Developing African mahogany (*Khaya senegalensis*) germplasm and its management for a sustainable forest plantation industry in northern Australia: progress and needs

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**Summary**

The demonstrated wide adaptability, substantial yield potential and proven timber quality of African mahogany (*Khaya senegalensis*) from plantings of the late 1960s and early 1970s in northern Australia have led to a resurgence of interest in this high-value species. New plantations or trials have been established in several regions since the early 1990s — in four regions in north Queensland, two in the Northern Territory and one in Western Australia. Overall, more than 1500 ha had been planted by early 2007, and the national annual planting from 2007–2008 as currently planned will exceed 2400 ha. Proceedings of two workshops have summarised information available on the species in northern Australia, and suggested research and development (R&D) needs and directions.

After an unsustained first phase of domestication of *K. senegalensis* in the late 1960s to the early 1970s, a second phase began in northern Australia in 2001 focused on conservation and tree improvement that is expected to provide improved planting stock by 2010. Work on other aspects of domestication is also described in this paper: the current estate and plans for extension; site suitability, soils and nutrition; silviculture and management; productivity; pests and diseases; and log and wood properties of a sample of superior trees from two mature plantations of unselected material near Darwin. Some constraints on sustainable plantation development in all these fields are identified and R&D needs proposed. A sustained R&D effort will require a strategic coordinated approach, cooperative implementation and extra funding. Large gains in plantation profitability can be expected to flow from such inputs.

**Keywords**: plantations; domestication; treebreeding; provenance; clones; seed orchards; nutrition; soil; silviculture; stand establishment; management; productivity; pests; diseases; wood properties; research; planning; *Khaya senegalensis*; Northern Territory; Queensland; Western Australia

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**Introduction**

African or ‘dry zone’ mahogany (*Khaya senegalensis* (Desr.) A.Juss.) (Meliaceae) is a high-value hardwood species. Supplies of its wood and other products from the native range in central Africa (Fig. 1) are diminishing, and there is little management of the limited natural regeneration or replacement by plantations (Opuni-Frimpong et al. 2008a; Gary Sexton, University of Queensland, 2007 pers. comm.). Plantation establishment in Asia is not extensive (Arnold 2004) nor is it known to be in progress substantially elsewhere outside Australia. This presents both an opportunity and a challenge in northern Australia, where the species has a vast homocline (Fig. 2) and where it has been planted on only a small scale in farm and, until recently, industrial forestry systems, though it has much promise as indicated in this paper. A mahogany industry based on plantations in northern Australia might learn from the wide experience in plantation forestry gained from establishing a number of subtropical and temperate species in mainly southern and eastern Australia (where more than 1.7 million ha of plantations were established by 2005 — Parsons et al. 2006), and confer social, environmental and economic benefits.

Although significant areas of *K. senegalensis* (henceforth referred to as KS in this paper) have been and are being planted in several regions in northern Australia (see section ‘Current estate and plans for extension’ below), the species is still in the early stages of its domestication (Nikles 2006). Hence, focused R&D is needed to underpin the expanding plantations. In order to assemble and discuss the disparate information available on KS in northern Australia and to identify R&D needs, two workshops have been held (Bevege et al. 2004, 2006a; Nikles et al. 2006b; Underwood 2006). This paper draws on contributions to and outcomes of these workshops to provide an overview of the status of KS domestication, its performance and the constraints to developing sustainable plantations, and to identify R&D needs.
The species in Africa

The species occurs naturally in the tropics of 19 central African countries discontinuously from Senegal and neighbouring countries in the west (mostly between about 8°N and 15°N but extending to about 6°N in Nigeria) through to Sudan and Uganda in the east where it extends southward to about 2°45'N as shown very approximately in Figure 1. (The sparse and scattered information found on the natural distribution was derived mainly from Aubreville 1950; Hutchinson et al. 1958; Viart 1960; Eyog Matig 1987; Styles and White 1991; FAO 2003 and REFORGEN 2007). This distribution covers a wide range of climatic, altitudinal, ecological and edaphic conditions from sea level to 1800 m, encompassing mean annual rainfalls from < 700 mm (under which it is often associated with seasonal watercourses) to about 1750 mm, with dry season lengths of 2–8 months (Anon. 2004a). The species occurs on a wide variety of sites and soil types including those within gallery forest (where it attains heights of around 35 m with a bole diameter of 1.5 m and length of 10 m) and drier open savanna with lateritic soils and on rocky places (where it mostly occurs as solitary trees attaining heights of 15–20 m, often with a sinuous bole) (Eyog Matig 1987; Anon. 1988; Dupuy and Mille 1993; Anon. 2004a). In view of the great diversity of its habitats and its disjunct populations, KS is expected to show a large amount of provenance variation, reflecting genetic and physiological adaptation.

KS has numerous uses in Africa including high-value timber products, round wood, fuel, medicines, dyes, tannin and fodder, shade, and avenue and park plantings. Due to heavy exploitation (e.g. Anon. 1988), the conservation status of the species is ‘endangered’ (REFORGEN 2007). It was one of the first west African forest tree species to be imported by Europeans due to its excellent timber and veneer. Very limited quantities are still exported, including some to Australia, and consequently command high prices. Supply is so limited that KS does not feature in the current ITTO trade statistics as the volume is less than 1000 m³ y⁻¹. Export volumes for K. ivorensis and K. anthotheca combined were 16000 m³ and 17000 m³ for 2002 and 2003 respectively (Anon. 2004b).

Enrichment plantings with K. anthotheca, K. grandifoliola and K. ivorensis commenced about 100 y ago in the moist forest zone; more recently, various other regimes have been tried (Dupuy and M’bila 1992). Later, trials of KS were planted in the savanna region (Brunck and Mallet 1993; Dupuy and Mille 1993). Few plantations, however, have succeeded, the main constraint being severe attacks from Hypsipyla shoot borers (Lepidoptera: Pyralidae) (Brunck and Mallet 1993; Sokpon and Ouinsavi 2004; Oponi-Frimpong et al. 2008a,b). Current information indicates that there are three species of Hypsipyla in Africa including Madagascar, all distinct from Hypsipyla robusta Moore of Australasia (Griffiths and Wylie 2006).

There are indications of genetic variation in resistance to Hypsipyla attack for several Meliaceae species (Newton et al. 1993; Watt et al. 2001), including species of Khaya (Brunck and Mallet 1993; Dupuy and Mille 1993; Oponi-Frimpong et al. 2008b). With a view to using resistant, superior Khaya trees identified to date, research on micro- and macro-propagation of the species has been undertaken (Danthu et al. 2003; Oponi-Frimpong 2006 — the former work being with KS). Limited selection and grafting of KS trees has been undertaken in Burkina Faso (Tolkamp et al. 1992); additional genetics work was initiated there and in Cameroon; and a range of activities recommended for regional collaboration (Eyog Matig and Abdou Salam 1999). As far as could be ascertained by the authors, however, there is little documented sustained conservation and tree improvement work in Africa.

Brief history of introduction and testing in Australia

KS was introduced in the Northern Territory (NT) in 1959 (Heame and Rance 1975) becoming popular as a shade tree. It was soon extended across northern Australia for amenity purposes. In the mid-1960s it began to be used in rehabilitation of mined land at Weipa on the north-western coast of Cape York Peninsula, Queensland (Nicholson 1974).

By the late 1960s the potential of the species in the NT was judged sufficiently promising to warrant establishment of trials aimed at securing information and developing methodologies that would enable successful plantations to be established. Consequently, a number of research trials with KS were planted in the Darwin region and on Melville Island in the late 1960s and early 1970s by the NT forestry research unit of the then Commonwealth Forestry and Timber Bureau. These included studies of provenance variation, nutrition, espacement, planting stock type, termite control and other related matters (Cameron 1972, 1985; Rance et al. 1983; Cameron et al. 2006). The provenance trials incorporated 23 provenances from 11 countries of nativity and three from a secondary source (New Caledonia ex Ivory Coast) (Figs 1, 3). Additional plantings were made with stock from local sources of unknown original provenance (Nikles et al. 2004). Research at Weipa, Queensland, showed that KS and Honduras Caribbean pine (Pinus caribaea var. hondurensis) were the most promising species for agro-forestry on back-filled land following surface mining for bauxite: 160 ha of KS had been established by 1985 (Nicholson 1985; Fig. 4). However, this early demonstrated promise of the species in the NT and Queensland was not pursued for some decades.

In the 1990s, a second wave of tests and pilot plantings of KS was established in the NT (Reilly et al. 2004), in north-eastern Queensland mainly between Ingham and Bowen (Dickinson et al. 2004; Collins 2006; Dickinson and Kelly 2006a) and in the Ord River Irrigation Area (ORIA), Western Australia (WA) (C. Done, Tropical Forestry Services and A. Wright, Integrated Tree Cropping, 2007, pers. comms) all based on unimproved seed, even wildlings. The early promise of the species in many of these plantings, the confidence engendered by its wide adaptability and the high quality of the timber from young and older stands (Heame and Rance 1975; Armstrong et al. 2004, 2006, 2007; Nikles 2006; Fig. 5a,b), led to more extensive plantings in several regions across northern Australia, including some by ‘small growers’ mainly in northern Queensland (Fig. 6), as outlined in the next section.

Current estate and plans for extension

Commercial plantations of KS have been or are being established in five regions in northern Australia. As of early 2007, these

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Figure 1. The approximate natural distribution of *Khaya senegalensis* in Africa. The numbers attached to the names of 11 of the 19 countries show the numbers of provenances therefrom represented in trials planted in the Northern Territory, Australia, in the early 1970s. Three seedlots obtained from New Caledonia originated from collections in Ivory Coast. (Map prepared by Wade Milne and Wendy Casey, DPI&F, Brisbane)

Figure 2. The notional homocline of *Khaya senegalensis* in northern Australia according to Arnold et al. 2004. Also shown are the names of the main locations mentioned in the text. (Map prepared by Tom Jovanovic, CSIRO, Canberra, 2007)

Figure 3. A provenance trial (age 31 y) at Gunn Point near Darwin, Northern Territory planted at 3 m × 3 m in 1972–1973 and unmanaged from a few years after planting; most trees exhibit typically poor stem form. (Photo: Beau Robertson)
regions, named in Figure 2 (and areas of KS established in them shown here), were in:

- Queensland — Weipa (163 ha), north of Cooktown (355 ha) and Ingham to Bowen (150 ha across many small growers)
- NT — basin of the Douglas–Daly rivers to south of Katherine (485 ha including about 5 ha by small growers around Katherine)
- WA — the ORIA (377 ha).

(The above information was gathered by the present authors via enquiries in each region in early 2007.)

The total to 2007 was 1530 ha. In all except the Weipa and the north-of-Cooktown regions, substantial annual plantings are current. Plantings of the 2007–2008 season, almost all in the Douglas–Daly basin, have raised the total area dramatically to nearly 4000 ha.

Most plantings of KS in the ORIA were made at low stockings in the late 1990s, in mixture with other species as potential host trees for the intended main crop of Indian sandalwood (*Santalum album* L.). In some cases, the KS trees have been or are being wholly removed to favour the Indian sandalwood; in at least one other case the KS is being managed for sawlogs.

Indicative of the increased scale of forthcoming plantings is that, while a total of some 500 kg of seed for plantation establishment has been imported to Australia across recent years, a larger amount was obtained in 2007 alone, and some 200 kg of seed was secured locally in 2006 (Ray Fremlin, Great Southern Limited, 2007, pers. comm.). Likely regions for substantial expansion of planting include:
• Douglas–Daly basin to south of Katherine (NT) — industrial plantings began in 2006
• Ingham to Bowen (Queensland) (including the lower catchment of the dammed Burdekin River, which flows northward to enter the sea some 80 km NW of Bowen) — mainly ongoing, significant plantings by ‘small growers’, but industrial planting could arise
• The ORIA (WA) — small-scale industrial planting is in progress.

Other possibilities for expansion might include two regions of early, discontinued plantings where new trials have been established — Melville Island, NT and Weipa — and Aurukun some 80 km S of Weipa. Under current activities and plans, the national annual planting from 2007–2008 is anticipated to exceed 2000 ha, almost all planting being in the Douglas–Daly basin in the NT.

Site suitability, soils and nutrition

The above-mentioned regions with potential for KS plantations as reflected in the homocline analysis (Arnold et al. 2004; Fig. 2) are characterised by a wide suite of topographic and edaphic conditions and, correspondingly, soils. No detailed KS-specific soil studies have been carried out, nor is there much documented information of preferred soil conditions in natural stands in Africa. A synoptic survey of growth and soil conditions in a wide suite of trial plots from NT and Queensland (Bevege 2006), however, has enabled a first approximation at the soil and landscape level of site suitability for KS, at least at the level of Soil Order in the Australian soil classification system (McKenzie et al. 2004). These Soils Orders do not have direct counterparts in the FAO system, but some analogies are provided in the overview below.

KS growth to date indicates that Kandosols (well-drained earths with gradational profiles) provide the major potential soil resource. They cover a huge area on gentle well-drained topography. The extensive areas of Tenosols (soils of limited profile development) and Rudosols (lithosols) remain largely untested, but their general shallowness or limited water-holding capacity (except for some alluvial Rudosols) will preclude their significant use. High-quality soils including Ferrosols and Dermosols (deep, well-structured clay loams and clays) would be highly suited to KS but it is unlikely that significant areas will be available due to competition from agriculture and horticulture. Chromosols (podzolics) and Sodosols (sodium-affected duplex clay soils) have potential, but sites need to be carefully chosen; the refractory nature of the latter requires amelioration through site management and amendments. Highly refractory soils that should be avoided include Hydrosols (hydromorphic soils) and Vertosols (cracking heavy clays), although the latter may have some potential with careful management under irrigation to minimise soil churning and root breakage under wetting/drying cycles. Anthroposols (soils extensively changed or created by human intervention) provide a special case; potential has been evident at Weipa where Anthroposols are derived from Kandosols extensively modified by bauxite mining.

The only detailed nutrition work with KS was conducted in the 1970s — in the Darwin area (Cameron 1972; Rance et al. 1983) on Kandosols, and at Weipa on Kandosol-based Anthroposols by the then Queensland Forestry Department and Comalco (Bevege 1974, 2006). These fertiliser trials indicated strong responses to applied phosphorus, nitrogen, sulphur, calcium, potassium and combined trace elements, putatively identified from foliar analysis as zinc, copper and boron. KS also responded to heavy dressings of gypsum and this has been interpreted, again based on foliar nutrient data, as a further nutrient response to calcium and sulphur, additional to the soil conditioning effect. Rance et al. (1983) established adequacy levels for N, P, K and S in the foliage of glasshouse-grown seedlings, and Bevege (2006) extended the range to include remaining macro- and micro-nutrients based on the 1970s Weipa field fertiliser trials. More recently, foliar analysis has been used to monitor nutrient status of the NT clone tests (outlined in Table 1) and first approximations of nutrient sufficiency levels have been established to aid in this; a foliar sampling protocol has been developed and is currently in use (Bevege 2006). Trial plots have generally been given starter doses of mixed fertilisers but concerted efforts to determine optimal fertiliser regimes are for the future (among R&D proposals in Table 2).

Silviculture and management

KS plantations in northern Australia differ markedly from typical industrial pine and eucalypt plantations geared to commodity production, as their objective is the production of high-value specialty purpose and appearance grade sawn timber and veneer products that attract market prices of the order of $1000 m⁻³ (Bevege 2004). In a recent auction in north Queensland, logs of a sister species, Khaya anthotheca (Welw.) C.DC., were sold for $250 m⁻³. To get such prices, the butt logs at harvest should be about 6 m long and 40–60 cm dbh, with minimal taper and knots. Producing logs of these specifications in a rotation of 20–25 y will require (based on current growth estimates) maximising the growth of a small number of crop trees through manipulation of planting spacing and thinning, and the use of pruning. This approach will have a strong influence on potential plantation volume productivity, the MAI of which is estimated to be 10–15 m³ ha⁻¹ merchantable volume over bark (MVOB) (see section ‘Productivity’ below). Logs of high quality could be produced if stands were established with stock of high genetic quality and appropriate silvicultural and stand management techniques were adopted.

Over the past 35 y, numerous small-grower and experimental plantations have been established in the NT and north Queensland on a wide range of sites, using a range of silvicultural prescriptions. Management of these plantings has been highly variable in intensity and effectiveness in terms of appropriate stocking and the likelihood of achieving the objective of producing a high-quality product. Overall there has been sufficient success, more particularly with plantings from the late 1990s, to encourage the entry of new growers into the sector, increasingly involving larger commercial entities.

Successful establishment generally involves the use of well-conditioned, container-grown stock, intensive site preparation, effective weed control and application of starter fertiliser (Collins et al. 2004; Bevege et al. 2006b; Reilly and Robertson 2006). In seasonally dry regions where the summer rainfall is erratic, irrigation may widen the planting window and, if applied for a
African mahogany for plantations in northern Australia

Few years, may ensure adequate plant survival and vigour. KS plantations of genetically unimproved stock in northern Australia are characterised on average by poor stem straightness, short bole length as a proportion of tree height, heavy branching and highly variable individual tree growth rates. In biomass terms, harvest index is low. With no improved KS germplasm currently deployed in commercial plantings, it has been the practice to establish plantations at high initial stockings (800–1100 trees ha\(^{-1}\)). Final crop trees (200–300 stems ha\(^{-1}\)) can be selected relatively early (probably at age 3–5 y) for intensive management (form and high pruning), the other trees being progressively thinned to minimise competitive effects while acting as trainers to reduce branch size on crop trees.

Optimal schedules for the thinning and pruning operations have yet to be developed through research; growers therefore apply their own empirical best-bet prescriptions with highly variable results. Because there is little current market for thinnings, direct thinning regimes are favoured whereby the plantation is thinned to near its final stocking as soon as possible (Dickinson and Kelly

### Table 1. The main facilities established to early 2008 under the *Khaya senegalensis* domestication program in the Northern Territory (NT) and Queensland (Qld)

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>Year planted</th>
<th>Composition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grafted seed orchards</td>
<td>Howard Springs, 25 km ESE of Darwin</td>
<td>2001+</td>
<td>143 clones ex 24 provenances in NT stands</td>
<td>Selection rate of the superior trees was low in all cases: approx. 1 in 50.</td>
</tr>
<tr>
<td></td>
<td>Berrimah RS, suburban Darwin</td>
<td>2001+</td>
<td>140 clone subset of above</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Walkamin RS, 45 km SW of Cairns(^b)</td>
<td>2003</td>
<td>68 clone subset of above</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weipa, NW coast of Cape York, Qld</td>
<td>2004</td>
<td>36 unique clones ex 2 provenances in Weipa stands</td>
<td></td>
</tr>
<tr>
<td>Seedling seed orchard</td>
<td>Weipa</td>
<td>2004</td>
<td>Open-pollinated (OP) seedlings of 20+ of the Weipa superior trees ex 1 provenance</td>
<td>Espacement 3 m × 3 m</td>
</tr>
<tr>
<td>Hedge gardens</td>
<td>Berrimah</td>
<td>2004</td>
<td>OP seedlings ex some 30 NT and Weipa superior trees; rooted cuttings (RCs) ex stump coppice of 10 superior trees; and wildlings — some 550 plants</td>
<td>Berrimah and Weipa hedge gardens are in-ground with one plant per hedge. At Gympie, hedges are in individual-plant pots, now with numerous hedges per clone.</td>
</tr>
<tr>
<td></td>
<td>Weipa</td>
<td>2004</td>
<td>Some 560 seedlings ex 20+ local superior trees</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gympie, SE Qld</td>
<td>2005</td>
<td>A 220-clone, selected subset of the Berrimah seedlings</td>
<td></td>
</tr>
<tr>
<td>Clone tests with various seedling controls</td>
<td>CPHRS(^c) (2 tests)</td>
<td>2005</td>
<td>RCs clones ex Berrimah hedges plus seedling controls</td>
<td>The numbers of clones per 2005 test range to more than 300.</td>
</tr>
<tr>
<td></td>
<td>Katherine RS, DDRS(^d)</td>
<td>2006</td>
<td>As above; many clones common to 2006 and 2005 tests</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Melville Is., NT (4 tests)</td>
<td>2006</td>
<td>As above</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Melville Is., ‘Why not’(^e), NT (2 tests)</td>
<td>2007</td>
<td>As above; many clones common to 2005–2007 tests</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Near Home Hill, 90 km NW of Bowen, Qld</td>
<td>2007</td>
<td>A large subset of Berrimah hedges propagated in Qld</td>
<td></td>
</tr>
<tr>
<td></td>
<td>‘What for’(^f), NT</td>
<td>2008</td>
<td>Many clones common to above tests</td>
<td>A test of about 50 clones to be in N Qld also</td>
</tr>
<tr>
<td>Cloned or seedling progeny tests</td>
<td>CPTs and SPTs at CPHRS, NT (2 tests)</td>
<td>2005</td>
<td>CPTs — clones of seedlings of 11 OP families SPTs — seedlings of up to 9 of the 11 OP families (CPTs and SPTs are integral parts of the CPHRS tests)</td>
<td>These tests are small. Cloned seedlings of 8 of the 11 families are present as bulks in the Mareeba test.</td>
</tr>
<tr>
<td>(CPTs, SPTs)</td>
<td>SPTs at CPHRS and Mareeba, 35 km W of Cairns (3 tests)</td>
<td>2008</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)RS = Research Station
\(^b\)A new seed orchard is being established at Walkamin using grafts of superior trees selected in stands in the Ingham to Bowen region, north Queensland.
\(^c\)CPHRS = Coastal Plains Horticultural Research Station, some 75 km SE of Darwin
\(^d\)DDRS = Douglas–Daly Research Station, some 170 km SSE of Darwin
\(^e\)Some 30 km SE of the Douglas–Daly Research Station
Table 2. Proposed R&D needs by field for successful plantations of *Khaya senegalensis* (KS) in northern Australia

<table>
<thead>
<tr>
<th>Field</th>
<th>Proposed R&amp;D needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genetic improvement</td>
<td>Expedite clone and family testing and breeding to develop genetically-improved trees across generations with deployment of such via seedling, vegetative family and or clonal forestry as determined to be appropriate in particular circumstances. Improve technologies for mass producing juvenile clones from young seedlings and develop the same for ‘selection-age’ trees, including optimising multiplication rate and maturation control; and study root systems of clones vs seedlings. Define provenance and family variation and the ‘genetic architecture’ of the species. Determine origins of some unknown seed sources and levels of co-ancestry in specific populations of the improvement program, including new accessions, using molecular and or other tools. Develop means for hastening and stimulating flowering and seed production in orchards, and for controlling pollination.</td>
</tr>
<tr>
<td>Silviculture and stand management</td>
<td>Develop nursery technologies for optimising planting stock condition and quality, and potential for extending the planting window. Develop establishment techniques including site preparation, drainage and irrigation, starter fertilising and weed management. Develop espacement, stocking, thinning and pruning regimes for producing defect-free quality logs of optimal size in medium-length rotations. Devise information and knowledge management and transfer systems that include data on plantation management experience elsewhere.</td>
</tr>
<tr>
<td>Plantation productivity</td>
<td>Extend and maintain permanent growth plots in existing and new stands representing the range of environments in which KS might be planted. Extend mensurational studies to develop tree and stand volume tables, and site index and yield tables, for determining rotation lengths, timber yields and economic returns. Create and maintain an inclusive growth and yield data base with agreed mechanisms for access and data sharing.</td>
</tr>
<tr>
<td>Site suitability, soils and nutrition</td>
<td>Map soil and site capability for target areas in major regions. Establish ‘productivity landscapes’ by linking through modelling climate, soils and landscapes into a site potential productivity classification using existing plantings. Determine economic fertiliser regimes for productivity landscapes. Establish nutrient deficiencies, visual symptoms of same and foliar analysis as a diagnostic tool for establishing critical nutrient levels as guides to fertilising. Define nutrient relationships of KS and the effects of nutrients and site amelioration on growth rates, growth habits, branch and crown development, stem form and wood properties. Investigate the physiology of water and nutrient use efficiency by selected genotypes and the potential for exploiting any genotype × environment interaction.</td>
</tr>
<tr>
<td>Log and timber quality</td>
<td>Identify essential log and wood quality criteria that affect value of returns and evaluate new, potentially superior trees for these quality criteria. Determine patterns of regional variation in the above or surrogate criteria. Develop conversion and processing technologies appropriate to the utilisation of the high-value KS resource. Find income-generating uses for thinnings and small wood.</td>
</tr>
<tr>
<td>Pests and diseases (P&amp;D)</td>
<td>Monitor plantations for P&amp;D and establish a data base collating this information. Undertake further work to understand the mechanisms of resistance to or escape from <em>Hypsipyla robusta</em>, <em>Mastotermes darwiniensis</em> and emerging P&amp;D. Develop risk assessment protocols and protection or containment strategies, including the potential use of biocontrol agents. Exploit any field resistance, incorporating any resistance genes into the breeding populations.</td>
</tr>
<tr>
<td>R&amp;D management</td>
<td>Integrate and coordinate the R&amp;D effort and investment through an articulated strategy agreed and supported by stakeholders. Establish a KS R&amp;D network to facilitate knowledge management, information exchange and cooperative research. Develop intellectual property protocols binding on R&amp;D participants, which ensure freedom to operate and facilitate information exchange and equitable sharing of the benefits flowing from the research.</td>
</tr>
</tbody>
</table>
If commercial products could be identified for the larger thinnings (10–20 cm dbhob, ages 8–15 y), however, overall plantation productivity and financial returns as well as silvicultural flexibility would be enhanced. Hence research on this aspect is flagged for attention in Table 2.

**Productivity**

Since the 1980s there have been numerous accounts of varying KS productivity across northern Australia, ranging from poor to exceptional, the latter including annual increments of > 5 cm dbhob for 15-y-old trees. Many of the exceptional claims are based on the performance of individual or widely spaced trees in backyard (compound) or park environments, which have little resemblance to commercial plantation conditions (Dickinson et al. 2004). In recent years, however, more reliable productivity information has been collected from a range of KS grown in larger blocks, across a range of site types and using a diversity of silvicultural practices (Reilly et al. 2004; Dickinson and Kelly 2006c). More than 35 inventory growth plots have now been established within Queensland plantations, and growth in these and in several trials in the NT is being monitored. It is apparent that site characteristics (rainfall, soil type and ground-water depth) and silvicultural management (site preparation, weed control, fertiliser application, irrigation, spacing, thinning and pruning) are the major factors influencing the productivity of these plots.

Estimating the yield potential of KS in northern Australia is problematic. The stands established near Darwin (at Gunn Point and Howard Springs some 30 km NE and ESE of Darwin respectively) in the 1960s to 1970s and at Weipa in the 1960s to 1980s were not managed silviculturally after a few initial years, and there are limited historical records of their growth. Very high survival (>90%) at more than 30 y of age has been observed in the Darwin trials (Nikles et al. 2004), though the figure varied considerably among provenances (Robertson et al. 2006). While overall productivity of such unthinned stands with many suppressed trees may be good (see below), much of the volume is distributed over a large number of small non-commercial trees and even at this age relatively few trees have attained a commercial size of > 40 cm dbhob. However, the height of the tallest trees at Gunn Point and Howard Springs at 32 y of age exceeded 27 m and 25 m respectively, and trees exceeding 50 cm dbhob were not rare (Armstrong et al. 2007), indicating the high potential of KS on these sites.

At Weipa, stands planted at 3 m × 3 m spacing in the mid-1970s on reconstituted bauxite pits, and unmanaged, have exhibited highly variable productivity at ages to 32 y, with MAIs of 5.4–11.3 m³ ha⁻¹ MVOB. The variability is attributed to variation in environmental conditions, including effects of back-filling techniques. A stand planted at 1100 trees ha⁻¹, with a residual stocking of 463 trees ha⁻¹, had a mean dbhob of 26 cm and an MAI of 5.4 m³ ha⁻¹ MVOB at 30 y (Bevege 2006) while another, planted at 3 m × 2 m with a residual stocking of 963 trees ha⁻¹, had a mean dbhob of 23.1 cm and an MAI of 11.3 m³ ha⁻¹ MVOB at 31.4 y (excluding unrecorded removed trees in both cases) (G. Dickinson, unpublished data).

In a more recent (post-1998) series of NT trials located from Darwin to Katherine (Reilly et al. 2004) on soils ranging from deep massive red and yellow earths (Kandosols) to shallow gravely lateritic podzolics (Chromosols), several trials were well established and maintained. Plantings were at 3 m × 3 m spacing. By 2004 (age 4.5 y) those on the massive earths, and even on the poorer laterite (but not poorest podzolic) soils, demonstrated promising growth rates, with MAIs covering a very narrow range of 12.7–13 m³ ha⁻¹ MVOB and bole lengths of 3.2–4.5 m. In an older series of unmanaged trials near Katherine on a massive earth, the 1996–1997 planting at 5 m × 2 m showed somewhat slower growth. MAI was 7.7 m³ ha⁻¹ MVOB at age 7.5 y. At age 9.5 y, predominant height was 10.6 m with a CAI of 0.75 m, and dbhob 12.9 cm with a CAI of 0.8 cm. Bole length averaged 3.5 m, reaching > 7 m in individual trees (D. Reilly, unpublished data).

In a number of the better-managed more recent (aged 8–10 y) Queensland plantations, where timely thinning was practised, incremental dbhob growth of the final crop trees (largest 200 stems ha⁻¹) has remained above 2.5 cm y⁻¹. With continued management, the final crop trees in these plantations should attain a dbhob of > 40 cm within the expected 20–25 y rotation. The highest productivity measured ranged from 8 to 14 m³ ha⁻¹ y⁻¹ MVOB. These figures were recorded for those plantations on higher-quality soils (Kandosols, Dermosols), which had received good silvicultural management (particularly weed control and supplementary irrigation) for the first 2–3 y. In a representative plot near Townsville on a Brown Dermosol soil, volume CAI was greater than MAI at age 8 y (10.8 m³ ha⁻¹ MVOB as against 8.0 m³ ha⁻¹), figures indicative of continued vigorous growth and the culmination of volume MAI some years in the future (Bevege 2006).

Over the next 10 y, periodic measurement of growth plots in the older plantations and of additional plots within new plantations established with improved germplasm would enable the development of comprehensive yield tables and provide much-needed information on the longer-term effects of site × genetics × silviculture × management interactions on productivity of KS plantation in northern Australia. This information would greatly enhance KS site selection and management prescriptions, and facilitate the development of a new plantation industry in this region. Hence R&D in this field is proposed (Table 2).

**Pests and diseases**

A number of pests and diseases have been recorded from KS in northern Australia. These include termites (*Mastotermes darwiniensis* Froggatt), species of Lepidoptera (Geometridae and Tortricidae) and Hemiptera (Coreidae), and a number of root (*Phellinus, Rigidoporus*) and leaf (*Colletotrichum*) diseases (Heare and Rance 1975; Griffiths et al. 2004; Peng and Christian 2006). While *M. darwiniensis* has been recorded as heavily attacking KS in the Darwin area since at least the early 1970s (Cameron et al. 2006), the incidence of attack is low and sporadic in stands planted since the 1990s on old agricultural or pasture sites without control measures in the NT and Queensland. Consequently, attack is not considered to be an economic threat in the NT (nor in Queensland) at present, but may be in the future with establishment of more extensive areas of plantations on recently-cleared, natural forest sites, especially if significant amounts of termite food such as woody debris remain on the sites.
Most of the other insect attacks are relatively new records, and the impacts to date have been minor. Current research is focused on biocontrol of a suite of insect pests (Peng and Christian 2006). There are pests and diseases with potential for concern including Cylindrocladium leaf blight, and, most importantly, Hypsipyla shoot borers (Griffiths et al. 2004).

Plantings of KS in Australia and the Asian region have remained relatively free of shoot borer attack to date (Griffiths and Wylie 2006). Shoot borer was first confirmed as attacking a small number of KS trees in two grafted seed orchards in the Darwin area in 2004 (Reilly et al. 2006a) and more recently in 2007 (Renkang Peng, Charles Darwin University Darwin, 2007, pers. comm.). The insect has also been found in a few grafts of KS at Walkamin, on the Atherton Tableland some 45 km SW of Cairns, Queensland. However, the shoot borer has not been found in the 355-ha plantation of KS north of Cooktown, even though it attacks adjacent native trees of Toona ciliata (Robin York, Northern Tropical Timbers, 2006, pers. comm.). In contrast, related native Swieteniaceae in these areas (e.g. Toona, Xylocarpus) suffer extensive damage. The reason for the low incidence of shoot borer damage to KS in this region has recently become apparent. Previously it was believed that the same species, H. robusta, was present in Africa, Asia and the Pacific. Recent morphological and molecular work has revealed, however, that the African populations in fact consist of a suite of three species, none of which is H. robusta (Marianne Horak, CSIRO, 2006, pers. comm.; Griffiths and Wylie 2006). The low damage in the Asia-Pacific region supports a general pattern in which Hypsipyla species favour endemic host species while non-endemic hosts are less attacked (Cunningham et al. 2005).

Hypsipyla robusta currently poses minimal threat to KS in northern Australia, due to both low oviposition and poor larval survival (Griffiths and Wylie 2006). It is important, however, to consider the risks in planting large areas of KS in regions where H. robusta is known to occur on native tree hosts. The risk of ‘host switching’ must be considered.

Genetic variation in tolerance to shoot borer has been demonstrated for various Meliaceae (see section ‘The species in Africa’ above). Managing to minimise any effect of shoot borer lies in an integrated approach combining silvicultural practices with genetic selection, the latter necessarily from a broad base — as is being assembled in northern Australia (see section ‘Genetic improvement’ below). Proactive laboratory screening of KS clones is proposed in Queensland and some work to facilitate this has been initiated (Griffiths and Wylie 2006). Biological control options are a possibility (Sands and Murphy 2001) and are currently being pursued (Peng and Christian 2006). In addition, strong quarantine measures are essential to ensure African Hypsipyla species are not transferred to Australia. To best protect the health of KS plantations, it is important to identify existing and potential pest and disease issues and prepare for their containment. Means to achieve this are summarised in Table 2.

Log and wood properties of unimproved germplasm in Australia

KS produces a valuable timber much sought after for high-value products including fine furniture and boat fit-outs. Its reputation stems from the excellence of wood from natural stands. Initial studies by CSIRO on wood from Darwin-grown material demonstrated the early promise of the species (Hearne and Rance 1975) and this has been confirmed in older material (Armstrong et al. 2004, 2006, 2007; Fig. 5a). Timber will be harvested from plantations at much younger ages than from natural stands, so growers will need to take cognisance of the likely impacts of genetics, environment, silviculture, age at felling and their interactions on variation in key utilisation traits such as green-off-saw recovery, end splitting, pith offset, density, hardness, heartwood proportion and homogeneity, distortion and others.

In 2003–2004, variation in such traits among 32-y-old plantation-grown trees was studied in logs and timber from 38 superior trees from the provenance trials at Gunn Point and other trials at Howard Springs, NT (Armstrong et al. 2004, 2006, 2007; Fig. 5a,b). Favourable results from this study included:

- great variation among trees in all traits assessed (indicating a potential to select and breed for improved properties, e.g.10 putatively superior trees and 14 putatively very inferior trees were identified)
- little end-splitting; easy and rapid drying of boards with little degrade
- excellent appearance characteristics, wood qualities and timber-use properties including high apparent durability.

Industry assessments were very favourable, and furniture crafted from project timber attracted state and national awards (Nikles 2006; Fig. 5a). Neither provenance nor site effects could be identified because of limitations of the sampling.

The study indicated that most of the negative features could be related to the lack of silvicultural management of the sampled stands, and to the genetically-unimproved nature of the seed used in their establishment. Hence, an R&D plan was proposed to address the issues relating to the wood quality of future plantations (Armstrong et al. 2006). Currently, consideration is being given to non-destructive sampling of younger superior trees selected in Queensland and NT in 2006 and subsequently, with similar sampling of neighbouring trees, to assess the relative wood properties of selects and neighbours. The results would help to refine the list of trees for cloning and breeding. Other R&D proposed includes studies of regional variation in key criteria of wood properties (Table 2).

Genetic improvement

Renewed domestication of KS began in northern Australia in 2001 as a collaborative venture between the then NT and Queensland forestry research groups, with assistance from the Rural Industries Research and Development Corporation (Project DNT-27A) during 2001–2003. The NT-Queensland collaboration continues (Nikles 2006; Reilly et al. 2006b) and is driven by:

- the effective rediscovery, during 2000–2003, of a wealth of germplasm in provenance trials (Fig. 1) at Gunn Point near Darwin and in other stands of the 1960s and 1970s in the Darwin region, on Melville Is. (NT) (Nikles et al. 2004) and at Weipa (Queensland) (Bragg et al. 2004)
African mahogany for plantations in northern Australia

- recognition of the many good features of the species and the likelihood that its few deficiencies could be remedied by well-planned R&D
- the good prospects for a sustainable plantation industry with the species in northern Australia (Bevege et al. 2004, 2006a).

Investigation of provenance variation in the Melville Is. and Gunn Point trials of the early 1970s has been constrained by their lack of management, non-uniformity of planting stock (age, type, size and condition), early failure of the Melville Is. trials, and the limited data available (1.5 or 2.5 y height growth and survival at both locations, and data for a number of growth and form variables at Gunn Point gathered in 2000 when plot stockings varied greatly) (Nikles et al. 2004). Co-variate statistical analyses of the year 2000 data of individual Gunn Point trials by Roger Arnold (unpublished) revealed little consistency in the relative ranking of the provenances tested. This seemed due to the confounding effects of differences of planting stock within trials and apparent large-scale variation in site conditions within replicates (possibly exacerbated by the site preparation differences) such that variance due to provenance × replication exceeded that due to provenance for many parameters. However, significant differences between provenances for a number of traits were indicated. In the 1970–1971 trial, provenance D417 – Senegal performed well in a number of desirable traits — diameter, bole length, form and sample-average height. In the 1971–1972 trial, D417 had highest survival, bole length and volume index; and, in the 1972–1973 trial, a different Senegal provenance ($10066) was superior in bole length (the only trait exhibiting a significant difference). Across the trials, provenances from five other countries were promising for up to two traits. Thus, there is evidence that Senegal might be a good seed source for sites like those of Gunn Point. However, new, multi-site provenances trials (that could serve a number of purposes) are required in order to determine provenance variation in the different environments of current and likely future commercial plantings. A series of new trials has been planted at appropriate locations in the NT (Douglas–Daly region — in 2007 and 2008, and Melville Is. — in 2008) and in Queensland (Cooktown and Ingham regions — early in 2008).

As a conservation measure and with possible future domestication in mind, above-average trees were selected in the NT and at Weipa in the stands planted in the 1960s–1970s with some 26 provenances from most countries of the natural range. Figure 1 shows the numbers of provenances per country of origin in the NT stands. (The information on provenances in plantings in the NT came from seed source records of CSIRO, Canberra, and the NT Department of Primary Industry, Fisheries and Mines (DPIF&M); and at Weipa via Alan Bragg and Ian Bevege respectively the Queensland Department of Primary Industries and Fisheries (DPI&F), Atherton, and Forestry Consultant, Lilli Pili, New South Wales, 2004 pers. comms). Relatedness among selections within provenances is unknown.

Grafts of the selected trees were used to establish seed orchards near Darwin (143 local clones) (Fig. 7a,b) and in Queensland at Walkamin (68 of the NT clones — 64 have survived) and at Weipa (36 local clones) (Table 1). The NT orchards are beginning to produce pods and viable seed (Fig. 8a,b). In the flowering of 2007, nearly a half of the 98 clones present in the oldest sections of the orchards near Darwin produced some flowers (Fig. 7b); pods from most of these clones have set and are due for collection in mid-2008. Extensive recombination of genes, through feasible, open-pollinated, intra- and inter-provenance crossing in the seed orchards (Nikles et al. 2006a) and subsequent phenological observations should provide seed of great genetic diversity and progeny with scope for long-term, recurrent-selection breeding, especially if supplemented by infusions of new material from the large accessions of seed of recent years (see section ‘Current estate and plans for extension’ above).

Observations across many stands in the NT and Queensland and quantitative assessments in various trial plots (not shown) have revealed great phenotypic variation among trees within stands in traits of economic importance including diameter, height, stem straightness, merchantable bole length (lengths exceeding 7.5 m have been recorded) and branching habit. Great variations in log and wood properties have been mentioned in the section above. Windfirmness under normal plantation conditions appears uniformly high. However, stands subjected to exceptionally severe wind may be damaged, especially if sited on soils that are poorly drained. Based on this variation, and the demonstrated successes with numerous other species in genetically improving economic traits (see, for example, Burdon and Libby 2006 for a brief historical survey, McKean et al. 2006 for a specific case, and White et al. 2007 for several examples), it is expected that KS too can be greatly improved by selection, breeding and propagation of the best material.

The tree improvement strategy (Nikles et al. 2006a) allows for the addition of new local superior material and infusions from the extensive acquisitions of native stand provenances — procured by industry in recent years — to broaden base populations for the next cycle of selection and breeding. Samples of the more recent accessions are being established in provenance trials and identified resource stands. They should provide the second opportunity in Australia to exploit provenance variation in the species (which is expected to be large — see section ‘The species in Africa’ above), the first having been the capture of the material now in seed orchards and hedge gardens outlined above and summarised in Table 1.

The main facilities established under the program — grafted and seedling seed orchards, hedge gardens and clone and progeny tests — are described in Table 1. Good results have been achieved with the rooting of cuttings from hedged seedlings (Pomroy and Lee 2006; Reilly et al. 2006b) enabling establishment of several clone tests (Table 1; Figs 9, 10). Current activities mainly entail:

- managing existing facilities, including checking the synchrony of flowering in the multi-provenance seed orchards (it appears to be high), assessing clone tests and using the information to guide selection of the putatively better clones for propagation and pilot-scale deployment
- establishing new clone tests to broaden the range of environments sampled.

A recent initiative is the grafting of ‘mature’ scions from superior trees selected in young stands in Queensland since 2006 (Fig. 11). It is hoped to propagate such trees as juvenile clones as well. After the seed orchards produce seeds from a heavy and general flowering, multi-site tests of the second-generation progeny, plus controls, are planned to be established to form part of the
next genetic base population. Infusions (new selected trees and seed accessions) can either be incorporated or developed as a second subline for the control of inbreeding in material for operational use. Seedling families of the putatively-best orchard clones may be established in second-generation hedge gardens to allow deployment options of family and or clonal forestry. Other improvement options exist.

Activities, scheduled in the flow charts of Nikles et al. 2006a, are designed to hasten and maintain the delivery of incrementally-improving planting stock through use of the best of the material captured so far, plus infusions. This approach has been successful in domestication and long-term breeding of many species (e.g. Simmonds 1979 on crop plants; Eldridge et al. 1993 on eucalypts). For KS, most attention is being given to improving stem straightness, bole length, branching, growth rate, and log and wood properties; attention is also being given to potential threats to tree and stand health (see section ‘Pests and diseases’ above).

The goal is to enhance plantation productivity and maintain the growing national regard for timber from mature KS plantations in northern Australia (Fig. 5a).

Looking to the more distant future, say the beginning of the third rotation (perhaps around 2060) and paraphrasing Bevege (2004), climatic conditions may have changed sufficiently to have inimical effects on survival and growth rates, creating a need for newly adapted germplasm. Based on climate modeling reported by IPCC (2004) and Pearman (2004), there may be greater variability in rainfall in the wet season and possibly an extended dry season with increased water stress in the current homoclime of the species in northern Australia (Arnold et al. 2004). The techniques proposed by Booth (1994) to model species and provenance adaptation to a range of climate scenarios might provide, through sensitivity analysis, a guide to genotype selection for future plantings.

Figure 7. (a) A grafted seed orchard (aged 4.7 y) planted in the Darwin region in December 2001. The poor apical dominance of the trees reflects the upper-, outer-crown scion sources in the 30+-y-old parent trees. (b) A graft in the orchard (Fig. 7a) at age 5.8 y in 2007 when a moderate flowering occurred throughout the orchard. (Photos: Don Reilly)

Figure 8. (a) Seed pods in January 2006 from the 2005 flowering of a graft in the orchard of Figure 7a. (b) Seedlings from seeds of the pods of Figure 8a collected in June 2006. These seedlings were established in various field trials in early 2007. (Photos: Beau Robertson, Don Reilly)
Figure 9. A clone test (aged 2.6 y) planted in the Darwin region in February 2005. Trickle irrigation was applied for 1.5 y. The central tree, a Control seedling, has a dbhob of 13.5 cm. The clear boles are due to natural abscission of the stem-clothing compound leaves present prior to branch development. (Photo: David Karnosky)

Figure 10. A clone test (aged 1.3 y) planted in the Katherine region, Northern Territory in January 2006. Trickle irrigation was applied for 1.5 y. The foreground tree, a rooted cutting of a vigorous clone, is 4 m high. (Photo: Don Reilly)

Figure 11. A superior tree selected within the stand shown in Figure 6. This tree, the largest in its vicinity, had a dbhob of 31.2 cm at age 9.25y, a bole length of 6 m and 'acceptable' stem straightness. (Photo: Geoff Dickinson)

Constraints on plantation sustainability and responses

Stands of KS of all ages in northern Australia developed from local or imported seed are characterised by high frequencies of trees with all or some of the following deficiencies: crooked stems, short boles, and excessive and heavy branching. Although a proportion of trees in these stands will provide useful logs, these characteristics constitute a major constraint on the potential economic yield of existing and near-future plantations. The issue is being addressed via the genetic improvement work, initially through the use of superior clones anticipated to be identified via the Series 1 clone tests (Table 1; Figs 9, 10) and by means of seed from the seed orchards. However, attention needs to be given to ensuring continuity and further development of the tree improvement program as outlined in the strategy of Nikles et al. 2006a, ideally via a 'customised' cooperative program (Nikles 2004; Nikles et al. 2006a) that would embrace other key needs among those items proposed for R&D in Table 2.

Trees greatly improved in ‘utilisation potential’ are not expected to be available from the domestication program for large-scale deployment for several years. Hence the general crookedness and aberrant crown characteristics of some of trees in existing stands are expected to be exhibited in most new plantings over the next
several years. Some of these form problems, as well as instances of poor vigour, may be related to nutrition expressed through genotype × environment interactions. It is proposed to address this, and the impact of nutrition per se on yield, via appropriate studies with clones and seedlings (Table 2).

A concerted effort is also required to initiate research into silviculture, stand management, mensuration and pest management. This is because of the young age of many of the plantings, the extremely limited application of proven silvicultural techniques to them and the general dearth of information on their growth and yield. Yield tables based on thinning regimes aimed at satisfying high-value niche market demands and therefore maximising economic returns. R&D proposed is listed in Table 2.

Conclusions

Intensified and focused R&D is now required urgently to underpin sustainability of the burgeoning plantation establishment program with KS in northern Australia. This is because the constraints identified in this paper are not being addressed adequately. However, the many good features of KS, including its inherent variation in traits of economic importance at least some of which can be expected to vary genetically, and the successful improvement of many forest tree species through recurrent selection or hybridisation (Burdon and Libby 2006; McKeand et al. 2006; White et al. 2007), engender optimism about similarly domesticating KS and developing a sustainable KS plantation industry in northern Australia. This optimism is justified only if the R&D proposed in Table 2 is undertaken in a strategically planned and coordinated way, and the results are implemented. The overriding constraint is the inadequacy of funds to manage the existing program most effectively and to implement the additional R&D proposed. A concerted effort is required to overcome this constraint. Large gains in profitability can be expected to flow from funding these activities.

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