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BIODIVERSITY REVIEW

Global uses of Australian acacias – recent trends and future prospects

A. R. Griffin[1]*, S. J. Midgley[2], D. Bush[3], P. J. Cunningham[4] and A. T. Rinaudo[5]

[1]School of Plant Science, University of Tasmania, PO Box 55, Hobart, Tas., Australia, [2]Salwood Asia Pacific, 35 Steinwedel St., Farrer, ACT 2607, Australia, [3]CSIRO Division of Plant Industry, Black Mountain Laboratories, Canberra, ACT 2600, Australia, [4]Serving in Mission, BP121 Maradi, Niger, [5]World Vision Australia, 1 Vision Drive, East Burwood, Vic. 3151, Australia

*Correspondence: A. R. Griffin, School of Plant Science, University of Tasmania, PO Box 55, Hobart, Tas., Australia.
E-mail: rodgriffin@treeimprovement.com

ABSTRACT

Aim This study reports on the contribution of the Australian Tree Seed Centre (ATSC) to the international dissemination of Australian acacias. It also describes the current uses and the scale of economic benefits derived from planting Australian acacias, and speculates about possible future trends in usage. This information is crucial for the evaluation of overall human-mediated transfers of Australian acacias as a global experiment in biogeography.

Location Australia and Global.

Methods ATSC databases were used to determine which taxa were sent to which regions of the world and in what numbers. Location, scale and value of uses of the most important species were described from a review of published and grey literature, and we drew on our collective experience to speculate about future trends.

Results The ATSC despatched samples of 322 taxa (or roughly a third of *Acacia* species native to Australia) between 1980 and 2010 to 149 countries. Plantations in SE Asia and South Africa supplying the pulp and paper industry cover an area of over 2 M ha and produce pulp worth around $US4.3B p.a. In SE Asia, pulpwood species also provide logs for an expanding industry based on solid wood product. Tannin is produced from *Acacia mearnsii* in South Africa and Brazil. A suite of multi-purpose species helps meeting the demand for food, fodder, fuelwood, poles and site amelioration in dry zone regions of Africa and elsewhere and are widely incorporated into agro-forestry systems. *Acacia saligna* is the most widely planted non-timber species with around 600,000 ha established worldwide. Many acacia species also have horticultural uses particularly in Europe.

Main conclusions The ATSC has been the major agent for systematic exploration and worldwide dissemination of Australian acacias over the past 30 years, but seed from local and regional sources of exploited species will dominate future movements. The scale of production from currently planted species will expand to meet the demands of population growth, using improved varieties. Plantations for energy and carbon sequestration might become increasingly widespread.

Keywords

Australian acacias, fuelwood, horticulture, pulpwood plantations, site amelioration, solid wood plantations.

INTRODUCTION

Species of *Acacia* and *Eucalyptus* dominate much of Australia's vegetation (Groves, 1994) and are adapted to produce woody biomass on sites where water and nutrients are limited. Globally, such land is poor for food production but often adequate for tree crops. Together acacias and eucalypts comprise over 40% of industrial tree plantations in the tropics and sub-tropics (Del Lungo *et al.*, 2006) and also supply wood to rural communities.

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The economic value of *Eucalyptus* was recognized from the earliest days of European settlement in Australia, and this stimulated the transfer of seeds of many taxa around the world (Boland *et al.*, 1980; Bennett, 2011). However, systematic collection and evaluation of Australian acacias (see Miller *et al.*, 2011; and Richardson *et al.*, 2011 for taxonomic details) only began in the 1970s. The major agency involved was the Australian Tree Seed Centre (ATSC; http://www.csiro.au/places/ATSC.html) of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) with the support of Australian development assistance agencies and multinational donors such as the Food and Agriculture Organization of the United Nations (FAO).

Australian acacias have a diverse range of uses in a correspondingly wide range of environments (Kull *et al.*, 2011), though they have been primarily introduced as fuelwood and fibre crops (Boland & Turnbull, 1981).

The seed is cheap and stores easily, while seedlings are easy to raise and most taxa grow fast with relatively little silvicultural input. These biological attributes favour use as crop plants but also contribute to invasiveness (Gibson *et al.*, 2011; Richardson & Rejmánek, 2011; Wilson *et al.*, 2011), and this has created some conflict between production and invasions, especially in South Africa (van Wilgen *et al.*, 2011).

This study reports the history of supply of acacia seed from the ATSC; documents the range of uses with statistics on the geographical distribution and scale of plantings and of economic benefits derived; and speculates about possible future trends. Such information is crucial for describing the dimensions and trajectories of the major global experiment in biogeography that has been created by the widespread movement of these taxa (Richardson *et al.*, 2011).

THE ROLE OF THE AUSTRALIAN TREE SEED CENTRE IN INTERNATIONAL DISSEMINATION OF AUSTRALIAN ACACIAS

The early history of collection and use of Australian acacias is treated in Carruthers *et al.* (2011). Here, we focus on the more recent era of systematic exploration and domestication which we date from 1973 when Centre Technique Forestier Tropical (CTFT) and the ATSC made a major collection of taxa for evaluation in dry tropical Africa (Cossalter, 1987).

The ATSC (originally the Eucalyptus Clearing House) was set up in 1962 as an Australian government response to an FAO request (FAO, 2002a). From 1979, FAO's Panel of Experts on Forest Gene Resources has consistently recognized the global significance of the Australian acacias and encouraged utilization. Most recently, the Panel listed 11 taxa (Table 1) as having high global, regional and national priorities (FAO, 2002b). From 1980, ATSC scientists in collaboration with international colleagues systematically assessed the potential economic utility of Australian acacias (Midgley & Turnbull, 2003) with major funding from the Australian Centre for International Agricultural Research (ACIAR). Potentially valuable taxa were identified, seeds were collected across the range of natural occurrence, and samples were exported to many countries for field evaluation. Parallel studies were conducted to evaluate products from the acacia trees, and genetic selection and breeding were addressed along with issues of diseases and quarantine. The preface to Doran & Turnbull (1997) describes the process used in reviewing taxa. They also noted that '… it must be recognized that under some environmental conditions these species have the potential to be invasive… such species should be introduced with care and their performance carefully monitored'. To our knowledge, ATSC has always been fully compliant with all regulations pertaining to invasive species and quarantine.

Progress with the programme was reviewed at a number of workshops and symposia and a strong publication record maintained (e.g. Doran & Turnbull, 1997). Although the major phase of taxon collection and testing is now completed, the process of domestication continues in many countries under the aegis of national research institutions, NGOs and private companies.

About one-third of Australian acacia taxa can grow to 5 m or more with potential for human use. These have been the focus of ATSC collections over the past 30 years, and almost 50,000 seed samples have been distributed worldwide. We determined the number of dispatches by geographical region as a measure of interest in each of the taxa collected and supplied at least once. For recipient countries within each region, see Table S2 in Supporting Information. The natural range of climatic zones for each taxon is also noted (see http://www.worldwidewattle.com for distribution maps) and taxa identified in five historical studies of prospective economic importance are flagged, to show the extent to which subsequent seed demand reflected these expert predictions.

Midgley & Turnbull (2003) reviewed the domestication history of five economically important taxa. We update and expand that content. Key taxa were classified according to their primary use, recognizing that most if not all have more than one use, the relative importance of which may vary from one region/class of grower to another.

Based on the published literature and other information obtained through our networks, we then defined five major usages of Australian acacias, and present the best available information on the global location and scale of plantings and the levels of economic activity generated. Monetary values are presented in USD 2010 prices (exchange rates from http://www.x-rates.com/), and production in bdt (bone-dry tonnes).

Comment on the future of each usage and possible new developments are largely opinion based on the authors' collective professional experience.

TAXA COLLECTED AND DISTRIBUTED BY THE ATSC 1980–2010

The ATSC has processed samples of 322 taxa, exporting to a total of 149 countries (see Tables S1 and S2). Demand for seed has, however, been highly skewed, with the 25 major taxa listed in Table 1 accounting for 85% of total orders. Demand has

Table 1 The 25 most frequently supplied Australian acacia species 1980–2010 showing the number of individual seedlot orders dispatched from the Australian Tree Seed Centre by geographical region (a seedlot represents one source population (provenance) but may contain seed from more than one tree. An order for seed of two provenances of a taxon is counted as two orders). Requests for further information from the database should be directed to atsc@csiro.au.

	Number of seedlot orders by geographical region										
Acacia species	Austral asia	Pacific	South America	Central America	S.E. Asia	E. Asia	S. Asia	Africa	Europe/ N. America	Med./Mid. East	World total
A. mangium	1358	529	240	295	6801	907	569	474	458	1	**11,632**
A. auriculiformis	1951	178	79	77	3177	608	630	354	332	2	**7388**
A. crassicarpa	927	172	50	42	2790	371	191	220	322	0	**5085**
A. aulacocarpa	1056	348	35	28	1665	425	121	109	43	0	**3830**
A. mearnsii	1074	4	470	21	368	582	90	275	58	17	**2959**
A. melanoxylon	960	20	209	22	73	491	112	52	50	48	**2037**
A. dealbata ssp.	394	1	133	5	24	161	37	128	74	9	**966**
A. ampliceps	247	19	6	11	49	39	344	123	25	27	**890**
A. colei	335	1	11	11	41	17	100	189	52	15	**772**
A. aneura	148	0	48	30	16	41	172	181	37	78	**751**
A. holosericea	201	4	12	14	116	21	80	136	15	9	**608**
A. saligna	323	0	40	4	6	4	65	49	29	56	**576**
***A. tumida* ssp.**	239	0	2	7	39	8	58	187	20	12	**572**
A. cincinnata	101	36	16	7	94	148	30	39	11	0	**482**
A. stenophylla	149	0	21	3	18	10	133	84	18	25	**461**
A. cowleana	173	0	6	10	21	4	54	114	40	16	**438**
A. victoriae	132	0	13	6	11	36	85	103	15	26	**427**
A. leptocarpa	51	8	4	6	122	25	59	67	5	0	**347**
A. torulosa	63	1	0	4	44	16	24	106	15	1	**274**
A. decurrens	104	1	18	4	25	40	20	29	23	3	**267**
A. salicina	86	0	16	3	13	14	59	39	16	17	**263**
A. coriacea	75	0	6	6	5	3	47	83	11	14	**250**
A. elata	125	2	14	0	16	26	15	16	7	3	**224**
A. implexa	108	1	0	2	9	79	3	3	10	0	**215**
A. difficilis	28	2	1	4	42	14	30	62	8	0	**191**
Total dispatches by Region	**10,408**	**1327**	**1450**	**622**	**15,585**	**4090**	**3128**	**3222**	**1694**	**379**	**41,905**
Total No. dispatches all 322 species	**13,650**	**1357**	**1634**	**719**	**16,254**	**4721**	**3993**	**4535**	**2116**	**692**	**49,671**
Total No. species sent to each region	**312**	**38**	**87**	**71**	**136**	**130**	**200**	**184**	**173**	**108**	

Priority species listed by FAO (2002b) in bold (an 11th species *A. elachantha* ranks 42nd in Table S1).

been particularly strong for the tropical acacias. *Acacia mangium* was the most common taxon requested from the Pacific, Central America, Asia, Africa and Europe/N. America and the second most common in southern Asia and Australasia. Clearly, tropical acacias are not climatically suited to northern temperate conditions, so we assume such orders were for re-export to destinations unrecorded by ATSC. *Acacia mearnsii* and *A. melanoxylon* were the most requested temperate acacias, with interest from East Asia (China) and South America (especially Brazil and Chile). Africa has also imported a wide range of taxa, most often those adapted to tropical dry environments.

Expert recommendations of future utility (see Table S1) were relatively successful as judged by seed demand. Of the 322 taxa, 101 were listed in one or more publication. All 25 taxa in Table 1 were listed at least twice. However, there are some anomalies, with 10 listed taxa in the bottom 50% in rank order with 10 or less requests for seed.

Uses, geographical distribution, scale and value of acacia plantings

Table 2 lists the mostly widely planted taxa ('plantation' referring to planted trees whether in large blocks or other planting configurations such as single line windbreaks or agroforestry systems). The dates of introduction and first reports of substantial establishment are often poorly documented but sufficient to indicate whether a taxon was an old or recent export from Australia. The time lag between introduction and substantial planting ranged from 9 to 46 years. If commercial potential is clear, then it seems that substantial planting can occur within a decade of introduction.

Table 2 Geographical distribution and plantation history of major species of Australian acacias planted primarily for wood and wood products.

Acacia species	Primary use	Minor uses	Countries with significant plantings	Earliest record of export from Australia	First substantial plantations	Estimated current global area of plantation (K ha)
A. mangium	Pulpwood	Solid wood, fuelwood, Site rehab.	Indonesia, Vietnam, Malaysia	1966 (1)	1976 (1)	1400
A. mangium × *auriculiformis* hybrid	Pulpwood	Solid wood, fuelwood, Site rehab.	Vietnam	1972 (4)	1998 (5)	230
A. crassicarpa	Pulpwood	Solid wood, fuelwood, site rehab.	Indonesia, Vietnam	1984 (6)	1993 (M. Werren pers. comm.)	330
A. auriculiformis	Solid wood	Pulpwood, fuelwood/ charcoal, site rehab.	Vietnam, India	1910 (2)	1930 (3)	(*) 220
A. saligna	Fuelwood/ Charcoal	Site rehab.	Libya, Ethiopia,	1870 (8)	1916 (9)	600
A. mearnsii	Tannin	Pulpwood, fuelwood/ charcoal, site rehab.	South Africa, Brazil, India	1864 (7)	1876 (7)	540

Data sources are given in brackets: (1) Awang & Taylor (1993); (2) Streets (1962); (3) Wiersum & Ramlan (1982); (4) Pinso & Nasi (1992); (5) Kha (2001); (6) Midgley & Turnbull (2003); (7) Sherry (1971); (8) Bert (1886); (9) El Lakany (1987).
* assumes 100,000 ha of *Acacia auriculiformis* in India and 120,000 ha in Vietnam.

Pulp wood and pulp production

Many acacias produce very acceptable pulp and paper (Clark *et al.*, 1994; Roberts, 2002; Midgley *et al.*, 2003). The biggest plantations are in SE Asia, where *A. mangium* and its natural hybrid with *A. auriculiformis* and also *A. crassicarpa* are grown (Table 2). We estimate the worldwide plantation estate of *A. mangium* to be 1.4 M ha (with 230,000 ha of hybrid, largely in Vietnam); and of *A. crassicarpa* to be 330,000 ha (mainly in Indonesia where it grows well on peatland). The only other notable pulpwood taxon is *A. mearnsii*. While *A. mearnsii* was initial grown for tannin production, the chips are now highly regarded by the pulp and paper industries particularly in Japan. Main plantations are in South Africa with an estimated area of 120,000 ha (C. Dyer, pers. comm.), and Brazil with up to 250,000 ha (Foelkel, 2008). Plantings were also made in India post-independence to achieve self-sufficiency (Rangan *et al.*, 2010).

Indonesia is the largest producer of acacia pulp. Indonesian pulp production grew from 1 Mt in 1990 to 7.5 Mt in 2008 (Barr, 2008) with a possible expansion to 16 Mt by 2020 associated with projected increase of 9 M ha of new plantation. As many Indonesian mills also produce pulp from Mixed Tropical Hardwoods, it is not easy to separate out the acacia component. Our judgement is that this is now about 3.3 Mt, worth \$US2.7 B year^{-1}).

There is also an international trade in acacia wood chips of about 3.5 Mbdt year^{-1} from Vietnam, South Africa and Brazil which are converted to about 1.9 Mt of pulp in mills in east Asia. The total annual value of acacia pulp production is therefore in the order of \$4.3B. We estimate the value of annual trade in woodchips as around \$0.5B. Sales of acacia pulpwood from South Africa averaged 1.42 Mbdt year^{-1} for the period 2003–09 (Godsmark, 2010) worth about \$185 M year^{-1}. The Brazilian industry which exported 1.2 Mt of acacia chips in 2007 (Foelkel, 2008) is of very similar size, while an estimated 50% of Vietnam's predicted 2010 hardwood chip export of 3.5 Mbdt is acacia, worth about \$162 M.

Solid wood products

Acacia melanoxylon has long been used for fine furniture production in Australia. It has been introduced to a number of other countries such as New Zealand, South Africa and Chile but proved difficult to manage in plantations. Some of the tropical acacias are making a far larger impact as a source of solid wood products. In SE Asia, substantial quantities of *A. mangium* wood are now bought for this purpose (Midgley & Beadle, 2007). The drivers are in demand for plantation-grown wood which can meet the certification requirements of furniture industries in Europe and North America; the reduced availability of logs from native forests; and increasing awareness that these acacias are very suitable for plywood, furniture, flooring and light construction. The wood of the *A. mangium* × *auriculiformis* hybrid is similar to *A. mangium* but has higher density and is more suitable for products where strength is important. *Acacia auriculiformis* is denser still and has a rich heartwood colour though it is slower growing than the other taxa. Vietnamese plantations are predominantly grown by small farmers, and it is the projected increase in national GDP from this sector and the associated processing industry that provides the rationale for continuing ACIAR support for Australian/Vietnamese collaboration in acacia breeding and silvicultural research. The main acacia wood product manufactured for export from SE Asia is furniture sold into Europe and the United States. It has similar characteristics to teak but is much cheaper. The total value is difficult to estimate, but

figures from Vietnam provide a lower bound (Midgley & Beadle, 2007). Export of finished wood products is worth around $3.0B annually (Vietnam Business News, 2010). The industry relies on imported wood, including *A. mangium* logs from Malaysia. However, based on field observations and factory interviews, we estimate that about 20% now comes from local acacia plantations and that this import substitution will increase.

Tannin production

Tannin was the first industrial product from wild Australian acacia trees (Searle, 1991). Bark of several taxa was investigated and *A. mearnsii* preferred. The industry declined through the late 19th and early 20th century to be replaced by cheaper plantation-grown products from South Africa and Brazil. The demand for *A. mearnsii* seed from ATSC has persisted, and it ranks as the 5th most widely dispatched taxon (Table 1). It has multiple uses and as the bark accounts for only 15% of total biomass production, acceptance by the pulp and paper industry has greatly improved economic returns. Together South Africa and Brazil produced 89% of the 67,000 Mt of internationally traded tannin extract in 2009 (see Table S3). Significant amounts of product are also used internally; indeed, only 40% of Brazilian product is exported (Foelkel, 2008). A South African industry estimate of national production (N. Slabbert, The Mimosa Extract Company Pty. Ltd., pers. comm.) is about 45,000 Mt year^{-1}. If 29 Mt are exported (see Table S3) then this implies 35% for local use in that country. We therefore estimate worldwide annual value of product as about $US130M including $US80M from international trade (see Table S3).

Food, fodder, domestic fuelwood and poles, and site amelioration

These uses are grouped as they tend to be serviced by the same suite of taxa particularly in Africa, though these demands, particularly for fuelwood and fodder, extend well beyond that geographical region (Kull *et al.*, 2011). Systematic testing of Australian acacias began in dry areas of West Africa in the 1970s (Cossalter, 1987; Le Houerou, 2000). A key conclusion was that the value of a taxon in a rural community was much enhanced if it has multiple uses. Thomson *et al.* (1994) documented the attributes of 125 Australian tropical arid-zone acacias that have potential for multi-purpose use.

The seeds of some taxa demonstrating promise in arid zone Africa have long been a part of the traditional diet of Australia's Aboriginal people and this encouraged exploration of the potential of Australian acacias to contribute to food security in regions which experience chronic droughts and famine (House & Harwood, 1992). *Acacia colei*, *A. cowleana* and *A. tumida* were recommended as they had already demonstrated rapid growth and early production of seed crops in West Africa. They are now also used for wind breaks, firewood, building poles, mulch to build soil fertility and nitrogen fixation. A renewed effort to trial taxa and provenances of *A. torulosa, A. tumida* and *A. elachantha* for use in agro-forestry production systems began in Niger in 2002. An improved sustainable farming system called the farmer-managed agro-forestry farming system (FMAFS) was developed (Rinaudo & Cunningham, 2008; Cunningham, 2010), and thousands of hectares of degraded land are now being rehabilitated through Government and NGO partnerships. The principle method is to use banquettes (large U-shaped earth constructions) that reduce water runoff and capture soil/organic residues while allowing grasses/herbs to recover (animals are excluded), along with the planting of acacia trees (P. Cunningham, pers. comm.).

In Australia, a significant economic use of the foliage and green pods of acacias has been as stock fodder. Worldwidewattle.com lists 16 taxa as particularly useful for this purpose. Of those, seeds of *A. aneura*, *Acacia saligna*, *A. stenophylla* and *A. victoriae* have been exported on a significant scale (Table 1). In general, Australian acacias have relatively low nutritive value and/or digestibility, and their prime role is as a drought fodder reserve (Thomson *et al.*, 1994). The role of nine acacia taxa is being researched in Australia by the Future Farm Industries CRC as components of diverse fodder systems (D. Revell, pers. comm.).

Fuelwood: In the 1970s, an estimated 86% of all the wood consumed in developing countries was used for domestic fuel (Boland & Turnbull, 1981). A primary rationale for the ATSC Australian acacia R&D programme was to contribute to sustainable wood supply for this purpose. It is difficult to quantify the use of fuelwood but as rural populations lack the means to purchase other forms of energy, it is reasonable to use population growth trends as a surrogate. The UN estimates that the world's rural population in less developed countries grew from 2.4B in 1980 to 3.1B in 2010 and will stabilize at that level for the next decade (Population Division Department Economic and Social Affairs, United Nations Secretariat, 2007) For sub-Sahara Africa, where use of Australian acacias is being promoted strongly, rural populations almost doubled between 1980 and 2010, with modest growth still projected for 2010–20 (see Table S4).

Australian acacias were planted for control of drift sands in South Africa from the 1840s (Poynton, 2009) and in North Africa from the 1870s (Carruthers *et al.*, 2011) The ability of *A. saligna* to thrive on sands and soils of high pH in dry areas was well recognized and this remains the most important of all the multi-purpose taxa in north Africa (El Lakany, 1987). About 600,000 ha of this species are planted (Table 2).

Of the new generation of candidate taxa, *A. tumida* has excellent potential as a low wind break in sandy soils in tropical dry zones, reducing sand blast on neighbouring crops and stabilizing deep loose sands (Thomson, 1992). *A. ampliceps*, *A. maconochieana* and *A. stenophylla* are tolerant of highly alkaline and saline soils and have performed successfully on such soil types in Pakistan where they are used for fuelwood (Marcar *et al.*, 1995). The ability of acacias to fix nitrogen is a major reason for their success in improving degraded soils.

These uses contribute to human well-being in non-cash economies and indirectly through enhanced agricultural production within the stabilized ecosystems.

Fragrances, floristry and horticulture

Economically, these are relatively minor uses but they have a disproportionate effect on the number of Australian acacias taxa planted around the world because they are largely additional to ones used for wood production. Introduction of Australian acacias to the Cote d'Azur France began over 200 years ago. The flowers were used by the local perfume industry which still persists. Flowers of *A. dealbata* are collected from local invasive stands as well as imported from elsewhere in the Mediterranean and even India (Roland, 2006). The Grasse region produces 300–400 kg of absolute acacia perfume product worth around \$US1300 kg^{-1} (source http://www.perfume2000.com), around \$US0.5 M $year^{-1}$.

Acacias, particularly the *A. dealbata* × *A. baileyana* hybrid variety, are favoured in winter floral displays in Europe. The centre of production is the Alpes Maritimes Department of France, where over 100 ha of cultivated fields yield 550 t $year^{-1}$, worth about \$US3.5 M (Kull *et al.*, 2011). Ratnayake & Joyce (2010) review the attributes affecting use as ornamentals and propose some new acacia taxa which could be evaluated (see Table S5 for these and also cultivars reported from UK and Australia).

Data on the value of the nursery plant trade were unobtainable. Fashions change in the horticulture market, but the favourable attributes of acacia (mass winter flowering and attractive foliage and form) have survived the test of time, and it is reasonable to assume that the genus will retain if not expand its role as commercial garden and landscaping plants. If problems with post-harvest life can be solved, then international trade in cut product can be expected to increase (Ratnayake & Joyce, 2010).

Future trends

New species and varieties?

Although two-thirds of Australian acacias are still untested, we doubt that economically important taxa remain to be discovered. The taxa trialled were not a random sample, they were selected by people who were very knowledgeable about the genus. Furthermore, 'the market' as reflected by the dispatches from the ATSC (Table 1) rapidly focussed on a very small subset of taxa. Similarly, of over 700 species of eucalypt hundreds have been trialled, but only about 10 were eventually chosen for large-scale planting around the world (Eldridge *et al.*, 1994).

The domestication of the genus *Acacia* has barely begun and over time we can expect to see all the tools of plant breeding brought to bear at least for the major pulpwood species. Trees with improved growth rate, stem form and wood properties are already being planted in Indonesia and Vietnam. Many taxa are widely distributed (Table S1) and contain much natural genetic variation which can be used to increase site adaptation; for example, users in the dry tropics of Africa have pin pointed the need to find the optimal provenances for low rainfall planting sites (P. Cunningham, pers. comm.).

Eucalypt breeders have sought to expand the range of genetic diversity through inter-specific hybridization, while, discounting a few ornamental varieties, the only commercial acacia hybrid yet in use is *A. mangium* × *auriculiformis* (Kha, 2001). The floral biology of acacia makes controlled crossing very difficult (Griffin *et al.*, 2010), and this has discouraged hybrid breeding to date. However, step changes in phenotype via polyploidy is possible in some Australian acacias. Associated sterility might play a role in managing invasiveness. The gigantism, which is commonly associated with increases in ploidy, could also be beneficial for food taxa and even the paper industry (Wang & Cui, 2000).

Prognosis for pulp, solid wood and tan bark industries

Demand for paper products is increasing, particularly in China and India, and the expanding Indonesian pulp industry is part of a worldwide migration of production to lower-cost southern hemisphere locations. Wood is increasingly sourced from plantations rather than native forest (Barr, 2008) and the Green Carbon Fund set up under UN Convention on Climate Change, Cancun 2010, which specifically mentions Indonesia as a target for funded preservation of native forest, may provide further incentive to source wood from acacia plantations. Other grower countries in SE Asia will mainly continue to export chips rather than process. Parts of Central and South America seem suitable for large-scale plantations of tropical acacias but to date this has not occurred.

Acacia wood for making furniture in Vietnam comes increasingly from plantations begun in the 1990s (Kha, 2001). International markets are now well established, and cost-competitive production coupled with expanded planting of source certified (Williams, 2005) improved acacia seeds and clones should see continued expansion of this industry. Other acacia-growing countries cannot match Vietnamese efficiency, so a major regional expansion is unlikely except for local consumption.

Tannin production is a mature industry with more or less flat export trade over the past 20 years (Table S3) which has long persisted in competition with mineral and synthetic tannins (Searle, 1991)and seems likely to survive. Research continues into new bonding components manufactured from acacia bark (Baba *et al.*, 2003) and phenol-formaldehyde fortified tannin adhesives are already used in plywood manufacture. Future expansion of such by-product industries probably depends on increase in the price of oil-based industrial chemicals.

Prognosis for rural uses

Rural populations in many less-developed countries are still increasing (see Table S4) albeit at reduced rates because of

urbanization, and wood remains their primary energy source. Empirical evidence from the sub-Saharan NGO projects cited in this paper suggests that the multi-purpose Australian acacias can make a significant contribution at the regional level. Use of acacia seed for food in Niger has prompted interest in Ethiopia where large areas of *A. saligna* have been planted for site amelioration since the 1970s, and also in Myanmar (A.T. Rinaudo, unpublished data). As knowledge of provenance/site matching is enhanced, reducing risk of crop failure, we can expect the range of plantable sites in these regions to increase (Rinaudo & Cunningham, 2008).

New uses of Australian acacias?

The relatively minimal silvicultural input required to grow acacias makes them particularly suited for both energy and carbon capture, neither of which will be high-value markets for growers. Foelkel (2008) noted that *A. mearnsii* presents some important advantages as it contains lower moisture at felling, dries faster and it has higher wood basic density than many fast-growing eucalypts. The possibilities of using invasive populations of *A. mearnsii* and *A. dealbata* as fuel are surely worth exploring. In general, biomass energy will be most valuable for small-scale local utilization in areas lacking service from a national grid; that is, countries that do not have good resources of fossil fuels or access to hydro generation; lack good power distribution infra-structure; and have widely distributed rural populations with few financial resources for increasingly expensive mains power supply. Island populations currently serviced by diesel generators are one obvious target.

Australian acacias could play a role in carbon sequestration plantings, but scale and location of development is unpredictable as they are entirely dependent on national and international policy decisions which encourage investment. The World Bank Carbon Finance Unit already supports Acacia projects in Mali, though currently planting the slower-growing native *A. senegal* rather than introduced Australian taxa. The high rate of carbon fixation of acacias must be offset against their comparatively short life span, so plantings would need to be in the context of a sustainably harvested system.

The problem of invasiveness

At least 23 Australian *Acacia* species are known to spread from plantings sites in areas well outside their natural ranges (Richardson & Rejmánek, 2011), and in some cases, these species have important negative impacts in invaded ecosystems (Le Maitre *et al.*, 2011). Strategies for managing the unwanted spread of Australian acacias are addressed by Wilson *et al.* (2011).

While ATSC has been fully compliant with import permits, and CSIRO now scrutinizes domestication projects for the weed risk posed in the specific test environments, for Australian acacias the time is long past when restriction on export from the native range alone will be effective in limiting invasiveness. Given that some of the widespread plantings reviewed in this paper are very recent (last 30 years), and as there is usually a substantial lag phase between plantings and the start of widespread invasions (e.g., Wilson *et al.*, 2007), further invasions are probably inevitable. Invasive success of Australian acacias is closely tied with propagule pressure and the extent of use and dissemination (Castro-Díez *et al.*, 2011). Consequently, those species most widely disseminated (e.g. those in Table 1), many of which are not yet known to be invasive, might be so in the future. It would be prudent to consider these issues when formulating overall national and regional management strategies. A cost : benefit approach (van Wilgen *et al.*, 2011) could assist objective decision making. Large forestry companies, particularly those seeking certification by the Forest Stewardship Council, generally acknowledge environmental responsibilities and should consider options for reducing the risk of invasion without compromising commercial production, e.g. through the use of sterile varieties and the introduction of reproductive feeding biological control agents (Wilson *et al.*, 2011). Managing weediness can benefit plantation growers as well as the wider environment, and constructive engagement may well produce sustainable solutions (van Wilgen *et al.*, 2011).

CONCLUSIONS

Over the past 30 years, the ATSC has played a major role in the global dissemination of Australian acacias, but regional demand for commercial seeds is now largely met from previous successful introductions. Wild germplasm for breeding is still sourced from Australia..

For ease of access, we summarize key statistics for all usage groups in Table 3. Of these, only tannin production and perhaps horticulture have plateaued. Demand for pulp and solid wood products is increasing in the developing world, met in part by wood of Australian acacias. Multi-purpose acacias are important for the well-being of rural populations in the tropics and sub-tropics, contributing to the interdependent goals of wood and food security. Climate change and human population growth will increasingly dictate that marginal and degraded land is made productive and acacias have proven utility on such sites. The domestication of acacias is only just beginning, and both productivity and site adaptation will increase with more extensive testing and breeding.

Given the wide range of economic uses well established in diverse environments, it seems unlikely that weediness can be managed by exclusion. Large growers are increasingly acknowledging their responsibilities and should be encouraged to engage constructively with environmental concerns. It is hoped that our attempts to put $ values on the various acacia products will assist cost benefit analyses of this difficult issue.

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Table 3 Summary statistics for different usages of Australian acacias showing major species and grower countries. Note that many species can be used for more than one purpose.

Use	Current total area planted (K ha)	Annual production	Annual value of industry (USD Million)	Main producer countries	Main *Acacia* taxa (listed in order of importance)	Status and future trends
Pulp for papermaking	2000	3.3 M Adt pulp	2700	Indonesia, Vietnam,	*A. mangium; A. mangium* × *A. auriculiformis; A. crassicarpa*	Expected to increase in SE Asia to meet world demand for paper
Wood chips for pulping (internationally traded)	Included in pulpwood + tan bark area estimate	3.5 M Bdt chips	500	Vietnam, South Africa, Brazil	*A. mangium; A. mangium* × *A. auriculiformis; A. mearnsii*	Exported product mainly to E. Asia. Excludes internal use for pulp production
Solid wood products for export	120 of *A. auriculiformis* + part of pulpwood area		600	Vietnam	*A. mangium; A. mangium* × *A. auriculiformis; A. auriculiformis*	Increasing manufacture for domestic use throughout SE Asia
Tannin Production	540	0.67 Mt Tannin extract. (export only)	80 (export only)	Brazil, South Africa	*A. mearnsii*	Large historical production declined to stable level over past 20 years. Continues despite competition with mineral and synthetic tannins
Food, fodder, poles and domestic fuelwood	Unknown but significant	?	?	Areas with chronic droughts and famine in Africa and Asia	Many	Fuelwood will remain primary energy source in such regions. Demand will mirror population
Site amelioration	600+	NA	?	Areas with degraded or unstable soil (north and sub-Saharan Africa, Myanmar, Pakistan)	*A. saligna; A. torulosa; A. tumida; A. ampliceps. A stenophylla*	Inclusion in new agroforestry management systems could increase use
Fragrances	Harvested from weedy trees	300–400 kg absolute perfume	0.5	France	*A.dealbata*	Small but stable industry
Flowers	0.1	550 t	3.5	France (Alpes Maritime Dept.)	*A. dealbata* × *A. baileyana*	Small but stable industry unless fashions change
Horticulture	?	?	?	Developed countries	Many	Continuing interest, many new taxa could be trialled and cultivars bred
Carbon sequestration	?	?	?	Developing countries	All fast growing taxa adapted to local environments	Could increase if policy settings favourable
Biomass energy	?	?	?	Developing countries	All fast growing taxa adapted to local environments	Could increase if policy settings favourable. Taxa well suited to short rotation harvest on poor sites

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1 Summary of all seedlot orders for Australian acacias dispatched from the Australian Tree Seed Centre between 1980 and 2010 by geographical regions.

Table S2 Countries within regions which received at least 1 seed order from the Australian Tree Seed Centre.

Table S3 International trade in tannin extract from *Acacia mearnsii* in 2009 and production over time from the two major producers (South Africa and Brazil).

Table S4 World Trends for Rural Populations 1980–2020.

Table S5 Some named Australian and UK ornamental cultivars of acacia species.

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BIOSKETCHES

A.R. Griffin led the writing of this paper. He has a long research career in forest genetics and breeding with a focus on eucalypts and acacias. He has published widely and has co-authored a book on Sexual Reproduction of Tree Crops. Following retirement as Director of the Forestry CRC in Hobart Australia, he holds an honorary position with U. Tasmania and also manages his own international consulting business. Current interests include polyploid breeding to improve tropical acacias.

S.J. Midgley, a past Head of the ATSC, helped structure the paper and contributed essential information on the economic benefits; D.B. interrogated the CSIRO databases and prepared the dissemination data; T.R. and P.C. are actively involved in using Australian acacias for the benefit of rural poor, particularly in sub-Saharan Africa, and contributed information on those uses.

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