs commenced recently in Qld and the NT should be encouraged so as to achieve conservation and improvement.

Ongoing domestication and further investment for commercial deployment of Ks in and beyond the Douglas-Daly hub should be considered for sub-coastal areas less prone to severe cyclones. Current and potential future plantation programs will need to be underpinned by appropriate and sustained R&D such as outlined in this paper.

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