

Australian Forestry

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This issue

This issue of *Australian Forestry* presents the sixth paper in the series titled 'Achievements in the genetic improvement of forest trees in Australia and New Zealand', which was introduced in the last issue.

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Cover

The front cover features African mahogany, *Khaya senegalensis*. This is a promising plantation tree for northern Australia, tolerant of difficult sites and producing a high-value timber. The story behind the recognition of its promise, and work to realise its potential, are described by Garth Nikles on pages 68–69 of Volume 69 of *Australian Forestry*. He also selected the photos and prepared the captions.

Photo 1. Butt logs (mainly), from selected trees in 32-y-old, unmanaged stands of African mahogany grown in the Darwin region of the Northern Territory (NT). They were used in a study of sawn timber recovery, timber drying schedules and wood properties, and for manufacturers' evaluations of the timber. (Photo by courtesy of Don Reilly.)

Photo 2. Award-winning set of chess table and chairs made from timber from a sample of the logs of Photo 1. It won three 'Australian Furniture of the Year Awards, 2004' sponsored by the Furniture Industry Association of Australia: the Queensland and national awards in the category 'Excellence in furniture using Australian plantation timber'; and the Queensland 'Best-of-the-best' (across categories) award. (Photo by courtesy of Ray Burgess, Sight Photographics, via the manufacturer, Paragon Furniture, Brisbane.)

Photo 3. A rooted cutting of African mahogany at 10 mo from planting in a clone test established in the Darwin region of the NT in January 2005. At 12 mo from planting, some trees were nearly 3.5 m high. (Photo by courtesy of Beau Robertson.)

Photo 4. Pods on a graft of African mahogany in a clonal seed orchard planted near Darwin in December 2001. The pods are about 35 mm in diameter some 3 mo after flowering. (Photo by courtesy of Beau Robertson.)

Photo 5. Part of an unmanaged stand of African mahogany aged 25 y derived from natural-stand seed. It was established on back-filled land following surface mining for bauxite at Weipa, Queensland. The central, dominant tree is 48 cm dbhob and one of 36 superior trees selected so far and used in the conservation and genetic improvement program at Weipa. (Photo by courtesy of Alan Bragg.)

Photo 6. A pruned, 8-y-old stand of African mahogany, derived from unimproved seed, planted privately at 5 m × 2.5 m (800 trees ha⁻¹), not thinned, near Bowen, in coastal central Queensland. The tree being measured had a dbhob of 17.1 cm. (Photo by courtesy of Geoff Dickinson.)



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Guest editorial

Collaboration between the Australian and New Zealand Institutes of Foresters

The ANZIF Conference held in June 2007 marked some 27 years since the first such conference involving collaboration between the Institute of Foresters of Australia (IFA) and the New Zealand Institute of Forestry (NZIF). Closer collaboration to help underpin the scientific basis of forestry, policy directions and standards of forest management within our region has been discussed by the membership and boards of the institutes. What has been achieved to date and what directions should future trans-Tasman collaboration take?

The first ANZIF Conference was held at Rotorua in 1980, with enthusiastic collaboration between Wink Sutton of the New Zealand Institute of Forestry (NZIF) and me. We shared the view, as did our respective institute governing boards, that our two economies would become increasingly integrated and that we had much to learn from each other in relation to forestry. Subsequent meetings were held in Hobart in 1985, Christchurch in 1991, Canberra in 1997 and Queenstown in 2003, with Coffs Harbour the location in June 2007. The increasing frequency perhaps reflects an increasing awareness of the interwoven environment in which the institutes now operate.

If the published reports and personal memories of these meetings are any guide, they were professionally useful and convivial. They were not, of course, the only source of interchange between members of the two institutes, thanks in part to the decline of real (i.e. deflated) costs of air travel between the two countries. But ANZIF is distinctive in embracing all elements of forestry¹ in membership and attendance, rather than involving a highly specialised audience or single topic. Both institutes are rightly proud of their orientation towards the professional practice of forest management and the forest science to guide it, without being precious or exclusive about that orientation.

Many changes have occurred in forestry and other interchanges between the two countries over this period. The extent of trans-Tasman changes of employment of members and potential members has grown as privatisation, commercialisation and formal collaborations have proceeded. The 2003 conference coincided with the 20th anniversary of Closer Economic Relations between the two countries — a relationship that has resulted 'in unprecedented integration' between the two economies according to the Director-General of the New Zealand Ministry for Agriculture and Forestry². Industrial

plantation and forest industry ownership now reflects that integration, as well as the growing trends in globalisation. The respective national institutes of forest research are collaborating through a partnership under the Ensis flag. Through that and other collaborative arrangements, regular interchanges exist in tree breeding, forest and timber disease and pest issues, valuation, fire protection and other areas. The Primary Industries Ministerial Council and Natural Resource Management Ministerial Council include New Zealand representation and have replaced the earlier Australian Forestry Council.

Understandably, both institutes have been somewhat passive towards these changes because most have been beyond the reach of their influence. The aftermath of the 2007 ANZIF Conference provides a timely opportunity to review the relationship between the institutes and to chart some future strategies in the light of further changes of similar character in the future. Three questions loom large in addressing these changes:

1. Would a strengthened and/or more formal relationship help the respective institutes to meet their aims and objectives?
2. Would a strengthened and/or more formal relationship provide better services and/or lower costs to members?
3. What form should such a relationship or structure take and should it be restricted to the two nations?

Effectiveness

Most of the policy issues of concern to the respective institutes relate to specific state and national concerns, so these are not primarily the basis for a strengthened relationship. Some issues, such as illegal logging, forest practices in neighbouring countries, international trade and marketing, poverty alleviation and climate change are of mutual concern. It might heighten the public standing of both institutes if they could speak with a common voice on these matters. Certification seems likely to become much more common within both countries and in our near neighbours. This raises issues concerning mutual recognition of registration (Registered Professional Forester (RPF) and Registered Forestry Consultant (RFC)) schemes, national plantation standards, valuers and certifiers, and mutual offerings for professional development, both in relation to plantations in the two countries and more generally in the South Pacific and Asian regions.

Regrettably, the history of mutual recognition of standards for timber grading suggests that mutual policy goals are not always simple to achieve, as witness the recent advent of different standards in the two countries. However, recognition and acceptance of irreconcilable differences is as essential to effectiveness of an integrating entity as adopting common ground, as the Australian history of differences between the IFA's state divisions has shown from time to time.

¹ 'Forestry', according to the IFA website, is 'the practical application of scientific, economic and social principles to the establishment and management of ecosystems dominated by trees, or at least where trees are major components of an ecosystem'. The NZIF website defines it as 'the art and science of managing forests so as to secure a wide range of environmental and socio-economic benefits'. Users of MS Word[®] software (and the institute boards) may wish to contrast these definitions with those in the Word[®] dictionary which collectively limit the scope greatly.

² See Stephen Jacobi (2003) ANZIF — Seeing the woods through the weeds. *New Zealand Journal of Forestry* 48(2), 2–3, http://www.nzjf.org/contents.php?volume_issue=j48_2

Efficiency

Efficiencies, be they in lower costs, better services, or both, loom large in any consideration of the future of two relatively small institutes. The IFA currently has about 1240 members, NZIF 750. Some growth in membership is likely to follow from the harvesting and marketing of the increased potential supply of wood over the next two decades, together with (hopefully) some increase in fire management and farm forestry roles. That growth is unlikely to be dramatic, being limited by the economies of scale we are now seeing materialise. The combined number, though still relatively small, offers scope to explore and develop efficiencies in administration, communication and registration, so there is a pressing need to look for cost savings and/or service improvements within current costs.

Administration is in some ways the most difficult area of change because the two Institutes have somewhat different systems and annual charges at present. The IFA has a full-time Executive Director and Member Services Manager, and the NZIF only a part-time administrator. Consequently annual IFA membership fees are almost twice those of the NZIF for voting members. Both use extensive voluntary and quasi-voluntary support (via honoraria) for editing, and in the case of the NZIF for Board Secretary work. A detailed investigation would be appropriate because there are potential economies of scale and scope involved. Location of the administration should not matter much in an era of increasing reliance on electronic communication, especially if the head of any joint body or arrangement rotated between the countries, assisted by each president.

Communication is an area most likely to undergo radical change over the next decade or two. Older members may lament it but purely newsletter-type publications will be replaced by internet newsletters, as witness the uptake and success of the *Friday Offcuts*, published by Innovatek Ltd in partnership with the Australian Plantation Products and Paper Industry Council (A3P), Ensis, and others.

The scientific publications of both institutes are available on the web but unfortunately they are not indexed by the leading global abstracting services and will therefore be ignored by the scientific community. This indexing has become essential in the scientific world³ and, in my view, dooms both journals to the scrap heap of history, unless changed. Efficiencies are also needed with respect to editing, which I suspect has outstripped or will soon outstrip volunteer or quasi-volunteer efforts. A merger would provide scale for two publications (one scientific and one professional) to replace the present four, greater attractiveness to libraries, greater administrative assistance to the editorial panels, and a better opportunity to bear the costs involved.

As noted earlier, registration is an area likely to increase substantially over the next decade or two, in line with the earlier observations regarding certification and illegal logging and poor forest practices in neighbouring countries. Privatisation and commercialisation in combination with certification and an increasingly litigious world will also push this along. The two

systems of the institutes differ, but not so radically that common ground could not be found. That common ground might also assist employment interchanges and opportunities across the Tasman because the two economies are seldom exactly synchronised. The annual NZIF charges for registration on a continuing basis appear to be higher than those of the IFA.

Structure

If there is a role for greater integration between the IFA and NZIF, what form should it take? The devil is in the detail, and the preceding sections have charted some of the detail that needs to be worked through jointly before seizing on some grand plan. Greater integration need not imply a merger, although in my view that might well be a long-term (10-year) goal if my concerns about the future membership, financial viability, communication and employment trends are shared. There are many potential intermediate steps, especially in communication and administration, that would assist in strengthening the bridges between the two institutes. Such moves could be managed by a joint not-for-profit company with a board consisting of a chair and the two presidents overseeing joint administration services operating under supply contracts to the parent institutes.

Nothing would dissuade each side more quickly and absolutely than to propose a take-over of one institute by the other. Maintaining national identities and regional structures is therefore a paramount consideration in any discussion of greater integration. That means the governing bodies and their key committees would need to operate on a federal system, with an agreed hierarchy of powers, especially in relation to policies and practices that are often inherently national or regional in character.

If, in the long run, a merger was to be contemplated, thought might also be given to our near-neighbours and their involvement, building on the IFA board's recent initiative in launching the Tropical Forest Interest Group. Clearly, that would be a second-order issue until the trans-Tasman house is in order. But many of the arguments extend to our near neighbours with even greater force because of their stage of development. Extension to a South Pacific entity would obviously need support and funding from our two governments and/or aid agencies.

Conclusion

If the Australian and New Zealand memberships and their respective boards share any of the concerns expressed above, the two institutes need to chart some strategies to investigate the issues prior to the next ANZIF conference, so that joint action might then be considered and set in motion. This requires a lot of detailed work by small joint committees based on clear terms of reference and reporting requirements, with some champions to drive them along. This may seem like an old fart's 'hasten slowly' dictum, but is as much a case of 'hasten surely' — there is much at stake; not least, survival of the institutes.

Ian Ferguson FIFA

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The University of Melbourne*

³ See Alan Brown (2006) Visited a library lately? *The Forester* 49(4), 26.

Achievements in forest tree improvement in Australia and New Zealand

6: Genetic improvement and conservation of *Araucaria cunninghamii* in Queensland

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Summary

Araucaria cunninghamii (hoop pine) typically occurs as an emergent tree over subtropical and tropical rainforests, in a discontinuous distribution that extends from West Irian Jaya at about 0°30'S, through the highlands of Indonesian New Guinea and Papua New Guinea, along the east coast of Australia from 11°39'S in Queensland to 30°35'S in northern New South Wales. Plantations established in Queensland since the 1920s now total about 44 000 ha, and constitute the primary source for the continuing supply of hoop pine quality timber and pulpwood, with a sustainable harvest exceeding 440 000 m³ y⁻¹. Establishment of these managed plantations allowed logging of all native forests of *Araucaria* species (hoop pine and bunya pine, *A. bidwillii*) on state-owned lands to cease in the late 1980s, and the preservation of large areas of araucarian forest types within a system of state-owned and managed reserves.

The successful plantation program with this species has been strongly supported by genetic improvement activities since the late 1940s — through knowledge of provenance variation and reproductive biology, the provision of reliable sources of improved seed, and the capture of substantial genetic gains in traits of economic importance (for example growth, stem straightness, internode length and spiral grain). As such, hoop pine is one of the few tropical tree species that, for more than half a century, has been the subject of continuous genetic improvement. The history of commercialisation and genetic improvement of hoop pine provides an excellent example of the dual economic and conservation benefits that may be obtained in tropical tree species through the integration of gene conservation and genetic improvement with commercial plantation development. This paper outlines the natural distribution and reproductive biology of hoop pine, describes the major achievements of the genetic improvement program in Queensland over the past 50+ y, summarises current understanding of the genetic variation and control of key selection traits, and outlines the means by which genetic diversity in the species is being conserved.

Keywords: provenance; variation; conservation; reproductive traits; genetic improvement; breeding programs; hoop pine; *Araucaria cunninghamii*; Queensland

Introduction

Mature trees of *Araucaria cunninghamii* Aiton ex A.Cunn. (hoop pine) in natural stands can reach 2 m in diameter and more than 60 m in height. The timber is firm, strong and finely textured (Swain 1928), and has been used for a variety of applications from flooring, framing, cladding, panelling, plywood, veneers and furniture through to taint-free food sticks, pulpwood and match splints. In the past, all of the timber of *Araucaria* species (hoop pine and bunya pine, *A. bidwillii* Hook.) was derived from natural stands, with a maximum of 146 million super feet Hoppus (equivalent to 439 000 m³) harvested from crown lands in Queensland during 1940–1941 (Anon. 2003). Today, *Araucaria* timber production in Queensland is almost exclusively from state-owned plantations, with nearly 450 000 m³ of predominantly hoop pine logs being harvested in 2004–2005 (Anon. 2005). Plantations are now producing larger volumes of hoop pine annually than were ever harvested from natural stands in a single year.

The history of the use and conservation of hoop pine, and the subtropical (mainly rainforest) communities dominated by this species, extends back for over 150 y. By the early 1900s it was recognised that the rate of cutting of *Araucaria* species from the native forests was not sustainable, and plans were made to establish plantations as a renewable source of *Araucaria* timber (Grenning 1925). By the 1920s plantation establishment had commenced at two major locations in south-eastern Queensland (Imbil and Yarraman, Fig. 1) on sites that previously carried hoop pine as part of the native forest. The current plantation area of hoop pine in Queensland is 44 000 ha, mostly in south-eastern Queensland on state-owned lands but including small areas on privately owned lands. Small areas have been established in northern New South Wales (NSW) (914 ha remained in 2005 — Parsons *et al.* 2006). Beginning in 1949–1950, about 3500 ha of plantations were established in the Bulolo–Wau region of Papua New Guinea (Wylie 1982; refer Fig. 2). At least three small plantations were established in the Kebar Valley of West Irian Jaya (Fig. 2) in the 1960s (Kapisa 2002).

Sustained research for genetic improvement of hoop pine commenced in Queensland in the late 1940s with studies on

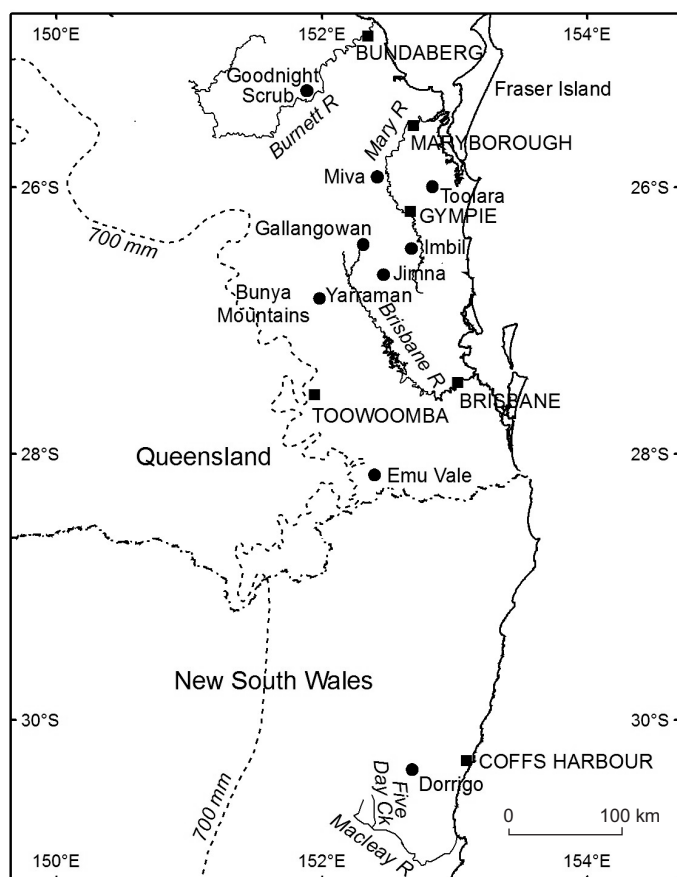


Figure 1. The location (●) of some provenance tests (Imbil, Yarraman) and provenance seed collections of *Araucaria cunninghamii* in south-eastern Queensland and northern New South Wales, and of grafted seed orchards (Imbil, Yarraman and Toolara)

reproductive biology and means to control crossing (Nikles *et al.* 1988). Later, many thousands of hectares of plantations were searched for superior trees, resulting in >200 000 trees being planted in progeny tests since the 1950s and the establishment of many clonal seed orchards since 1965. All new plantations since 1985 have been established with stock from orchard seed, yielding large genetic gains. Technologies have been developed for operational controlled crossing — enabling family forestry to be implemented through seedlings of superior families — and for vegetative propagation via stem cuttings, though the latter is not currently in use. Provenance variation, provenance hybridisation and genetic parameters of the species have also been studied. These achievements, background information and the conservation status of hoop pine are outlined in this paper.

Natural distribution

Hoop pine typically occurs naturally as an emergent in many rainforests and some woodlands and shrublands from the Sausapor region of West Irian Jaya (Indonesia, 0°30'S) through Indonesian New Guinea and Papua New Guinea (PNG), and along the eastern coast of Queensland from Captain Billy Creek (11°39'S) to the upper reaches of the Macleay River in northern NSW (30°35'S; refer Figs 1, 2 and 3). However, it is naturally most abundant in south-eastern Queensland and northern NSW within 300 km of Brisbane (Fig. 3) and the Telefomin–Oksapmin,

Mts Suckling and Dayman, and Bulolo–Wau regions of PNG (Gray 1973, Fig. 2).

The distribution is highly disjunct and encompasses diverse environmental types. Soils range from Rudosols to Ferrosols (McKenzie *et al.* 2004) developed on a broad suite of parent materials including sands, igneous and metamorphic rocks; mean annual rainfall varies from 750–1600 mm in Australia to 1600 to >5800 mm in PNG; and altitude extends from sea level to 1000 m in Australia and 500–2800 m in PNG (Howcroft 1978; Boland *et al.* 1985). The species occurs in six of the Queensland bioregions defined by Sattler and Williams (1999) (Fig. 3) and in five forest types in NSW (refer to subsequent section on 'Conservation of genetic resources'). However, the species is sensitive to fire and severe frost, being limited to sites where the mean temperature in the coldest month is >2°C (Jovanovic and Booth 2002).

Reproductive biology

A brief account of some key aspects of the reproductive biology of hoop pine is provided here; Nikles *et al.* (in press) give more detail. As is common in many coniferous species, hoop pine is monoecious (cones of both sexes occur on the one tree), unisexual (the female and male cones are separate) and is predominantly a cross-pollinated (that is, outcrossing) species. However, a number of unusual features of the reproductive biology and growth habits of hoop pine have affected the genetic improvement program. Some of these features and how they have been accommodated are outlined below.

Normally, planted trees do not produce substantial pollen crops until some 25 y of age, but female cones are produced from around age 12 y, and relatively regularly. No reliable means has been found to close the age gap between male and female reproduction, so mixed-generation mating has been adopted in the breeding program to reduce the length of breeding cycles.

Provenances differ by several months in their periods of anthesis. For example, in some provenances anthesis occurs as early as December and January while in others anthesis is delayed until April–June. Such provenances are reproductively isolated. This means that seed orchards can be effectively isolated from contaminating pollen if located within plantations of hoop pine that have been established using planting stock of a different anthesis period. Similarly, the long time-lag between planting and production of pollen has potential advantages for the isolation of seed orchards. If seed orchards are established in the midst of young plantations, the delay in the onset of male flowering in the latter provides a window of up to 25 y when there is effective isolation from contaminant pollen. As a consequence of these two features, seed orchards need not be established on sites isolated from the main plantation program, which in turn makes their maintenance and protection much easier.

Hoop pine has fixed shoot systems. Thus a shoot, once differentiated as a lateral shoot, always remains as a branch or branchlet (of plagiotropic habit); shoots emanating, under certain conditions, from leaf axils between branch whorls on the main stem, however, take on and retain an upright, tree-like, i.e. orthotropic, habit. Consequently, if lateral shoots are grafted onto seedling rootstock, trees with a plagiotropic (branch-like) form

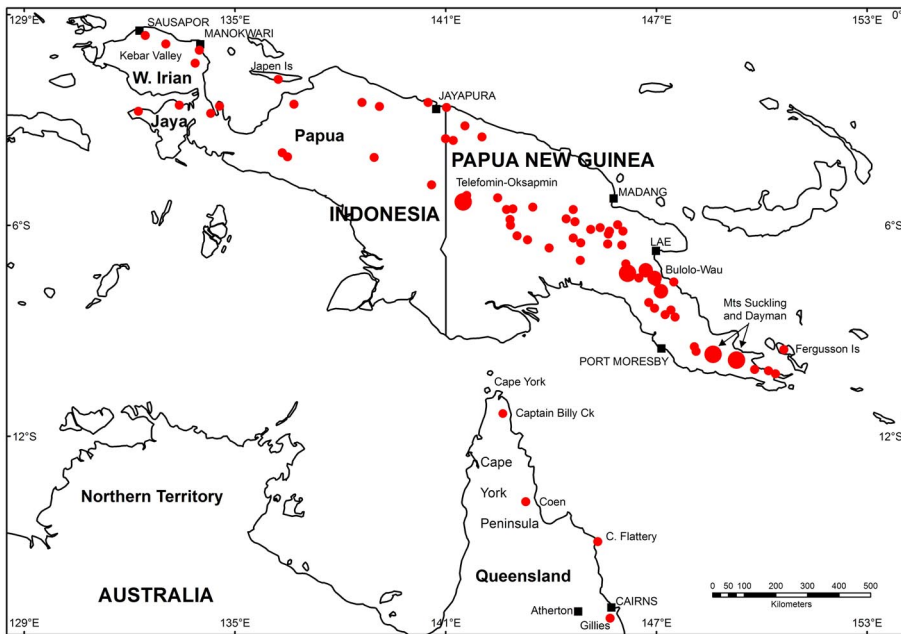


Figure 2. The approximate distribution of *Araucaria cunninghamii* in New Guinea showing the three regions of most widespread occurrence in Papua New Guinea (Telefomin–Oksapmin, Bulolo–Wau and Mts Suckling and Dayman) and four occurrences (of many) in eastern Cape York Peninsula, Queensland, mentioned in the text. Map compiled from data on occurrences of the species given by Gray (1973) and Howcroft (1978).

result. This type of plagiotropic graft, if made using branch tips taken from the pollen-bearing portion of the crown on a sexually mature tree, will produce pollen within a few years of grafting.

Grafts with an orthotropic growth habit are produced for clone banks and seed orchards by grafting scions excised from a short length (40–50 mm) of leading shoot taken from the main stem of trees older than 12 y. Each orthotropic scion comprises a few leaves and tissue as deep as the outer xylem in order to include axillary meristems (Burrows 1987). These orthotropic grafts tend to produce female strobili within 2 y of grafting, but little pollen for up to 10–15 y after grafting.

The differential flowering patterns in plagiotropic and orthotropic grafts is thought to be related to the position in the crown from which the grafting material is obtained. Mature hoop pine trees tend to produce female reproductive structures in only the upper part of the crown and pollen in only the central part of the crown; this is thought to be an adaptation to minimise self-pollination.

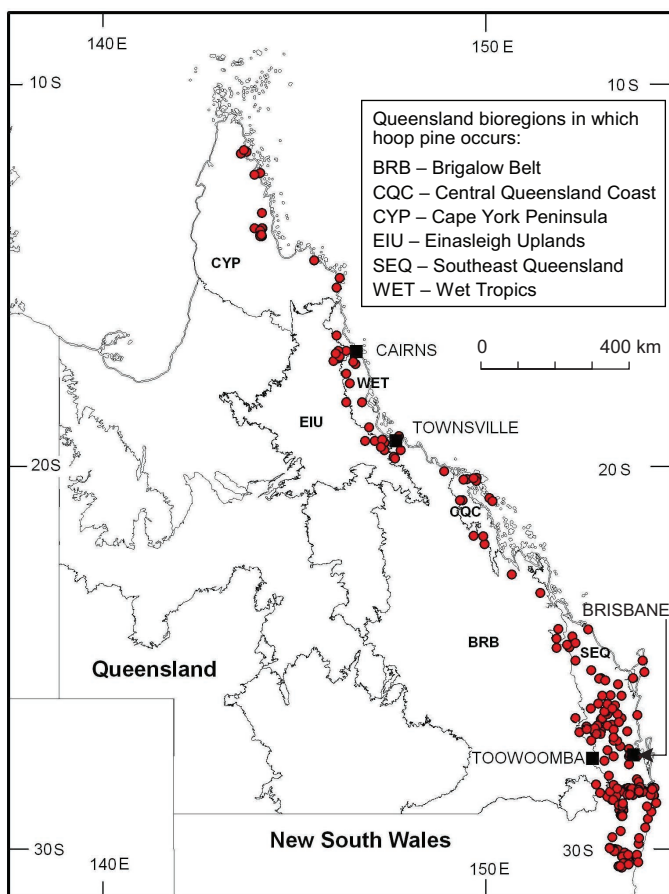


Figure 3. The approximate natural distribution of *Araucaria cunninghamii* in Australia. (Adapted from Jovanovic and Booth (2002) by T. Jovanovic in 2007 for this paper.) The identified bioregions in which the species occurs are those in Queensland (Sattler and Williams 1999).

Viable seeds can be quickly produced from a clonal hoop pine seed orchard established with a mixture both plagiotropic and orthotropic grafts. The plagiotropic grafts provide the main source of pollen in the earlier life of the orchard, and the orthotropic grafts act as the seed parents. As the orchard ages, the orthotropic grafts increasingly supplement pollen production as well as producing increasing amounts of seed. Cooler, drier sites have been found to be the most suitable for seed production; new orchards established on these sites have produced reasonable quantities of viable seed within 5 y of field-grafting. This is one example of how the fixed shoot systems in hoop pine have been used to assist the development of genetically improved seed supplies.

Mature trees will produce juvenile coppice when felled or girdled — thus clonal propagation strategies similar to those used effectively in tropical eucalypts could potentially be used in hoop pine. However, as a consequence of the fixed shoot systems and strong apical dominance in hoop pine, this species cannot be hedged efficiently, and multiplication rates using cuttings or tissue culture are very low compared to those possible with many *Pinus* and *Eucalyptus* species. Consequently, although juvenile shoots (obtained from coppice shoots or seedlings) can be propagated readily by the rooting of cuttings, vegetative propagation of planting stock using cuttings has not been cost effective.

Genetic variation

Provenance variation

Provenance trials planted in south-eastern and northern Queensland between 1929 and 1956 were reviewed by Reilly

(1974). Most of the provenances included in these trials were from areas in south-eastern Queensland, but a few trials also included some PNG and NSW (Dorrigo; Fig. 1) provenances. The most promising provenances for growth and stem straightness were from Jimna, Emu Vale and Gallangowan (Fig. 1).

The results were subsequently confirmed by a more comprehensive series of trials established between 1971 and 1973 throughout Queensland and northern NSW (Nikles and Newton 1983). These trials included more than 400 open-pollinated families from about 40 provenances. Based on stem volume at 20 y and stem straightness at 15 y (unpublished data), the most promising provenances on sites in south-eastern Queensland were those from Goodnight Scrub, Jimna, Miva and Yarraman (Fig. 1). This information was used to modify the breeding strategy (see 'Breeding strategy' below).

Genetic parameters

Estimates of genetic parameters for key selection traits in hoop pine have been published by a number of authors, including Dean *et al.* (1988), Dieters *et al.* (1990), Eisemann *et al.* (1990) and Harding and Woolaston (1991). Estimates obtained from a review of over 20 control- and open-pollinated progeny tests (unpublished results, Table 1) indicate that growth traits and straightness have low but useful heritability, while the heritability of internode length is much higher. Importantly, the genetic correlations between these traits are either favourable or close to zero, so there is considerable scope for the concurrent genetic improvement in growth, stem straightness and internode length.

Studies by Eisemann *et al.* (1990) and Harding and Woolaston (1991) indicate that spiral grain angle maximises at around 8 y

of age in hoop pine, is under a moderate level of genetic control, and is either uncorrelated or favourably genetically correlated with stem straightness, internode length and growth traits. Funding supplied by the Forest and Wood Products Research and Development Corporation allowed examination of the genetic control of spiral grain as assessed in bark windows (Harris 1984; Sorensson *et al.* 1997; Kain 2003) and of its relationship with other key selection traits (Table 2). Results from this study indicate that spiral grain as assessed using bark windows is under a moderate level of genetic control, and consequently selection should lead to rapid reductions in grain angle, thereby reducing the severity of distortion in sawn timber. The results also indicate a favourable association between spiral grain and stem straightness, but unfortunately adverse genetic associations between spiral grain angle and both growth traits and internode length. These results contrast with earlier findings (*op. cit.*) based on 12 mm bark-to-bark cores taken from a much smaller number of trees, and indicate that joint improvement in all four traits will be difficult. Follow-up studies are being conducted to confirm the direction and strength of additive genetic correlations between spiral grain and the other key selection traits (growth, internode length and stem straightness).

Genetic improvement

Production of genetically improved seed

The first practical steps towards providing a source of genetically improved seed began in 1955 with the establishment of seed production areas (SPAs) by heavily thinning selected areas of the plantation estate. With the exception of 1976–1977, the SPAs

Table 1. Average heritability estimates (bold, on diagonal), genetic correlations (above diagonal) and phenotypic correlations (below diagonal) from multivariate analyses of individual progeny tests of *Araucaria cunninghamii*. The age at measurement is indicated in parentheses.

| Trait | Height (4 y) | Height (8 y) | Diameter (8 y) | Diameter (12 y) | Straightness (8 y) | Internode length (8 y) |
|------------------------|--------------|--------------|----------------|-----------------|--------------------|------------------------|
| Height (4 y) | 0.20 | 0.86 | 0.79 | 0.69 | 0.23 | 0.25 |
| Height (8 y) | 0.82 | 0.21 | 0.83 | 0.58 | 0.06 | 0.43 |
| Diameter (8 y) | 0.82 | 0.65 | 0.22 | 0.93 | 0.24 | 0.21 |
| Diameter (12 y) | 0.73 | 0.70 | 0.87 | 0.25 | 0.11 | 0.26 |
| Straightness (8 y) | 0.14 | 0.17 | 0.16 | 0.21 | 0.19 | -0.05 |
| Internode length (8 y) | 0.31 | 0.43 | 0.27 | 0.29 | 0.04 | 0.48 |

Table 2. Heritability and correlations (and standard errors) of spiral grain (assessed in bark-windows), height, volume under bark, stem straightness and internode length assessed at 8 y of age in three trials of *Araucaria cunninghamii* grown in south-eastern Queensland (Ex728TBS). Heritability is on the diagonal (bold), genetic correlations above the diagonal and phenotypic correlations below the diagonal.

| Trait | Height (se) | Volume (se) | Straightness (se) | Internode length (se) | Spiral grain (se) |
|------------------|--------------------|--------------------|--------------------|-----------------------|--------------------|
| Height | 0.31 (0.08) | 0.88 (0.06) | 0.10 (0.25) | 0.37 (0.18) | 0.44 (0.19) |
| Volume | 0.89 (0.01) | 0.25 (0.07) | 0.24 (0.25) | 0.20 (0.21) | 0.41 (0.20) |
| Straightness | 0.15 (0.04) | 0.17 (0.04) | 0.13 (0.05) | 0.11 (0.23) | -0.28 (0.26) |
| Internode length | 0.38 (0.04) | 0.25 (0.04) | 0.06 (0.04) | 0.36 (0.09) | 0.35 (0.19) |
| Spiral grain | 0.12 (0.05) | 0.18 (0.05) | -0.01 (0.05) | 0.06 (0.05) | 0.30 (0.09) |

contributed only relatively small amounts of seed of high viability, although being old enough to produce pollen. In 1976/1977 collection season a total of 2023 kg of seed with a mean viability of 41% was harvested from the SPAs, which represented 40% of the total seed collection in that season when the total seed harvest was well below average (Gould 1979). Plantation 'crop trees' selected at a rate of one in five for high pruning became a significant source of seed during the run-down in the availability of seed from natural stands from the 1960s until supplies of orchard seed became adequate in the early 1980s.

The first major phase in the selection of phenotypically superior trees commenced in 1957 in the plantations of south-eastern Queensland. The selected trees were assigned to one of three categories (seed orchard, breeding, or other seed-tree). To increase the seed yield from these trees as an initial source of improved seed, any competing trees were removed. Open-pollinated seed was collected from the selected trees and assigned to one of three seed-quality classes. Unfortunately because these trees were scattered throughout the plantations, often in remote locations, and because of the irregular and unpredictable seed production in hoop pine, relatively little open-pollinated seed was collected from these trees for plantation establishment (Slee and Reilly 1967; Gould 1979). Consequently, until clonal seed orchards (CSOs) began producing large quantities of seed in the early 1980s, the primary source of seed for plantation establishment in Queensland was essentially unimproved seed from either natural stands or crop trees in mature plantations (Nikles 1996).

Eleven CSOs were established in Queensland between 1965 and 2001 (Table 3). Establishment of the first CSO was delayed until a suitable grafting method had been developed and then by uncertainty caused by the appearance of graft incompatibility (Haines and Dieters 1990; Dieters and Haines 1991) in the very dry spring of 1963. Field grafting of the first CSO (Imbil 1, Table 3) did not commence until 1965. Grafting of the second CSO (Taromeo) started in 1970, and this orchard had separate sections containing early-flowering and late-flowering clones. The first two CSOs did not produce substantial amounts of pollen until 1979–1980. The seed collected from the CSOs since 1981–1982 has provided sufficient planting stock for the establishment

of all operational plantations since the 1984/1985 planting season. Subsequent seed production in the CSOs has exceeded requirements for plantation establishment in Queensland, so seed collection is now restricted to the better (i.e. higher breeding value) clones in the orchard.

Genetic gain

Substantial genetic gains have been captured in operational plantations through the deployment of planting stock raised from seed produced in CSOs. The magnitude of gains that may be obtained in operational plantations is illustrated by results from one of the first full-sib family trials, planted near Imbil in December 1964. In this trial, trees of each family and a control (seed collected in a local Imbil plantation), were planted in up to four replicates of 49-tree (7 rows × 7 trees) plots. The trial was thinned twice, first in 1984 and again in 1994. The first thinning retained a constant basal area per plot of 25 m² ha⁻¹; but because this resulted in major differences in the number of trees in each plot, all plots were reduced to a constant stocking of 18 trees plot⁻¹ in the second thinning. Trees were visually assessed for stem straightness at 8 y of age (1 = crooked, ... 8 = straight), and all remaining trees were measured for diameter and height at 35 y of age. If total productivity (i.e. the standing volume at 35 y plus the volume removed in the two thinning operations) and stem straightness are examined (Fig. 4), it can be seen that genetically improved material (for example, the 'mean of families') is faster growing and straighter than the unimproved 'routine control'. It should be noted, however, that some of the observed differences in this trial may be due to provenance effects — the local control is early flowering while some of the selected trees are late flowering.

Family forestry

The reproduction of elite families identified in progeny tests (e.g. H20 × I108, Fig. 4) provides an opportunity to capture significantly more gain than is provided by a general collection from an open-pollinated seed orchard. It has now become possible in Queensland to deploy elite families. Predicted breeding values

Table 3. Inventory of clonal seed orchards of *Araucaria cunninghamii* established in Queensland

| Orchard | Location | Period established | Area (ha) | Cycle no. ¹ | No. clones ² | Flowering time | Breed type ³ |
|----------------------|----------|--------------------|-----------|------------------------|-------------------------|----------------|-------------------------|
| Imbil 1 | Imbil | 1965–1968 | 7.0 | 1 | 23* | Early, late | GF |
| Taromeo | Yarraman | 1970–1973 | 6.3 | 1, 1.5 | 30*, 21* | Early, late | GF |
| Yarraman | Yarraman | 1986–1988 | 2.0 | 1.5, 2 | 13* | Late | GF |
| Grenning | Yarraman | 1987–1988 | 2.0 | 1.5, 2 | 16* | Early | GF |
| Imbil 2 | Imbil | 1988 | 2.0 | 1.5, 2 | 13 | Late | GF |
| Tinana | Toolara | 1988–1989 | 1.9 | 1.5, 2 | 20 | Late | GF |
| Valley A | Yarraman | 1989–1992 | 2.4 | 1, 2 | 41 | Early | I |
| Valley B | Yarraman | 1989–1992 | 0.8 | 1, 2 | 20 | Late | I |
| Wongabe ¹ | Atherton | 1995–1997 | 3.0 | 1 | 26 | Early–late | GFN |
| Geritz | Yarraman | 2000–2001 | 4.5 | 1.5, 2 | 45 | Late | GFI |
| Paddock 30 | Yarraman | 2000–2001 | 4.1 | 1.5 | 7 | Late | GFIW |

¹Parents used are from different cycles of breeding:

1 = untested, first-generation parents; 1.5 = tested, superior, first-generation parents; 2 = untested, second-generation parents

²The original numbers of clones included; the marker * indicates orchards which have been fully or partially culled

³Breed type – G = growth, F = form, I = internode length, W = wood quality (primarily spiral grain), N = northern Queensland or PNG provenance origin.

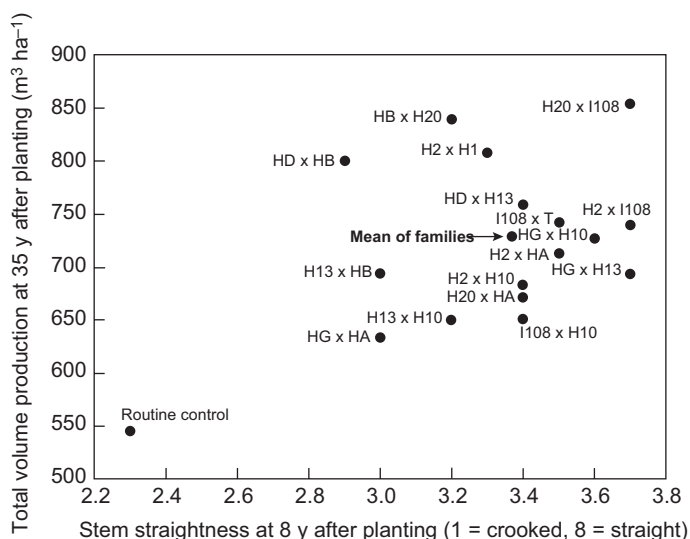


Figure 4. Mean total volume (sum of standing volume, plus volume removed by thinning) at 35 y of age, and mean stem straightness at 8 y of age, of families in an *Araucaria cunninghamii* progeny trial established near Imbil in December 1964.

are being used to select parents for the operational-scale production of families from known, high-performing parents. The criteria used to select parents for inclusion in the family forestry program aim to at least maintain the gains achieved in growth and stem straightness, while placing emphasis on improving both internode length and spiral grain. We aim to increase average internode length (above about 6 m on the stem) to ≥ 1.2 m and to keep maximum spiral grain angle $< 4^\circ$. A special clonal seed orchard was established in 2001 (Paddock 30 — Table 3) for the production of fully control-pollinated seed from parents with high genetic merit. Pollination commenced in this orchard in 2003, with 58, 58 and 241 kg of control-pollinated seed collected in 2005, 2006 and 2007 respectively. The 2007 collection of control-pollinated seed represents 85% of the annual seed requirement, with an average of 285 kg of seed required per year over the last four years.

Breeding strategy

A major change in the direction of the breeding program was made in 1990 following the adoption of a multiple-population breeding strategy. Prior to this time the genetic improvement of hoop pine had been managed within a single large breeding population. The primary factors driving this change were:

- most of the superior provenances of hoop pine were so poorly represented in the initial breeding population that selection of new plus trees was required to adequately capture the yield benefits of these provenances
- the new plus trees could form a separate, unrelated population
- there was a strong commercial drive towards the development of a long-internode breed (Dieters *et al.* 1990)
- there was a case for developing a population adapted to the tropical north or for use in producing hybrids with southern provenances.

The four breeding populations adopted under this strategy are described below. Mating and selection are confined within populations for breeding, but crosses can be made between the populations for deployment purposes.

First southern population (FSP). This consists of (i) 400 first-generation plus trees selected phenotypically (from 1957 to the late 1970s) in southern Queensland provenances (mainly those from the Mary and Brisbane River valleys — Fig. 1), many of which have now been progeny tested, and (ii) second- and third-generation progeny of the original, selected parents now represented in field trials.

Second southern population (SSP). Two hundred and forty-four first-generation selections were assembled in the late 1980s and early 1990s by phenotypic selection within plantations of known superior (southern Queensland) provenances. Most trees selected are from the Jimna provenance. Unfortunately the other superior provenances which were identified in the provenance trials were not well represented in plantations suitable for plus-tree selection.

Long-internode population (LIP). One hundred and twenty-two individuals (81 first-generation and 41 second-generation trees) were selected in the late 1980s. These trees had an average internode length in the upper crown (i.e. above 6 m) of 2–3 m, combined with good stem quality and vigour. Very long internode trees (i.e. > 3 m) were available for selection, but most were rejected because such trees generally were not sufficiently straight. Some individuals in this population are also represented in the FSP. The purpose of the LIP was to enable the rapid development of a long-internode breed (Dieters *et al.* 1990) and many of these trees were grafted into the Valley CSO (Table 3).

Northern provenances population (NPP). One hundred and fifty-one first-generation trees selected at a relatively low intensity in plantations established with seed from the northern provenances of Papua New Guinea (several provenances; 63 trees selected) and far-northern Queensland (Coen — 60 trees, Gillies — 18 trees and Cape Flattery — 10 trees: see Fig. 2 for these locations).

The intensity of genetic improvement activities with hoop pine in Queensland has been significantly reduced since 2002, when the last series of progeny trials was established. Economic considerations dictated that continued, intensive breeding of hoop pine could not be justified — long rotations (now > 50 y), breeding cycles of about 15–20 y, and a lead time from selection to seed production of at least 10 y mean that returns from further breeding will not be realised for at least 75 years. As a result genetic improvement activities now focus on selection of elite parents (based on the performance of their progeny in field trials) for use in the production of superior families by operational controlled crossing for subsequent deployment in plantations. It is anticipated that up to 80% of future hoop pine plantations established by Forestry Plantations Queensland (the government-owned corporation now responsible for plantation forestry in Queensland) will be derived from superior full-sib families.

Future directions

A detailed review of the hoop pine breeding populations planned for 2007/2008 will use data collected from all progeny tests

currently over 8.5 y of age. After completion of this review Forestry Plantations Queensland is expected to reassess its investment in the continued genetic improvement of hoop pine.

Options that may be explored include:

- maintenance of a low-intensity breeding program possibly relying on wind-pollinated mating, and/or
- establishment of a small elite breeding population that will be targeted to future seed requirements via family forestry.

There is likely to be on-going investment in the development of enhanced deployment systems (e.g. family forestry), but investment by traditional sources in research to underpin the on-going genetic improvement of this species will probably cease. Alternative funding sources will be needed if the genetic diversity currently preserved in the breeding populations of this species in Queensland is to be maintained.

Conservation of genetic resources

The Queensland regional ecosystems (REs) which contain or may contain hoop pine, by land tenure types, in each bioregion as defined in Sattler and Williams (1999), are summarised in Table 4. The current 'biodiversity status' of these forests in each RE is listed as either 'not of concern', 'of concern' or 'endangered'. Of the relevant REs listed in Table 4, five are shown to be 'endangered', and in a sixth the biodiversity status is currently under review. However, in no case is the extent of such REs less than 1000 ha, and the others range from 4100 ha to 9600 ha.

In NSW vegetation has been mapped, in a manner different to that adopted in Queensland, using the regional ecosystems model (EPA 2005). Nevertheless, rainforest types broadly analogous to several of those recognised as including hoop pine in south-eastern Queensland are identifiable in NSW (John Hunter, NSW National Parks and Wildlife Service, *pers. comm.* 2002). These, five in number, with the numbers of subtypes involved, are dry rainforest (5), riverine rainforest (1), littoral rainforest (2), warm temperate rainforest (2) and cool temperate rainforest (2), for a total of 12 subtypes. Of these, three riverine or littoral subtypes are considered 'endangered' in terms of conservation status, while three of the others are 'of concern' and the remaining six are 'of no concern at present' (John Hunter, NSW NPWS, *pers. comm.* 2002).

It is evident that while some REs that include hoop pine are considered to be endangered, within the natural range of the species in Australia it is not under any serious threat — over 236 000 ha of natural forests (potentially containing hoop pine) are preserved on lands controlled by the Queensland government alone (Table 4). Moreover, it is expected that social, political and legal constraints on further clearing or logging of rainforests in Queensland and NSW will continue to be tightened, such that stands on private (i.e. freehold) lands are unlikely to be greatly diminished in the future.

Although considerable areas of rainforest containing hoop pine have been cleared for agriculture and other land uses in NSW and Queensland, substantial areas of native forests in which this species is dominant have been protected within a network of publicly-owned national parks, forest reserves and state forests.

Hence, throughout the range of hoop pine in Australia, large areas of natural stands remain intact, and the species as a whole is not endangered. The extent of conservation of native stands of hoop pine, particularly on non-government lands, however, is more serendipitous than designed. Although hoop pine often occurs on highly fertile soils that would be desirable for conversion to agriculture, many of these sites are also very steep and therefore unsuitable for intensive agriculture. Swain (1928, p.68) notes: 'private timber estates ... although holding only 25% of the soft-wood volume, have contributed a larger yield than the State's own much more important [forest estate]', largely due to 'the generally better accessibility, and because of the haste to realise upon the stumpage values in order to convert the land to farming ends.' While conversion to agriculture of privately-owned forests dominated by *Araucaria* has almost eliminated this forest type in some REs (Table 4) and has undoubtedly led to further fragmentation of the natural stands, significant areas of native forests have been retained on private lands.

The management of state-owned *Araucaria* forest lands early in the 20th century could have followed one of two paths, as described by Swain (1928, p. 18):

there are only two economic policies from which to choose — the first, to cut out the natural stagnant and over-mature hoop and bunya stands within these ten years from 1928 to 1938, when the pine-milling industry would suddenly disappear, or to ration the cut over a more extended period, and by dilution and import ease the decline in our small resources down to the point at which the incline of the new plantations of Forest Service creation can assume the responsibility for providing increasing supplies of log material. This latter policy has been chosen.

This deliberate policy of reducing the harvest from natural stands while at the same time investing in the development of a viable plantation program has led to the preservation of large areas of natural *Araucaria* forests in Queensland. The volume of logs now harvested from the hoop pine plantations exceeds the highest annual removals from native forests, recorded in the 1940s. Hence these plantations provide:

- an alternative source of high quality timber from a relatively small land base, thereby allowing native forests to be excluded from logging
- an ongoing source of revenue, which is able (indirectly via financial returns to the state government) to support non-profit forest-based activities by government agencies, including the conservation and management of native stands
- an addition to the genetic conservation base, as some are derived from seed collected from natural stands that were heavily logged or cleared and are no longer extant in the wild.

The breeding and deployment program with hoop pine constitutes an important component of the genetic conservation of this species in Queensland. As outlined previously, 876 first-generation plus trees of many provenances are represented in the four breeding populations. These genotypes are preserved in grafted clone banks and clonal seed orchards. This method of gene conservation has the advantage of preserving genotypes with known performance (McCutchan 1999). As pointed out by Dvorak (1999) in the context of southern pines, but nevertheless relevant here, 'these

Table 4. Regional ecosystems (REs) within Queensland bioregions that contain or may contain natural stands of *Araucaria cunninghamii*, and their areas in hectares by land tenure. (Note that the actual areas of *A. cunninghamii* forest types are less as the species does not occur throughout each RE, even when it is characteristic as in those REs in bold below). Data extracted from EPA (2005).

| Bioregion and regional ecosystem | National park | State† | Free-hold | Lease-hold | Other | Short description of RE and examples of some occurrences in for example particular national parks (NPs) where hoop pine may be present |
|---|---------------|--------|-----------|------------|-------|--|
| Cape York Peninsula Bioregion | | | | | | |
| 03.02.12, A‡ | 122 | 19 | 7609 | 40 | 16 | AMVF§ on coastal dunefields and beach ridges. Heathlands Resources Reserve, Shelburne Bay coast (Captain Billy Landing area), Temple Bay coast north, C. Flattery and C. Bedford sand ridges |
| 03.05.04×4, A? | 228 | | 316 | | 1711 | AMVF on sand sheets. Heathlands R'ces Res., Shelburne Bay coastal plains, e.g. Captain Billy Landing |
| 03.12.02, B | 2310 | | 15 | 1 | 1 | ANVF on granitic ridges and mountains — southern area. C. Melville NPs incl. Altanmoui Ra. and part of Starcke Holding, C. Bedford and S to Hopevale Mission |
| | 185 | | 635 | 1433 | 3473 | ANVF on granitic ridges and mountains — northern area. Mungkan Kandju NP, McIlwraith Ra. near Coen |
| Wet Tropics Bioregion | | | | | | |
| 07.12.10, B | 242 | 629 | 14 | 499 | 576 | NVF on granitic foothills and uplands S of Herbert R., Seaview and Paluma Ranges, Tully Gorge NP, Hann Tableland |
| 07.12.46, B | | | 425 | | 3 | MVF on steep rock granite talus and boulder slopes of Great Palm Island |
| Central Queensland Coast Bioregion | | | | | | |
| 08.11.02, B | 348 | 16 | 2082 | 91 | 4 | NMVF on coastal hills and low ranges on sediments +/- volcanics. Eungella and Mt Ossa NPs |
| 08.12.02, A | 9298 | 11028 | 4385 | 5903 | 538 | N-CNVF on drier uplands and coastal ranges on igneous rocks, Eungella–Pioneer Peaks areas |
| 08.12.03, A | 7244 | 21405 | 18961 | 13482 | 704 | N/MRf on low to medium ranges on igneous rocks. Major Rf type in many NPs in Mackay region |
| 08.12.10, B | 197 | 101 | 2170 | 37 | 2 | Shrub/heathland, emergent hoop pine on exposed igneous plateaus, Homevale and Pioneer Peaks NPs |
| 08.12.11, B? | 11763 | 187 | 934 | 955 | 2361 | SDMVF/T in coastal areas and islands on various igneous rocks. Brampton Is., Whitsunday Is. etc. NPs |
| 08.12.18, A | 13869 | 7109 | 4161 | 274 | 597 | N-CNVF on coastal ranges and islands on igneous rocks. Whitsunday region NPs, Conway, Dryander Ra. |
| Einasleigh Uplands Bioregion | | | | | | |
| 09.12.34, A | | 702 | 1584 | 9486 | 1121 | SEVT on slopes of steep hills on volcanics in the SE of the bioregion. Leichardt and Hervey Ranges |
| 09.12.35, A | | | 1074 | 30396 | 1 | Open woodland on granitic hills in SE of the bioregion. W of Hidden Valley (WSW of Mt Spec) |
| Brigalow Belt Bioregion | | | | | | |
| 11.11.05, A | 2472 | 2444 | 18538 | 10109 | 852 | MVF on hilly terrain with steep slopes; sedimentary rocks. Goodedulla and Rundle Ra. NPs |
| 11.12.04, A | 10767 | 4102 | 21559 | 18393 | 2733 | SEVT and MVF on low hills and ranges on igneous rocks. NPs, e.g. Cape Upstart, Magnetic Is., Mt Archer |
| 11.12.12, B | 299 | | 2 | 5 | 76 | Araucarian woodland on islands, headlands and coastal hills with igneous rocks, Magnetic Is., Cape Upstart NPs |
| 11.12.16, B | 2631 | | 322 | 1861 | 1407 | Low woodland–shrubland on islands and coastal hills; igneous rocks. Bowling Green Bay, Magnetic Is. NPs |

† State-controlled land includes both state forests and forest reserves

‡ Biodiversity status: A = no concern at present; B = of concern; C = endangered; ? = under review. For definitions, see www.epa.qld.gov.au/nature_conservation/biodiversity/regional_ecosystems/introduction_and_status (accessed 17 April 2007) and EPA (2005)

§ A = Araucarian, C = complex, D = deciduous, E = evergreen, F = forest, L = low, M = microphyll, N = notophyll, Rf = rainforest, S = semi-, T = thicket, V = vine

Table 4. (continued)

| Bioregion and regional ecosystem | National park | State† | Free-hold | Lease-hold | Other | Short description of RE and examples of some occurrences in for example particular national parks (NPs) where hoop pine may be present |
|---|---------------|---------------|---------------|---------------|--------------|--|
| South-eastern Queensland Bioregion | | | | | | |
| 12.03.01, C | 104 | 1970 | 6148 | 236 | 597 | Gallery rainforest (NVF) on alluvial plains to about 100 km inland. Extensively cleared. Great Sandy NP |
| 12.03.11, B | 1054 | 18710 | 31038 | 3979 | 10905 | Open forest to woodland on sub/coastal alluvial plains mostly S of Bundaberg. Great Sandy and other NPs |
| 12.05.13, C | 179 | 3487 | 1179 | 92 | 31 | M-NVF on remnant Tertiary surfaces. Yarraman–Tarong–Boat Mt. Heavily cleared |
| 12.08.04, A | 7024 | 2736 | 4464 | 81 | 30 | CNVF on basalts. Areas in Bunya Mts, Lamington, Main Range, Mt Barney NPs; near Levers Plateau |
| 12.08.13, B | 2891 | 7574 | 3873 | 153 | 77 | M and M/NVF on igneous rocks. Areas in Bunya Mts, Moogerah Peaks NPs. Isis and Kalpowar scrubs |
| 12.08.21, C | 965 | 150 | 2907 | 20 | 62 | LMVF and SEVT on igneous rocks. Small areas in Bunya Mts NP and Lockyer Valley in S of bioregion |
| 12.09-10.15, C | 136 | 1591 | 3584 | 26 | 46 | SEVT on sedimentary rocks. Extensively cleared. In for example Lockyer and Fassifern valleys |
| 12.09-10.16, C? | 835 | 4978 | 3535 | 70 | 184 | AM-NVF on sedimentary rocks. Extensively cleared. Seaview Ra., Tinana Ck, Flinders Peak, Mt Barney |
| 12.11.10, A | 1392 | 25979 | 11589 | 322 | 708 | NVF on metamorphics and volcanics in coastal/subcoastal ranges, Enoggera Ck, Mary Valley, Pinbarren |
| 12.11.11, A | | 7994 | 6266 | 111 | 72 | AMVF on metamorphics and volcanics. Extensively cleared. Imbil–Kilkivan–Nanango. W foothills of D'Aguiar Ra. |
| 12.11.12, B | 5226 | 1331 | 2354 | 87 | 102 | ACMVF on interbedded metamorphics and volcanics. Woolooga; hoop pine may invade eucalypt forest, e.g. in Goodnight Scrub |
| 12.11.13, B | 12 | 1567 | 562 | 9 | 3 | SEVT on interbedded metamorphics and volcanics. Fire and weeds threats on edges. Goodnight Scrub |
| 12.12.01, B | 327 | 5464 | 1838 | 23 | 20 | SNVF in gullies on igneous rocks. Often present on margins. Brisbane FP, Kondalilla NP, Mt Eerwah |
| 12.12.13, A | 937 | 29347 | 8803 | 1364 | 415 | ACM-NVF on igneous rocks. Hills near Somerset Dam, Burnett Ra. (Goomeri-Biggenden), Mt Perry Ra. |
| 12.12.16, A | 490 | 17965 | 5044 | 145 | 195 | NVF on igneous rocks. Includes Mt Mee, Yandina, Bauple areas in S; Bulburin, Kroombit Tops in N |
| 12.12.17, C | 0 | 715 | 374 | 4 | 1 | SEVT on igneous rocks. Further clearing, fire and weed invasion threats. Nangur, Mt Beppo |
| 12.12.18, B | 243 | 2976 | 2243 | 710 | 61 | SEVT on igneous rocks. Comment as next above. Central, Gayndah part of bioregion; Kroombit Tops NP |
| Total areas | 83551 | 182276 | 181002 | 100425 | 25373 | |

† State-controlled land includes both state forests and forest reserves

‡ Biodiversity status: A = no concern at present; B = of concern; C = endangered; ? = under review. For definitions, see

www.epa.qld.gov.au/nature_conservation/biodiversity/regional_ecosystems/introduction_and_status (accessed 17 April 2007) and EPA (2005)

§ A = Araucarian, C = complex, D = deciduous, E = evergreen, F = forest, L = low, M = microphyll, N = notophyll, Rf = rainforest, S = semi-,

T = thicket, V = vine

clone banks only have value when their genetic composition is well documented and the genetic material is accessible'. Ex situ conservation of hoop pine in Queensland is currently facing challenges brought on by a rapid reduction in funding for traditional tree improvement activities and by organisational segregation of research and operational forestry activities. Short-term instability brought on by institutional change can vitiate viable long-term ex situ gene conservation programs. In these circumstances information, knowledge and material can be

rapidly and easily lost, thereby nullifying many years of conscientious scientific endeavour. Continued effective long-term conservation of genetic resources will pose significant challenges in a future increasingly dominated by commercial imperatives. Consequently, in situ conservation will 'remain fundamentally important for the conservation of forest genetic diversity' (Kanowski 2000, p. 283).

Although much of the native hoop pine in the Bulolo and Wau valleys in PNG has been harvested, this is not the case for most of the numerous occurrences of the species elsewhere in PNG nor in Indonesian New Guinea (Howcroft 1978). These populations remain largely intact because they are frequently remote and occur on mountain tops and or steep terrain (Gray 1973; Kapisa 2002). Some preliminary work has been done on in situ and ex situ conservation in PNG and Indonesian New Guinea (Howcroft 1978; Kapisa 2002), but more work is required.

The formal conservation status of hoop pine in New Guinea is unknown; in the Bulolo–Wau area the existence of plantations based on local provenances provides some insurance, but the long-term future of these plantations may be in doubt. Natural stands in other regions are largely inaccessible and this should provide a modicum of protection by default, at least in the medium term. Several PNG provenances are represented in Queensland experimental plantings and this will offer a reasonable degree of long-term ex situ genetic conservation.

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Physical and mechanical properties of plantation-grown *Acacia auriculiformis* of three different ages

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Summary

We assessed the physical and mechanical properties of timber of plantation-grown 8-, 12- and 13-y-old trees of *Acacia auriculiformis* A.Cunn. ex Benth. from Sirsi, Karnataka, India. The timber of the 13-y-old trees was dense, very strong, moderately tough, stable in service and hard, and it compared favourably with teak in several properties. The results suggest that it can be used for tool handles, oars, paddles, packing cases, ammunition boxes, etc. It was also found suitable for the rural construction industry where timbers of small diameter can be used. If trees are allowed to grow older to attain greater size the range of potential uses will increase.

Keywords: plantations; wood properties; shrinkage; mechanical properties; modulus of elasticity; *Acacia auriculiformis*

Introduction

Acacia auriculiformis A.Cunn. ex Benth. is native to savannas of Papua New Guinea, islands of Torres Strait and northern Australia. In natural stands it is a vigorous tree, reaching a height of 30 m with a trunk up to 60 cm in diameter. Because of its ability to grow on very poor soil and in areas with an extended dry season, it has been introduced into countries such as India, Indonesia, Malaysia, Tanzania and Nigeria.

Acacia auriculiformis was introduced into India about three or four decades ago. In 1990, provenances with straight boles from Papua New Guinea and northern Queensland were planted in the Uttar Kannad and Dharwad districts of Karnataka, India, and their performance was considered good (Rai 1995). The species has also been grown as an avenue tree in other parts of India, viz. Tamil Nadu, Bihar, Orissa and West Bengal, and in fuelwood plantations in Dharwad and other areas of Karnataka. The trees are useful for shade, for ornament, for screening boundaries and for windbreaks, as well as for agroforestry and for mitigating soil erosion. The tree produces a considerable amount of litter from branches and dead leaves that can be gathered for fuel. It is one of the species recommended for firewood farming in degraded lands (Chaturvedi 1985) because of its excellent quality as firewood. The wood burns without smoke or sparks and has a calorific value of 4800–4900 cal kg⁻¹ (20.1–20.5 MJ kg⁻¹) (Anon. 1980). The timber also provides a good pulp yield (Guha and Pant 1966).

Recently this species has become popular among both public and private-sector planters¹. As the planting has been a pioneering effort, there is not much scientific information available about the tree's performance in this region. Information on growth rate and wood properties — which is helpful in evaluating its potential for various end-uses — is essential for informed investment in extensive plantation programs. An understanding of the wood properties and their variation with age (Rao *et al.* 2004) provides a basis for assessing opportunities for value-added uses.

Comments on properties and processing of wood of *A. auriculiformis* have been provided by Rajan *et al.* (1979), Ananthnarayana *et al.* (1987), Kumar *et al.* (1987) and Shukla *et al.* (1990). Keating and Bolza (1982) provided some details of wood characteristics. Kazmi *et al.* (1990) discussed the properties of the wood for the purpose of identification. Verghese *et al.* (1999) reported limited quantitative information pertaining to fibre and vessel morphology in 15-y-old trees from Maharashtra. Rao *et al.* (2004, 2007) described anatomical variation in 8–13-y-old trees.

Because of the lack of systematic information on physical and mechanical properties in relation to tree age, we have investigated those properties. In this paper, we present information on the physical and mechanical properties of wood from trees 8, 12 and 13 y old, and compare them with published values for teak.

Material and methods

Sampling

Five logs each of 8-, 12- and 13-y-old plantation-grown *A. auriculiformis* were procured from Sirsi, Uttar Kannad (Karnataka) to provide wood for evaluation of the physical and mechanical properties of the species. The stands from which the logs were obtained were grown from a single unspecified seed source and in the same locality. Table 1 shows the details of

¹ Rao, R.V., Rao, K.S., Shukla, S.R., Kothiyal Vimal, Kumar, P., Sudheendra, R., Chandrashekhara, M.N., Jayakumar, M.N., Malkhede, S.K., Madhav Ambadi, Mohamed Amanulla, B.K. and Sathishchandra, K.M. (2005) Evaluation of physical and mechanical properties of *Acacia auriculiformis* × *A. mangium* hybrid, *A. mangium* × *A. auriculiformis* hybrid, *A. auriculiformis* (Spring Vale provenance and local) and *A. mangium*. Report to The Mysore Papermills Ltd, Bhadravathi, Karnataka, India, 37 pp. (unpublished).

Table 1. Environmental factors at Sirsi, Uttar Kannada (Karnataka, India) near the *Acacia auriculiformis* study site

| Factor | Value |
|---------------------------|---------------------------------------|
| Latitude | 14.96°N |
| Longitude | 74.72°E |
| Altitude | 600 m asl |
| Maximum daily temperature | 23–28°C |
| Annual rainfall | 2500 mm |
| Soil type | Deep, clayey soil on laterite plateau |
| Drainage | Good (well drained) |

environmental factors at the stands. Average, minimum and maximum girths and average length of logs from each age group of trees are given in Table 2.

All the logs were marked and numbered on the top end and sawn directly into full-length scantling of 6.25 cm × 6.25 cm cross-section to obtain the maximum number of test specimens from each log. One or two scantlings were obtained per log. Each scantling was halved along the radius of the log to provide samples for green and air-dry testing based on IS: 2455 (Anon. 1974).

Measurement of properties

Small clear specimens were tested, in both green and air-dry states, for the following physical and mechanical properties using the procedure given in IS: 1708 (Anon. 1986).

Physical properties

- (i) *Moisture content.* Moisture content was measured using test specimens of 2 cm × 2 cm × 2.5 cm on the basis of oven-dry weight as per the standard procedure. The numbers of specimens taken to determine moisture content in the green and air-dry states were 525 and 580 respectively.
- (ii) *Density and specific gravity.* Density (colloquially 'weight' or 'heaviness') in both the green and air-dry condition was calculated from the weight of specimens in the green condition and their volume in the green condition, and similarly the air-dry weight and air-dry volume (adjusted to 12% EMC) respectively. Specific gravity was estimated from volume at test (green or air dry) and oven-dry weight using the standard mercury displacement method. Specific gravity based on green volume is referred to here as standard specific gravity. The numbers of specimens taken to determine both density and specific gravity in green and air-dry states were 531 and 578 respectively.

- (iii) *Shrinkage.* For the measurement of shrinkage, true radial, tangential, longitudinal and volumetric samples were prepared. The specimen size for volumetric shrinkage was 2 cm × 2 cm × 6 cm, while for radial, tangential and longitudinal shrinkage the specimen size was 2 cm × 2 cm × 5 cm. Specimens were weighed in the green condition to 0.001 g accuracy and their length was measured to 0.002 cm accuracy using Mitutoyo digital screw gauge calipers of 0.001 cm accuracy. Specimens were allowed to air dry, and periodically weighed and lengths measured until no further loss of weight was observed. The specimens were then oven dried and the dimensions measured. The numbers of specimens taken to determine radial, tangential, longitudinal and volumetric shrinkage from the green to an oven-dry state were 164, 160, 151 and 162 respectively.

Mechanical properties

The mechanical testing was conducted on a computer-controlled Universal Timber Testing Machine (UTM) as described below:

- (i) *Static bending strength.* The size of specimens was 2 cm × 2 cm × 30 cm with a span length of 28 cm. The loading was applied at a constant rate of 1.0 mm min⁻¹ on the tangential surface of the sample. The numbers of specimens used in green and air-dry states were 159 and 162 respectively. Three different static bending strength parameters, fibre stress at elastic limit (*FS at LP* in MPa), modulus of rupture (*MOR* in MPa) and modulus of elasticity (*MOE* in MPa) were computed using the equations:

$$FS \text{ at } LP = 3 \times P \times l / 2 \times b \times h^2 \quad (a),$$

$$MOR = 3 \times P_{\max} \times l / 2 \times b \times h^2 \quad (b),$$

$$MOE = P \times l^3 / 4 \times D \times b \times h^3 \quad (c),$$

where P = load at the limit of proportionality (kN); P_{\max} = maximum load (kN), l = span of the test specimen (mm), b = breadth of the test specimen (mm), h = depth of the test specimen (mm) and D = deflection at the limit of proportionality (mm).

- (ii) *Compressive strength parallel to grain.* The size of specimens was 2 cm × 2 cm × 8 cm in length, and the rate of loading was 0.6 mm min⁻¹. The numbers of specimens used in green and air-dry conditions were 124 and 156 respectively. The compressive strength parallel to the grain (maximum crushing stress, *MCS*) was calculated by the equation:

$$\sigma_{\text{cpl}} = P_{\max} / A,$$

where σ_{cpl} = *MCS* (MPa), P_{\max} = maximum crushing load at

Table 2. Length and girth of five logs in each age group

| Tree/log no. | Age (y) | Average available length of log (m) | Girth (diameter) at breast height (cm) | | |
|--------------|---------|-------------------------------------|--|-----------|-----------|
| | | | Mean | Minimum | Maximum |
| T1–T5 | 8 | 4.55 | 38.2 (12.2) | 32 (10.2) | 42 (13.4) |
| T6–T10 | 12 | 4.55 | 42.8 (13.6) | 36 (11.5) | 44 (14.0) |
| T11–T15 | 13 | 4.24 | 50.8 (16.2) | 46 (14.6) | 53 (16.9) |

break point (kN) and A = area of cross section of the specimen on which force was applied (mm^2).

- (iii) *Compressive strength perpendicular to grain.* The size of specimens was $2 \text{ cm} \times 2 \text{ cm} \times 10 \text{ cm}$. Load was applied at the $2 \text{ cm} \times 2 \text{ cm}$ cross-section on the tangential surface at a rate of 0.6 mm min^{-1} . The numbers of specimens used in green and air-dry conditions were 117 and 147 respectively. The compressive strength perpendicular to the grain (compressive stress at limit of proportionality — *CS at LP* in MPa) was calculated by the equation:

$$CS \text{ at } LP = P/A,$$

where P = load at the limit of proportionality (kN) and A = area of cross-section of specimen on which force was applied (mm^2).

- (iv) *Hardness under static indentation.* The size of specimens was $5 \text{ cm} \times 5 \text{ cm} \times 5 \text{ cm}$. Load (kN) required to penetrate into the specimen a steel bar with an hemispherical end or a steel ball of 1.128 cm diameter to a depth of 0.564 cm was recorded. Measurements were made at the centre of the radial, tangential and end faces; no splitting or chipping occurred. The rate of loading was kept constant at 6 mm min^{-1} . The numbers of specimens used in green and air-dry conditions were 125 and 115 respectively.
- (v) *Shear strength parallel to grain.* The size of specimens was $5 \text{ cm} \times 5 \text{ cm} \times 6 \text{ cm}$. The specimens were notched at one end to produce shear failure in an area of $5 \text{ cm} \times 5 \text{ cm}$ in the radial or tangential plane. The numbers of specimens used in green and air-dry conditions were 50 and 36 respectively. The shear strength parallel to the grain in radial and tangential planes (maximum shearing stress — *MSS* in MPa) was calculated by the equation:

$$MSS = P_{\max}/A,$$

where P_{\max} = maximum load required for shearing the area (kN) and A = shearing area of the specimen on which force was applied (mm^2).

- (vi) *Tensile strength perpendicular to grain.* The size of specimens was $5 \text{ cm} \times 5 \text{ cm} \times 6 \text{ cm}$. The specimens were notched on the two surfaces perpendicular to the grain so as to produce a failure on an area of $5 \text{ cm} \times 2 \text{ cm}$. The numbers of specimens used in green and air-dry conditions were 21 and 26 respectively. The tensile strength perpendicular to the grain in radial and tangential planes (*TS* in MPa) was calculated by the equation:

$$TS = P_{\max}/A,$$

where P_{\max} = maximum load required for failure perpendicular to grain (kN) and A = area of the specimen on which force was applied (mm^2).

- (vii) *Nail- and screw-holding power.* Nails of 50 mm length and 2.50 mm shank diameter and screws of 50 mm length and 8 gauge were used for testing. The size of the specimens was $5 \text{ cm} \times 5 \text{ cm} \times 15 \text{ cm}$. The numbers of specimens used in green and air-dry conditions were 31 (in total from trees of all three ages) and 19 (from 13-y-old trees only) respectively. Nails and screws were driven in for 25 mm at right-angles to the surface of specimens. Two nails or screws were driven on each of the radial and tangential surfaces and one on each end. The maximum load required (kN) to pull out the nails or screws was recorded for radial, tangential and end

surfaces. The average values of radial and tangential surfaces were named 'side values'.

Statistical design and analysis

The three stands from which each of which five logs were obtained were aged 8, 12 and 13 y respectively. Although the stands were growing near each other in an apparently-uniform environment, the effects of tree age on the sample logs are inevitably confounded with unquantified effects of the stand environments. Although in discussion in this paper we attribute differences between the three sets of sample logs to the effects of stand age, it is important to recognise that stand effects are due to both stand age and stand environment: the field design does not permit these factors to be separated. The comparison with teak has similar constraints.

Results and discussion

General properties and description of wood

Average thickness of the bark for the entire tree was measured as 4.2 mm, 4.8 mm and 5.4 mm for the 8-, 12- and 13-y age classes respectively. The sapwood and heartwood were distinct. The heartwood, which is yellowish-brown in colour, occupied on average 76–85% of the area of each cross-section. The wood is moderately hard and moderately dense, with shallowly interlocked grain and medium texture. Fine lines of parenchyma simulate the presence of growth rings; the actual growth rings are indistinct. Wood structure is diffuse porous. Axial parenchyma is paratracheal, vasicentric and also diffuse-in-aggregate. Rays are very fine and closely spaced.

Physical and mechanical properties

Air-dry values were adjusted to a sample moisture content of 12% using the method of Sekhar and Rajput (1968) where relevant.

Average values of the physical and mechanical properties as determined in green and air-dry conditions are presented in Table 3 for 8-, 12- and 13-y-old trees, along with the corresponding values for 'standard teak', *Tectona grandis* (Sekhar and Rawat 1966), for the purpose of comparison.

Average standard specific gravity was highest in 13-y-old trees (0.62) followed by 12-y (0.60) and 8-y-old trees (0.57) as shown in Figure 1. In other studies, 14-y-old trees from Mudigere, Karnataka, had an average specific gravity of 0.72 (air-dry) (Kumar *et al.* 1987), whereas 9-y-old trees from Gaya, Bihar, had a specific gravity of 0.62 (Shukla *et al.* 1990). Verghese *et al.* (1999) reported that specific gravity was 0.59 for 15-y-old plantations from Wada, Maharashtra. Keating and Bolza (1982) reported that the specific gravity of timber obtained from Indonesia was 0.58–0.64. Mohd Noor Mahat (1999) reported variation in specific gravity (0.53–0.61) of different provenances tested in Malaysia. Thus specific gravity appears to be widely influenced by age, environmental factors and seed origin.

Longitudinal shrinkage was lowest in the 8-y-old trees and volumetric shrinkage was highest in the 13-y-old trees (Table 2).

Table 3. Average physical and mechanical properties of *Acacia auriculiformis* of 8-, 12- and 13-y-old trees and *Tectona grandis* (teak) in green and air-dry condition

| Properties | <i>Acacia auriculiformis</i> | | | | | | | | | <i>Tectona grandis</i> | | |
|---|------------------------------|---------|------|-------|---------|------|-------|---------|-------|------------------------|---------|-------|
| | 8 y | | | 12 y | | | 13 y | | | Green | Air-dry | I.F. |
| | Green | Air-dry | I.F. | Green | Air-dry | I.F. | Green | Air-dry | I.F. | | | |
| MC (%) | 54 | 12 | — | 48 | 12 | — | 44 | 12 | — | 76 | 12 | — |
| Density# (kg m ⁻³) | 875 | 665 | — | 869 | 711 | — | 883 | 729 | — | 1056 | 672 | — |
| Specific gravity | 0.570 | 0.590 | — | 0.603 | 0.616 | — | 0.625 | 0.645 | — | 0.596 | 0.604 | — |
| Longitudinal shrinkage (%) | 0.53 | — | — | 0.61 | — | — | 0.61 | — | — | — | — | — |
| Radial shrinkage (%) | 2.66 | — | — | 2.66 | — | — | 2.64 | — | — | 2.30 | — | — |
| Tangential shrinkage (%) | 5.34 | — | — | 5.06 | — | — | 5.43 | — | — | 4.80 | — | — |
| Volumetric shrinkage (%) | 7.84 | — | — | 7.35 | — | — | 8.22 | — | — | 6.80 | — | — |
| Static bending | | | | | | | | | | | | |
| <i>FS at LP</i> (MPa) | 48.6 | 61.1 | 26 | 57.5 | 66.1 | 15 | 63.1 | 72.7 | 15 | 49.9 | 63.9 | 28 |
| <i>MOR</i> (MPa) | 73.9 | 99.7 | 35 | 87.8 | 100.7 | 15 | 91.6 | 106.6 | 16 | 82.5 | 94.1 | 14 |
| <i>MOE</i> (GPa) | 8.9 | 9.8 | 11 | 10.8 | 11.4 | 6 | 10.9 | 13.0 | 19 | 10.8 | 11.7 | 9 |
| Compression parallel to grain: max. stress (<i>MCS</i>) (MPa) | 32 | 12 | (61) | 36 | 45 | 25 | 37 | 50 | 34 | 41 | 52 | 28 |
| Compression perpendicular to grain: compression stress at <i>LP</i> (<i>CS at LP</i>) (MPa) | 6.6 | 9.6 | 45 | 7.1 | 10.1 | 41 | 7.9 | 11.0 | 39 | 8.4 | 9.9 | 17 |
| Hardness (static indentation) | | | | | | | | | | | | |
| Radial (kN) | 3.6 | 3.7 | 4 | 3.2 | 3.6 | 13 | 3.6 | 4.8 | 31 | 5.5 | 4.9 | (10) |
| Tangential (kN) | 3.7 | 3.8 | 1.6 | 3.4 | 4.0 | 18 | 3.7 | 4.9 | 32 | 5.4 | 5.1 | (5) |
| End (kN) | 3.6 | 3.6 | 0.3 | 3.1 | 3.2 | 2.6 | 3.9 | 4.0 | 3 | 4.8 | 4.8 | (0.4) |
| Shearing stress parallel to grain (<i>MSS</i>) | | | | | | | | | | | | |
| Radial (MPa) | 5.0 | 8.2 | 64 | 6.1 | — | — | 6.8 | 6.9 | 2.4 | 8.8 | 9.5 | 8 |
| Tangential (MPa) | 6.7 | 9.1 | 35 | 6.8 | — | — | 7.7 | 9.0 | 17 | 9.8 | 10.6 | 8 |
| Tensile stress perpendicular to grain (<i>TS</i>) | | | | | | | | | | | | |
| Radial (MPa) | 3.2 | 3.1 | (4) | 2.6 | 1.3 | (42) | 2.7 | 1.2 | (55) | 6.7 | 5.6 | (16) |
| Tangential (MPa) | 3.5 | 4.1 | 17 | 2.9 | 1.9 | (36) | 3.8 | 2.0 | (47) | 7.9 | 6.5 | (18) |
| Nail-holding power | | | | | | | | | | | | |
| Side (kN) | 0.92 | *— | — | 0.81 | *— | — | 0.96 | 0.62 | (35) | 1.25 | — | — |
| End (kN) | 0.34 | *— | — | 0.54 | *— | — | 0.71 | 0.52 | (27) | 0.89 | — | — |
| Screw-holding power | | | | | | | | | | | | |
| Side (kN) | 2.49 | *— | — | 2.70 | *— | — | 3.02 | 2.99 | (1.0) | 3.25 | — | — |
| End (kN) | 1.31 | *— | — | 1.57 | *— | — | 1.69 | 2.37 | 40 | 2.32 | — | — |

FS at LP = Fibre stress at limit of proportionality

MOR = Modulus of rupture

MOE = Modulus of elasticity

MSS = Maximum shearing stress

I.F. = Improvement factor (%)

Numbers in brackets indicate negative values

#Colloquially density may be referred to as 'weight' or 'heaviness'

*Insufficient samples were available to obtain these figures directly. Estimates used in the preparation of Table 4 were calculated using the method of Rajput *et al.* (1991).

Radial and tangential shrinkage were more or less age-independent. Figure 1 shows the variation of modulus of rupture (*MOR*), modulus of elasticity (*MOE*) and maximum crushing stress (*MCS*) parallel to the grain in the green and air-dry state for all the tree ages. *MOR*, *MOE* and *MCS* increased with tree age from 8 to 13 y. Improvement factors (I.F.), indicating the percentage increase in the observed values of various mechanical properties from the green to air-dry state, were also calculated and are listed in Table 3. Air-dry values for most mechanical properties were substantially higher than the corresponding green values except for *MCS* (of 8-y-old trees), tension perpendicular to grain, and nail-holding powers. Hardness and tension values determined in radial, tangential and end directions and tension

perpendicular to the grain appear to be independent of age, whereas the shear values were found to be age related, being highest for the 13-y-old specimens. Nail-holding power was age-related only in end grain, whereas screw-holding power was age-related for all the directions studied and highest in the 13-y-old trees.

A comparison with teak using suitability indices

The data obtained on testing the samples in green and air-dry conditions were used to calculate 'suitability' indices, assigning a value of 100 to teak as a reference. From Table 4, it can be seen that the suitability of even 8-y-old acacia in 'strength as a beam'

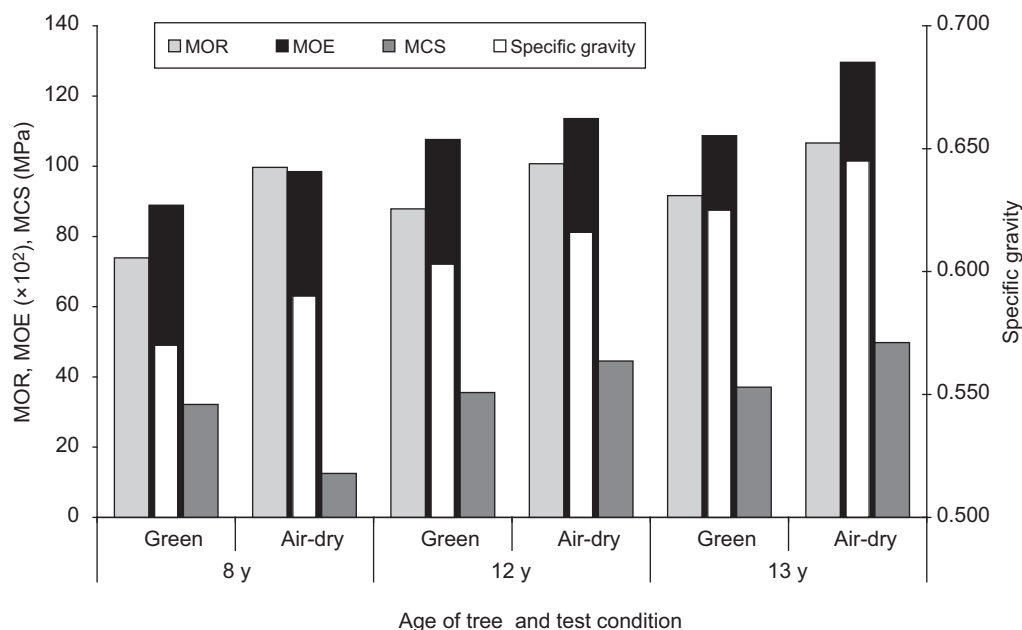


Figure 1. Specific gravity, modulus of rupture (*MOR*), modulus of elasticity (*MOE*) and maximum crushing stress parallel to grain (*MCS*) in plantation-grown *Acacia auriculiformis* 8-, 12- and 13-y-old in green and air-dry condition

Table 4. Suitability of various properties of green *Acacia auriculiformis* wood from trees of three different ages (8, 12 and 13 y) compared with *Tectona grandis* (teak) from 14 locations rated as 100. Both green and air-dry data have been taken into account in preparing this table.

| Property | Suitability index value | | |
|---------------------------------|-------------------------|------|------|
| | 8 y | 12 y | 13 y |
| Strength as a beam | 104 | 116 | 123 |
| Stiffness as a beam | 91 | 104 | 109 |
| Suitability as a post | 71 | 90 | 95 |
| Shock-resisting ability | 89# | 95# | 100# |
| Retention of shape | 85 | 89 | 83 |
| Shear | 72 | 62 | 79 |
| Surface hardness | 85 | 84 | 97 |
| Splitting coefficient | 57 | 37 | 44 |
| Nail-holding power | 77# | 85# | 64 |
| Screw-holding power | 73# | 81# | 82 |
| Density (colloquially 'weight') | 99 | 106 | 109 |

Figures based on data computed from a strength — specific gravity relationship using the method described by Rajput *et al.* (1991)

is better than teak. The suitability as a post was found to be 95 for 13-y-old trees, an improvement over 8- and 12-y-old trees. The shock-resistance ability of the 12- and 13-y-old trees was comparable to that of teak. Retention of shape was best (89) in 12-y-old trees. The 13-y-old trees had the highest comparative rating for shear (79) of three age classes. Surface hardness values were 97 and 85 in 13- and 8-y-old trees respectively. The 12-y-old trees were less refractory than those of other ages. Samples of requisite dimensions were not available for testing the nail- and screw-holding powers of air-dry samples from 8- and 12-y-old trees due to the small girth of those trees, so values were computed from a strength-specific gravity relationship (Rajput *et al.* 1991). While nail-holding power was found to be independent of age, the screw-holding power was better for 12-

and 13-y-old trees than for 8-y-old trees. In terms of density, 8-y-old trees are similar to standard teak. The suitability indices presented by Kumar *et al.* (1987) for 14-y-old trees differ from the results of this trial.

Safe working stresses and a comparison with teak

Safe working stresses were determined for the acacia wood when used in internal, external and wet conditions (using standard discount factors, as a safety measure), and results are presented in Table 5 along with standard teak values for comparison. The stresses are those relevant in load-bearing situations in the three different conditions. This information is important for using timber from trees of different species, different ages and different

girth classes, assuming that the material is available in the required sizes. On comparing the safe working stresses of *A. auriculiformis* of different ages with the corresponding values for teak in the table, it is seen that the extreme fibre stresses in beams of 12- and 13-y-old trees are higher than those of teak in all three conditions. Other safe working stresses like shear along the grain, horizontal shear in beams, maximum compressive stress parallel to the grain and compressive stress perpendicular to the grain for the 13-y-old trees are comparable with values for teak.

It is customary in studies of the wood properties of a species to compare the data for the timber with the available published information and to group the species with others having similar properties (Sekhar and Gulati 1972). In this study, the data may be used to compare the timber from trees of different ages with that of other species. Thus the timber of 8-y-old *A. auriculiformis* was dense (as in *Acer* spp., *Tectona grandis*, *Acacia leucophloea*), strong (as in *Acacia arabica*, *Anogeissus pendula*), not tough (as in *Dalbergia sissoo*, *Adina cardifolia*, *Chlorophora excelsa*), and stable in service and moderately hard (as in *Bridelia retusa*, *Morus serrata*, *Schima wallichii*). Timber of 12-y-old trees was dense, very strong, not tough, stable and moderately hard. Similarly 13-y-old *A. auriculiformis* was dense, very strong, moderately tough (as in *Acrocarpus fraxinifolius*, *Canarium bengalense*), stable and hard.

Suitability for different end uses

Indices of suitability for different uses were calculated (Sekhar and Gulati 1972) for *A. auriculiformis* of all three ages. The timber is well suited for tool handles, oars and paddles, as the relevant values are comparable to those of teak or better. The figures indicating suitability for construction purposes are very encouraging, and trees of greater size can be used for this purpose: the larger trees are required because recovery after sawing will be greater and costs of milling will be correspondingly reduced. The suitability figures relevant to furniture and ammunition boxes are encouraging, and are independent of age. Similarly, the suitability figures suggest the potential use of the wood for light packing cases. The data on nail and screw-holding should be used cautiously: it was found that pre-boring would minimise problems of splitting, and for most of the uses mentioned above it is important that the timber should not split when nailed or screwed. Preliminary studies on natural durability by Nagaveni and Anathapadmanabha (1991) showed that the wood of the

species was highly resistant and can safely be used in decay-prone environments. Turnery articles, furniture, handicrafts and artifacts were made to confirm the multi-purpose nature of the species.

Conclusion

Investigations of physical and mechanical properties of plantation-grown *A. auriculiformis* of three different ages (8, 12 and 13 y) from Sirsi, Karnataka, indicate that the wood can be used for tool handles in workshops, factories and the agricultural sector; oars and paddles; light packing cases; ammunition boxes; etc. It can also satisfy the requirements of the rural construction industry where timbers of small diameter can be used. If the trees are allowed to grow to greater age and size, the wood will have an expanded range of applications. Processing technologies like seasoning and preservation have to be studied to maximise opportunities for value-adding and improving sapwood durability.

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Table 5. Safe working stresses of 8-, 12- and 13-y-old *Acacia auriculiformis* compared with values for *Tectona grandis* (teak)

| Strength property | Location | | | | | | | | | | | |
|--|----------|------|------|------|---------|------|------|------|------|------|------|------|
| | Inside | | | | Outside | | | | Wet | | | |
| | 8 y | 12 y | 13 y | Teak | 8 y | 12 y | 13 y | Teak | 8 y | 12 y | 13 y | Teak |
| Extreme fibre stress in beams (MPa) | 14.7 | 17.6 | 18.3 | 16.5 | 12.3 | 14.6 | 15.3 | 13.7 | 9.9 | 11.7 | 12.2 | 11.0 |
| Shear along grain (MPa) | 0.92 | 1.01 | 1.13 | 1.46 | 0.92 | 1.01 | 1.13 | 1.46 | 0.92 | 1.13 | 1.13 | 1.46 |
| Horizontal shear in beams (MPa) | 0.64 | 0.71 | 0.79 | 1.02 | 0.64 | 0.71 | 0.79 | 1.02 | 0.64 | 0.71 | 0.79 | 1.02 |
| Maximum compressive stress parallel to grain (MPa) | 8.05 | 7.8 | 9.3 | 10.2 | 7.2 | 7.9 | 8.2 | 9.0 | 5.8 | 6.5 | 6.7 | 7.4 |
| Compressive stress perpendicular to grain (MPa) | 3.8 | 4.1 | 4.5 | 4.8 | 3.0 | 3.2 | 3.5 | 3.7 | 2.4 | 2.6 | 2.9 | 3.0 |

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A regionalised growth model for *Eucalyptus globulus* plantations in south-eastern Australia

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Summary

A whole-stand distribution growth and yield model was developed for *Eucalyptus globulus* plantations in south-eastern Australia. The model was developed and parameterised using growth measurements from permanent sample or experimental plots established within plantation estates across the Gippsland, Central Victorian and Green Triangle regions. Regional variation of stand height and basal area growth, and mortality, was statistically tested using selected base models and indicator variables. Stand-level component models were constructed for projecting the stand heights, basal areas and stockings sampled in inventories into the future. Tree-level component models were developed for estimating the relationship between height and diameter, stem taper, and bark thickness at 1.3 m height from ground. To derive the diameter distributions of trees at any age, models were developed for predicting the 0th, 25th, 50th and 95th percentiles of cumulative diameter distributions. The Weibull distribution-based diameter distributions are estimated using the diameter percentiles and quadratic mean diameter predicted at the ages of interest (parameter recovery). In general, the developed models represent the mean growth of the *E. globulus* plantations in the three regions, and the observed and predicted yield trajectories agreed well for stand height, basal area and stocking. The accuracy of the developed stand models was evaluated using an independent data set. In general, for a prediction interval of 5 y or less, average bias in stand height, basal area and volume predictions is within ± 1.0 m, ± 0.5 m² ha⁻¹ and ± 1.0 m³ ha⁻¹ respectively. The models are reliable for projecting the stand parameters sampled in inventories at ages 5 or 6 y to the end of the rotation at about age 10 y. The developed growth model is particularly useful for strategic planning and wood flow analysis.

Keywords: plantations; management; growth models; yield; regions; size; frequency distribution; planning; wood; flow; *Eucalyptus globulus*

Introduction

Australia's total plantation area of 1.74 million ha (Mha) at December 2005 consisted of 0.74 Mha (43%) hardwoods and 0.99 Mha (57%) softwoods (Parsons *et al.* 2006). Between 1995 and 2005, there was a rapid expansion (0.54 Mha) of the total hardwood area, particularly in southern Australia where *Eucalyptus globulus* (Labill.), total 0.45 Mha, is mainly planted

in Western Australia, South Australia and Victoria, while *E. nitens* (Deane and Maiden), total 0.14 Mha, is usually planted in Tasmania. In Victoria and South Australia, industrial plantations of *E. globulus* have been established mainly in the Gippsland, Central Victorian and Green Triangle regions, with smaller-scale farm-forestry plantations in north-eastern Victoria.

Most *E. globulus* plantations are managed for pulpwood production on a nominal rotation of 10 y. Typical establishment silviculture includes soil cultivation by ripping, discing and/or mounding, pre-planting weed control, planting at a stocking of 1000–1200 trees ha⁻¹, and fertiliser application. Generally *E. globulus* tolerates a wide range of site conditions (Beadle and Inions 1990), and has rapid growth (maximum mean annual increment up to 40 m³ ha⁻¹) on favourable sites (e.g. Inions 1992; Duncan *et al.* 2000). However, across the range of sites planted (about 600–1000+ mm annual rainfall), water availability is a primary limitation to growth.

Effective management of a plantation estate requires periodic inventories as a basis for assessing the yield potential (site productivity) of individual stands, and for predicting wood availability. Stand growth models for these purposes have been traditionally developed using repeated measurements from permanent sample plots established across the plantation population where the model will be applied (i.e. forest growth and yield models, Vanclay 1994). Many stand growth models have been developed around the world for different species and forest types (e.g. Clutter *et al.* 1983). However, there are few published models for *E. globulus* plantations in Australia, mainly because of the relatively short history of this industry, and because the plantations are owned and managed by numerous organisations, a situation that is not conducive to sharing data for model development.

The recent collaborative development of a 'Blue Gum (*E. globulus*) Plantation Management System' (Strandgard *et al.* 2005) provided an opportunity to develop *E. globulus* stand growth models for application across south-eastern Australia. The primary objective was to develop the growth models that can be used for projecting stand characteristics sampled in plantation inventories into the future for strategic planning and wood flow analysis. This paper presents the methods used and the developed models.

Plantation regions and previous modelling

There are 15 regions in the Australian National Plantation Inventory (Parsons *et al.* 2006). *E. globulus* growth data from the Central Gippsland, and East Gippsland/Bombala (Victoria/New South Wales), Central Victorian and Green Triangle (Victoria/South Australia) regions were available for the present study. The Gippsland data were combined, and therefore the plantation regions for model development were Gippsland (GL), Central Victoria (CV) and Green Triangle (GT).

Forest growth and yield models vary in structural complexity and output detail, and from whole-stand to individual-tree resolution. Depending on the availability of data and application requirements, different methods may be used to develop forest growth models (Vanclay 1994). Previous growth modelling for *E. globulus* plantations in Australia, based on limited data, includes:

- A set of whole-stand growth models developed for south-eastern Australia (Wong *et al.* 2000). These models consist of three stand-level component models for predicting the temporal development of stand height, basal area and volume. Models were developed separately for *E. globulus*, *E. nitens* and *E. viminalis*, and a grouping of *E. botryoides*, *E. grandis* and *E. saligna* (Salignae series) using data from permanent plots in 12 plantation species trials in Gippsland and some data from south-eastern South Australia.
- A whole-stand growth model developed for south-western Western Australia (Inions 1992). Because of the lack of growth

data from permanent plots, the model was parameterised mainly using data from temporary plots. Component models were developed for estimating stand basal area and volume respectively. A stand height growth and site index model was also developed using height growth data derived from stem analysis of 87 trees sampled in 57 plots.

- An individual-tree, distance-independent growth model for northern Tasmania (Goodwin and Candy 1986). This model was developed using a limited data set from a single plantation. Component models for predicting tree height and diameter increments were derived. Diameter distributions of trees were modelled using a Beta probability stocking function, and stand mortality was approximated by the 3/2 self-thinning rule.

Most other published forest growth and yield models for *E. globulus* plantations have been developed in Portugal and Spain. These include stand-level models (e.g. Tome *et al.* 1995, 1997), tree-level growth models (e.g. Soares and Tome 2003) and a tree cohort model (i.e. Garcia and Ruiz 2003).

Materials and methods

The main variables and mathematical expressions used in this paper are defined in Table 1.

Data description

Three data sets were used for model development:

Table 1. Mathematical expressions, and abbreviations and definitions of variables

| Symbol | Explanation or definition |
|--|---|
| dbhob | Tree diameter (cm) over bark at 1.3 m height |
| dbhub | Tree diameter (cm) under bark at 1.3 m height |
| H | Total tree height (m) |
| MDH | Dominant height or stand height (m), defined as the mean H of the largest-diameter 100 trees ha^{-1} |
| S | Site index (m), defined as stand height at the reference age of 10 years |
| MDD | Dominant diameter (cm), defined as the mean dbhob of the largest-diameter 100 trees ha^{-1} |
| D_q | Quadratic mean diameter (dbhob, cm) |
| N, BA, V | Stand stocking (trees ha^{-1}), basal area ($\text{m}^2 \text{ha}^{-1}$), volume ($\text{m}^3 \text{ha}^{-1}$) at any age |
| MDH ₁ and MDH ₂ | Stand height (m) at stand age T_1 and T_2 years respectively |
| BA ₁ and BA ₂ | Stand basal area ($\text{m}^2 \text{ha}^{-1}$) at stand age T_1 and T_2 years respectively |
| N_1 and N_2 | Stand stocking (trees ha^{-1}) at stand age T_1 and T_2 years respectively |
| D_0, D_{25}, D_{50} and D_{95} | 0th, 25th, 50th and 95th percentiles (cm) of cumulative diameter (dbhob) distributions |
| h | Height (m) along tree stem above the ground ($0 \leq h \leq H$) |
| d_h | Stem diameter under bark (cm) at height h (m) |
| DBT _{1.3} | Double bark thickness at 1.3 m height from ground (cm) |
| ln | Natural logarithmic transformation |
| exp | The base of natural logarithms (≈ 2.71828) |
| β_0 | Intercept parameter in a regression model |
| $\beta_0, \beta_1, \dots, \beta_k$ | Slope parameters associated with each predictor variable in a regression model |
| $\hat{\beta}_0$ | Estimated intercept parameter in a regression model |
| $\hat{\beta}_1, \hat{\beta}_2, \dots, \hat{\beta}_k$ | Estimated slope parameters in a regression model |
| n | Total number of observations used in a regression |
| rmse | Root mean squared error of a regression model |
| R_{Adj}^2 | Adjusted coefficient of determination of a regression model |

1. Permanent plot data. This data set of repeated measurements of trees in permanent sample plots established by each collaborating organisation included:

- trial (series) information: seedlots, planting stocking, planting date and silvicultural treatments
- site and plot information: aspect, average slope, plot dimensions or area
- multiple measurements of trees: attributes recorded at each measurement include the identification number, status codes for health and mortality, diameter of all trees, and total height of a subset of trees.

The data set was used for the model selection and parameterisation in developing the stand-level component models, and also for the tree height–diameter relationship. Summary statistics for these data are presented in Table 2.

2. Stem taper data. Two sets of sectional stem diameter data from felled trees were available. The first set included 66 trees sampled across Victoria, and the second set included 189 trees sampled in central Gippsland. For each sample tree, stem diameter measurements (over and under bark) were recorded at 0.1 or 0.3 m (stump height), 1.3 m, 2.5 m, and thereafter at 1 or 2 m intervals along the stem, until a 2-cm top diameter was reached. These data were used to develop

the stem taper model and the bark thickness prediction model. Summary statistics for these data are presented in Table 3.

3. Additional permanent plot data. This data set was provided at a later stage of model development, and included information similar to that in the first set. In total, 579 plots in first-rotation *E. globulus* plantations on ex-agricultural sites in the Central Victoria region were available. Among these, 338 plots with three or more measurements were used. These data were reserved for evaluating the prediction accuracy of the developed models.

Model structure and strategy for yield projection

A size-class growth model based on diameter distribution (Vanclay 1994) was used in this study because:

- size distribution information is essential for analysing the structure of plantations and making management decisions (e.g. estimating product assortment, or harvesting and transportation costs)
- the developed model should be flexible to permit analysis of alternative management options (e.g. spacing, thinning)
- available data including tree- and plot-level information should be used efficiently.

Table 2. Summary statistics¹ for permanent sample plot data used to develop the stand-level component models

| Statistic | Region | | |
|---|-----------------------|-----------------------|-----------------------|
| | Green Triangle | Central Victoria | Gippsland |
| Number of sites | 52 | 20 | 14 |
| Number of plots | 138 | 192 | 338 |
| Plot area (ha) | 0.033 – 0.041 – 0.101 | 0.024 – 0.033 – 0.038 | 0.010 – 0.036 – 0.040 |
| Total number of measurements | 362 | 1049 | 949 |
| Number of measurements per plot | 2 – 2.8 – 8 | 4 – 6.3 – 9 | 1 – 3.4 – 7 |
| Measurement interval (y) | 1 – 1.3 – 3 | 1 – 1.1 – 2 | 1 – 2.3 – 6.4 |
| Planting stocking (trees ha ⁻¹) | 1000 – 1143 – 1301 | 960 – 1127 – 1300 | 900 – 1054 – 1236 |
| Age (y) | 1.0 – 3.2 – 12.0 | 2.0 – 5.1 – 10.0 | 1.8 – 6.5 – 12.4 |
| Stand height (m) | 1.2 – 8.6 – 32.6 | 2.5 – 10.5 – 26.3 | 1.7 – 12.3 – 31.1 |
| Stocking (trees ha ⁻¹) | 706 – 1143 – 1297 | 582 – 940 – 1295 | 398 – 1050 – 1200 |
| Basal area (m ² ha ⁻¹) | 2.1 – 21.3 – 49.3 | 0.2 – 19.5 – 33.1 | 0.0 – 19.9 – 37.1 |
| Volume (m ³ ha ⁻¹) | 2.7 – 76.2 – 336.2 | 0.2 – 43.3 – 249.3 | 0.0 – 53.7 – 328.9 |
| Site index (m) | 9.7 – 22.7 – 28.8 | 11.0 – 17.5 – 26.5 | 7.7 – 16.9 – 27.6 |

¹Minimum – mean – maximum

Table 3. Summary statistics¹ for the two sets of sample trees used to develop the stem taper model

| Statistic | Victoria various | Gippsland |
|--------------------------|-----------------------|-----------------------|
| Number of trees | 66 | 189 |
| Age (y) | 5 – 8.7 – 30.2 | 6.4 – 11.0 – 25.1 |
| dbhob (cm) | 6.2 – 27.4 – 57.8 | 7.6 – 18.6 – 34.6 |
| Height (m) | 10.0 – 23.4 – 40.0 | 9.7 – 17.9 – 28.4 |
| Volume (m ³) | 0.011 – 0.676 – 2.959 | 0.002 – 0.182 – 0.765 |
| Measurements per tree | 8 – 13.3 – 19 | 8 – 16.1 – 26 |

¹Minimum – mean – maximum

A basic requirement for growth models based on diameter distributions is the integration of the estimates of total yield of forest stands and the predictions of size class distribution of individual trees (Chang 1987). This is usually achieved by predicting stand attributes using stand-level component models, and then recovering the parameters of a theoretical distribution for tree diameters from the stand attributes predicted at any target age. Various approaches have been developed for such tasks (Vanclay 1994).

Yields may be predicted by using algebraic difference equations (ADE) to project the current stand conditions observed in inventories into the future (Clutter *et al.* 1983). In general, this approach uses the functional form of $Y_2 = f(Y_1, T_1, T_2)$, where Y_2 is stand yield predicted at age T_2 years, and Y_1 is the measured yield at age T_1 years. Desirable properties of an ADE model for yield projection include mathematical consistency, projection path invariance and flexibility in functional form (e.g. polymorphic versus anamorphic models). The stand-level component models used in existing growth models for *E. globulus* plantations (i.e. Inions 1992; Tome *et al.* 1997; Wong *et al.* 2000) and for *E. nitens* plantations (e.g. Candy 1997) were constructed using the ADE approach. To estimate an ADE model, the data need to be arranged into measurement pairs. Borders *et al.* (1988) studied the effect of different data arrangements on model estimation. In the present study, all possible measurement pairs with non-decreasing ages were used.

To develop the size class growth model, stand-level component models were first developed to predict the temporal development of stand height, basal area and stocking respectively. Tree-level component models were also developed for estimating the height–diameter relationship, under-bark diameters along the stem (taper) and stem bark thickness of individual trees. For these purposes, various functional (model) forms were initially evaluated, and the best model form was then selected as the base model for each of the modelled stand or tree characteristics. Details of this preliminary modelling and the evaluation of alternative model forms have been reported by Strandgard *et al.* (2005). The base models then selected for each of the stand and tree component models are presented in Tables 4 and 5 respectively.

Diameter distributions

The cumulative density function of the three-parameter Weibull distribution was used to model tree diameter distributions over time:

$$p(x) = 1 - \exp \left[- \left(\frac{x - a}{b} \right)^c \right], \quad (1)$$

where x represents the response variable (i.e. tree diameter at breast height over bark (dbhob)); a , b , c are the location, scale and shape parameters respectively; and $a \leq x < \infty$. The Weibull distribution is superior to other theoretical distributions because

Table 4. Functional forms selected for the stand-level component models

| Component model | Functional form |
|--------------------------------|--|
| Stand height growth/site index | $MDH_2 = \beta_1 \left[1 - \left(1 - \left(\frac{MDH_1}{\beta_1} \right)^{1/\beta_2} \right)^{(T_2/T_1)} \right]^{\beta_2}$ |
| Stand basal area projection | $BA_2 = BA_1^{(T_1/T_2)^{\beta_3}} \times \exp \left[\left(\frac{\beta_1}{\beta_3} + \frac{\beta_2}{\beta_3} \times S \right) \left(1 - \left(\frac{T_1}{T_2} \right)^{\beta_3} \right) \right]$ |
| Stand stocking projection | $N_2 = \left[\frac{1}{\sqrt{N_1}} + \beta_1 \left(\left(\frac{T_2}{100} \right)^2 - \left(\frac{T_1}{100} \right)^2 \right) \right]^{-2}$ |

Table 5. Functional forms selected for the tree-level component models

| Component model | Functional form |
|---------------------------------------|---|
| Height–diameter | $H = 1.3 + \beta_1 \times MDH \left(\frac{1 - \exp(-\beta_2 \times dbhob)}{1 - \exp(-\beta_2 \times MDD)} \right)^{\beta_3}$ |
| Stem taper | $d_h = \beta_0 + \frac{\beta_1}{1 + \beta_2 h} - \beta_3 h - \beta_4 h^2$ |
| Double bark thickness at 1.3 m height | $DBT_{1.3} = \beta_1 \times \exp \left(\beta_2 - \frac{\beta_3}{dbhob} \right)$ |

of its flexibility in shape and ease of parameterisation (e.g. Bailey and Dell 1973). Weibull distribution-based diameter distributions may be estimated by different methods (Clutter *et al.* 1983). In this study, parameter recovery methods based on moment estimators (ME) (Nanang 1998) and percentile estimators (PE) (Da Silva 1986) were initially evaluated. The PE-based methods were found to be superior and consequently were adopted (see Strandgard *et al.* 2005 for detailed discussions). The method has been used for modelling diameter distributions for various applications in plantations, including testing growth responses to fertiliser application (Bailey *et al.* 1989), studying the impact of inter-specific competition (Knowe 1992) and investigating the effect of site preparation (Knowe and Stein 1995).

The PE-based procedures for modelling diameter distributions over time involve recovering the three parameters of the Weibull distribution analytically from tree diameter percentiles of D_0 , D_{25} , D_{50} , D_{95} and D_q (see Table 1 for definitions) at the prediction ages:

1. The location parameter is estimated using D_0 and D_{50} , and the sample size (n) (i.e. average number of trees included in the sample plots):

$$\hat{a} = \frac{n^{1/3} D_0 - D_{50}}{n^{1/3} - 1}. \quad (2)$$

2. The shape parameter is estimated using D_{25} and D_{95} , and the estimated location parameter (\hat{a}):

$$\hat{c} = \frac{2.343088}{\ln(D_{95} - \hat{a}) - \ln(D_{25} - \hat{a})}. \quad (3)$$

3. The scale parameter is estimated using the estimated location and shape parameters and the quadratic mean diameter (D_q) by solving the positive root of:

$$\hat{b} = \frac{\hat{a}\Gamma_1}{\Gamma_2} + \sqrt{\left(\frac{\hat{a}}{\Gamma_2}\right)^2 (\Gamma_1^2 - \Gamma_2) + \frac{D_q^2}{\Gamma_2}}, \quad (4)$$

where $\Gamma_1 = \Gamma(1 + 1/\hat{c})$, $\Gamma_2 = \Gamma(1 + 2/\hat{c})$ and Γ is the Gamma function.

To apply the PE procedure, models are required for predicting D_0 , D_{25} , D_{50} and D_{95} at any age of interest. These models are developed by relating the observed percentiles of cumulative distributions of tree diameters to stand characteristics such as MDH, MDD, S , BA, N and D_q .

Regional differences

The nonlinear extra sum of squares method (Bates and Watts 1988) was used to test for regional differences in the parameters of selected models for stand height, basal area and stocking. The method has been widely used in forestry, for example to test taper equations (Huang 1994), tree volume equations (Pillsbury *et al.* 1995) and tree height–diameter relationships (Huang *et al.* 2000). Application of the method requires fitting the tested models with dummy variables for indexing every region being compared (full model), as well as the tested models with no dummy variable or

dummy variables for indexing two or more regions combined (i.e. restricted or reduced models). The dummy variables are used to separate data in regressions. For example, a dummy variable (x) is needed for testing the difference between two regions (i.e. $x = 1$ if data are from Region 1, otherwise $x = 0$ for Region 2). The dummy variables are then related to each of the parameters of a tested model using linear equations. The regional difference in the parameters of the tested model is statistically tested using the sum of squared errors of nonlinear regressions for estimating the full and reduced models and associated degrees of freedom respectively.

The appropriate statistic for testing the null hypothesis that there is no difference in the parameters of a tested model between any pairs of regions is:

$$F = \frac{sse(r) - sse(f)}{df(r) - df(f)} \times \frac{df(f)}{sse(f)}, \quad (5)$$

where $sse(f)$ and $sse(r)$ are the sum of squared errors from the regressions for the full and reduced models respectively, and $df(f)$ and $df(r)$ are the degrees of freedom associated with $sse(f)$ and $sse(r)$ respectively. Under the null hypothesis, F follows an F -distribution with the degrees of freedom $df_1 = df(r) - df(f)$ and $df_2 = df(f)$. If the resultant $F \geq F[1 - \alpha; df_1, df_2]$, where $F[1 - \alpha; df_1, df_2]$ is the 100(1 - α) percentile from an F -distribution with the degrees of freedom df_1 and df_2 , the null hypothesis is rejected, indicating a significant difference in the parameters of a tested model between the regions. Therefore, the model should be estimated separately for each region. If $F < F[1 - \alpha; df_1, df_2]$, the null hypothesis is accepted, indicating no significant difference in the parameters of a tested model between the regions, and the model should be estimated by pooling the data from the regions compared.

For each base component model, the test procedure was used to compare all three regions, and each pair among the three regions. The final stand height, basal area and stocking projection models were determined and parameterised based on the results of the tests.

Model parameterisation

The underlying statistical assumptions required for justifying regression analysis, including independent and identically distributed (iid) random errors with a normal distribution and constant variances, may not be met when repeated measurements from permanent plots are used (West *et al.* 1984). Thus the parameter estimates of regression models derived using the ordinary least squares (ols) method may be biased and inconsistent, and hypothesis tests performed for determining the best model and predictor variables invalid. To address these problems, the feasible generalised least squares (fgls) method was used whenever initial ols regressions indicated a potential violation of the underlying statistical assumptions. The fgls method allows variance-covariance structures (i.e. heteroscedasticity and/or autocorrelation) to be specified that better model the variability of the data (Greene 1990). The parameter estimates obtained using the fgls method are unbiased, consistent and asymptotically normally distributed. For example, Rivas *et al.*

(2004) used a nonlinear fgls approach to remove the heteroscedasticity of error variances when estimating a stand height growth model for five pine species in Mexico.

The MODEL procedure in the SAS/ETS module (SAS Institute 1993) was used in all nonlinear regression analyses for estimating stand and tree component models. The procedure can perform the nonlinear ols, and also the fgls estimation for a range of variance-covariance structures. The final stand and tree component models were adjudged by the three criteria: (1) all parameter estimates were statistically significant; (2) the residual plot showed no indication of violating the underlying statistical assumptions (i.e. iid errors); and (3) there was generally good agreement between the predicted and observed yield trajectories (values).

Results

Regional differences

The base models selected for modelling stand height, basal area and stocking (Table 4) were tested for regional differences. There was no significant difference in the parameters of the stocking base models for the three regions, and consequently further investigation was limited to the stand height and basal area base models, with statistical tests (Tables 6 and 7) concluding that:

- significant differences exist in both stand height and basal area base models across the three regions

- for the stand height base model, significant differences exist between the Green Triangle and Central Victorian regions, and between the Green Triangle and Gippsland regions, but not between the Central Victorian and Gippsland regions
- for the stand basal area base model, significant differences exist between the Gippsland and Green Triangle regions, and between Gippsland and Central Victoria, but not between the Green Triangle and Central Victorian regions.

Stand height growth and site index model

The statistical tests suggested that separate stand height growth models should be developed for the Green Triangle, and for the Central Victorian and Gippsland regions combined. However, a reliable model could not be derived for the Green Triangle because the available data were limited to stands aged 4 y or younger. Therefore, it was decided to develop a single stand height growth and site index model for use across all three regions. This model can be improved when data become available from older plantations in the Green Triangle. The fitting algorithm was found difficult to converge if the asymptote parameter β_1 of the stand height model was not fixed. The problem appears to be associated with this specific model form; Candy (1997) had similar difficulty for the same functional form applied to model stand height for *E. nitens* plantations in Tasmania and New Zealand. To overcome this problem, regressions were performed for a fixed value of parameter β_1 , between 40 m and 70 m. The best model was

Table 6. *F*-tests for testing the regional differences in the base stand height model (Equation 1, Table 4)

| Regions compared ¹ | Full model ² | | Reduced model ³ | | <i>F</i> -value ⁶ |
|-------------------------------|-------------------------|-----------------|----------------------------|------|------------------------------|
| | sse ⁴ | df ⁵ | sse | df | |
| GT, CV, GL | 7524 | 2326 | 8028 | 2328 | 78* |
| GT and CV | 1186 | 1283 | 1506 | 1284 | 346* |
| GT and GL | 6700 | 1278 | 7201 | 1279 | 96* |
| CV and GL | 7162 | 2091 | 7163 | 2092 | 0.2 |

¹Green Triangle (GT), Central Victoria (CV), Gippsland (GL)

²Model fitted with pooled data from the regions being compared

³Model fitted with dummy variables for data separation for the regions being compared

⁴sse = sum of squared errors from fitting the reduced or full model

⁵df = degrees of freedom associated with sse

⁶*F*-values estimated using Equation 5, and * = the regions compared are significantly different ($P < 0.05$)

Table 7. *F*-tests for testing the regional differences in the base stand basal area model (Equation 2, Table 4)

| Regions compared ¹ | Full model ² | | Reduced model ³ | | <i>F</i> -value ⁶ |
|-------------------------------|-------------------------|-----------------|----------------------------|------|------------------------------|
| | sse ⁴ | df ⁵ | sse | df | |
| GT, CV, GL | 5569 | 2085 | 6745 | 2091 | 73* |
| GT and CV | 926 | 1155 | 931 | 1158 | 2.2 |
| GT and GL | 4748 | 1039 | 5528 | 1042 | 57* |
| CV and GL | 5463 | 1976 | 5967 | 1979 | 61* |

¹Green Triangle (GT), Central Victoria (CV), Gippsland (GL)

²Model fitted with pooled data from the regions being compared

³Model fitted with dummy variables for data separation for the regions being compared

⁴sse = sum of squared errors from fitting the reduced or full model

⁵df = degrees of freedom associated with sse

⁶*F*-values estimated using Equation 5, and * = the regions compared are significantly different ($P < 0.05$)

adjusted by fit statistics (e.g. R^2_{Adj} rmse), and accuracy statistics estimated using a cross-validation procedure for prediction (e.g. mean error, mean relative error and mean squared error).

The regression residuals from the ols fit showed no indication of violating the underlying assumptions (Fig. 1a). Therefore, the nonlinear fgls regression was not considered, and the best stand height growth model was:

$$MDH_2 = \hat{\beta}_1 \left[1 - \left(1 - \left(\frac{MDH_1}{\hat{\beta}_1} \right)^{1/\hat{\beta}_2} \right)^{T_2/T_1} \right]^{\hat{\beta}_2}, \quad (6)$$

where $\hat{\beta}_1 = 50.0$, $\hat{\beta}_2 = 0.8903$, $R^2_{Adj} = 0.88$, and $rmse = 1.76$ m (Table 8).

The corresponding site index model was obtained by replacing MDH_2 and T_2 with site index (S) and the reference age (i.e. 10 y), respectively:

$$S = \hat{\beta}_1 \left[1 - \left(1 - \left(\frac{MDH}{\hat{\beta}_1} \right)^{1/\hat{\beta}_2} \right)^{10/T} \right]^{\hat{\beta}_2}, \quad (7)$$

where MDH is the stand height measured at any age T y.

There was generally good agreement between predicted and observed MDH trajectories (Fig. 1b).

Stand basal area model

The statistical tests suggested that separate stand basal area models should be developed for Gippsland, and for the Central Victorian and Green Triangle regions combined. An indicator variable (x) was used to index the data records and the three parameters in the basal area base model (i.e. Equation 2 in Table 4) were replaced by the following linear functions:

$$\begin{aligned} \beta_1 &= a_0 + a_1x, \\ \beta_2 &= b_0 + b_1x, \\ \beta_3 &= c_0 + c_1x, \end{aligned} \quad (8)$$

where $x = 1$ if a data record was from Gippsland, and $x = 0$ if the

data record was from the Central Victorian or Green Triangle region. The extended model was estimated using the MODEL procedure in SAS. Regression residuals from the initial ols fit indicated increasing variance as the initial stand age T_1 increased. A weighting function of $T_1^{-\alpha}$, $\alpha = 0.5, 1.0, 1.5$ and 2.0 was then specified for the nonlinear fgls regressions, and with $\alpha = 1$ best for improvement of the residual plot (Fig. 1c) and fit statistics.

The parameter estimates for Equation 8 were:

$$\begin{aligned} \hat{\beta}_1 &= 2.4445 - 0.00146x, \\ \hat{\beta}_2 &= 0.05855 - 0.0605x, \\ \hat{\beta}_3 &= 0.9594 - 0.5506x, \end{aligned}$$

with $R^2_{Adj} = 0.96$ and $rmse = 1.63$ m² ha⁻¹ (Table 8).

Parameter estimates for the stand basal area model (Equation 2 in Table 4) were thus:

1. $\hat{\beta}_1 = 2.4431$, $\hat{\beta}_2 = -0.00195$ and $\hat{\beta}_3 = 0.4088$ for the Gippsland region
2. $\hat{\beta}_1 = 2.4445$, $\hat{\beta}_2 = 0.05855$ and $\hat{\beta}_3 = 0.9594$ for the Central Victorian or Green Triangle regions.

In general, there was good agreement between predicted and observed basal growth trajectories, for example as presented in Figure 1d for Gippsland (i.e. $x = 1$) with $S = 10, 15, 20, 25$ and 30 m.

Stand stocking model

Measurements from the three regions were pooled to estimate the stand stocking projection model (i.e. Equation 3 in Table 4). To test if there was any effect of site quality on stand stocking, a linear function was used to relate the parameter of the model to the site index (S) values of individual plots (i.e. $\beta_1 = a_0 + a_1S$). However, the slope parameter estimate was not statistically significant, and the relationship was not subsequently used. The regression residuals derived from the ols fit indicated no violation of the underlying assumptions (Fig. 1e) and therefore the fgls regression was not pursued.

Table 8. Parameter estimates and fit statistics for the stand-level component models

| Component model | Response variable | Parameter estimate (standard error) | | | | Fit statistic | | |
|--|-------------------|-------------------------------------|--|--|---------------------------------------|---------------|--------|-------------|
| | | $\hat{\beta}_0$ | $\hat{\beta}_1$ | $\hat{\beta}_2$ | $\hat{\beta}_3$ | n | rmse | R^2_{Adj} |
| Stand height (Eqn 6) | MDH ₂ | — | 50.0 (NA ¹) | 0.8903 (0.0101) | — | 2170 | 1.758 | 0.877 |
| Stand basal area (Eqn 2 in Table 4) ² | BA ₂ | — | 2.4445 - 0.00146 x (0.041, 0.003) | 0.05855 - 0.0605 x (0.002, 0.006) | 0.9594 - 0.5506 x (0.012, 0.060) | 2094 | 1.634 | 0.962 |
| Stand stocking (Eqn 9) | N_2 | — | 0.3387 (0.009) | — | — | 2024 | 24.111 | 0.977 |
| Diameter percentiles (Eqn 17) | D_0 | 3.8386 (0.264) | 0.02863 (0.002) | -0.1001 (0.030) | -0.06909 (0.016) | 1245 | 2.012 | 0.555 |
| | D_{25} | 7.6138 (0.203) | 0.03867 (0.002) | -0.1164 (0.011) | -0.06122 (0.006) | 1245 | 1.452 | 0.855 |
| | D_{50} | 8.7702 (0.162) | 0.05166 (0.001) | -0.1423 (0.009) | -0.06640 (0.005) | 1245 | 1.239 | 0.921 |
| | D_{95} | 10.9861 (0.203) | 0.06992 (0.002) | -0.1944 (0.011) | -0.06579 (0.006) | 1245 | 1.591 | 0.918 |

¹Standard error not available when a parameter was fixed during fitting

² x is the region indicator: Gippsland ($x = 1$), Central Victoria ($x = 0$) and Green Triangle ($x = 0$)

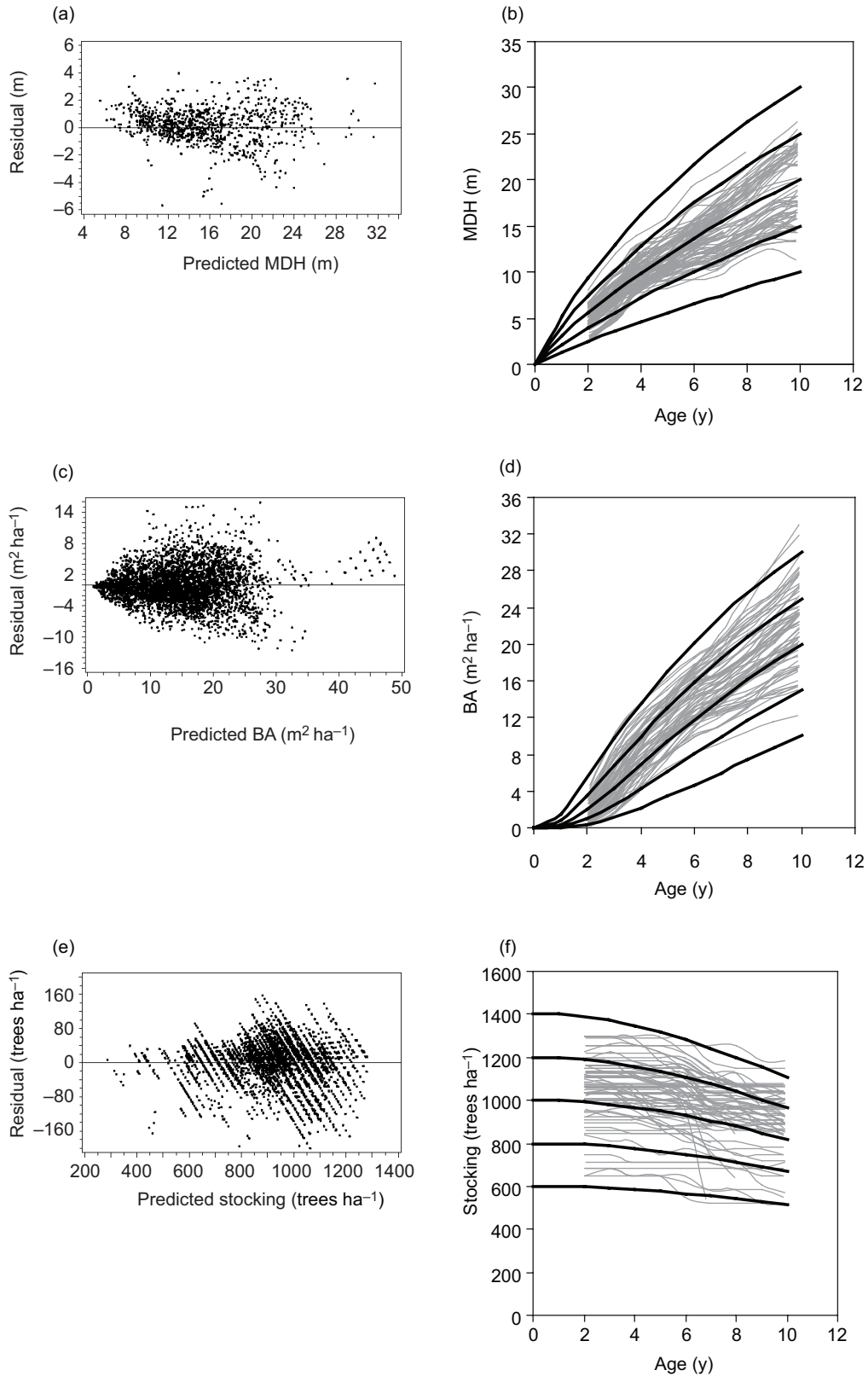


Figure 1. Stand height (MDH), basal area (BA) and stocking (N) component models: (a), (c) and (e) regression residuals versus predicted values; and (b), (d) and (f) observed versus predicted growth trajectories for different initial values

The estimated stand stocking projection (mortality) model was:

$$N_2 = \left[\frac{1}{\sqrt{N_1}} + \hat{\beta}_1 \left(\left(\frac{T_2}{100} \right)^2 - \left(\frac{T_1}{100} \right)^2 \right) \right]^{-2}, \quad (9)$$

where $\hat{\beta}_1 = 0.3387$, $R^2_{Adj} = 0.98$, and $rmse = 24.1$ trees ha^{-1} (Table 8).

Stand stocking predictions for the initial stocking of 600, 800, 1000, 1200 and 1400 trees ha^{-1} , overlain with the observed stocking trajectories, are presented in Figure 1f.

Tree height–diameter model

A relationship between tree height and diameter is required where actual or predicted diameter distributions are the basis for calculation of individual tree volumes (and then by summation to total stand volume, or volume by size classes) using either a tree volume or stem taper equation. Stand characteristics such as age, stocking, basal area or dominant height can improve tree height–diameter relationships (e.g. Bi *et al.* 2000; Staudhammer and LeMay 2000).

Alternative functional forms were initially evaluated for estimating the tree height–diameter relationship (see Strandgard *et al.* 2005 for detailed discussion). For each of the model forms evaluated, different strategies were tested to include stand variables to improve predictions of tree height. In general, stand height (MDH) or site index (S), and dominant diameter (MDD, Table 1) improved predictions of tree height, but stand age, stocking or basal area did not. The following modification of the Chapman-Richards function after Bi *et al.* (2000), i.e. Equation 1 in Table 5, was found to be best:

$$H = 1.3 + \hat{\beta}_1 \times MDH \left(\frac{1 - \exp(-\hat{\beta}_2 \times dbhob)}{1 - \exp(-\hat{\beta}_2 \times MDD)} \right)^{\hat{\beta}_3}, \quad (10)$$

where $\hat{\beta}_1 = 0.9148$, $\hat{\beta}_2 = 0.1504$, $\hat{\beta}_3 = 1.6079$, $R^2_{Adj} = 0.97$ and $rmse = 1.01$ m (Table 9). The regression residuals showed no indication of violating the underlying assumptions (Fig. 2a). In this model, the intercept is fixed at 1.3 to account for tree $dbhob = 0$ cm at $H = 1.3$ m.

In the developed height–diameter relationship, the predictor variables of MDH and MDD provide measures of site productivity and stocking respectively; the prediction of tree height can thus be improved over different site and stocking

conditions. For a given dbhob, the predicted height increases as MDH increases, but decreases as MDD increases. It must be noted that the height–diameter relationship was developed using tree data sampled mainly from plantations with diameters and total heights of trees smaller than 35 cm and 30 m respectively, and height predictions for trees outside these ranges need to be validated.

Tree stem taper model

Alternative functional forms of stem taper models were initially examined, including those of Max and Burkhart (1986) and Kozak (1988). The extended segmented taper model suggested by Goodwin and Thompson (2003) was found to be the most appropriate for the available data, and was selected as the base model for further evaluation (i.e. Equation 2 in Table 5).

To determine the parameters of the base stem taper model, Goodwin and Thompson (2003) first related the parameters β_1 and β_3 analytically to tree height (H). This was realised by imposing the constraints that when $h = H$, $d_h = 0$ (i.e. the predicted stem diameter is zero if the sectional height input for prediction is total height), and that when $h = h_1$, $d_h = d_1$ (e.g. $h = 1.3$ m, then $d_h = dbhob$), where $h_1 \neq H$. These constraints gave:

$$\beta_0 = -\frac{\beta_1}{1 + \beta_2 H} + \beta_3 H + \beta_4 H^2, \quad (11)$$

$$\beta_3 = \frac{dbhob}{H - 1.3} - \frac{\beta_1 \beta_2}{(1 + 1.3\beta_2)(1 + \beta_2 H)} - \beta_4 (H + 1.3). \quad (12)$$

They then related the parameters β_1 , β_2 and β_4 to tree height through the best species-specific relationship selected using a two-stage modelling approach. For *E. globulus* plantations in Tasmania, the relationships selected were:

$$\beta_1 = \gamma_1 H, \quad (13)$$

$$\beta_2 = \frac{\gamma_2}{H}, \quad (14)$$

$$\beta_4 = \lambda_0 + \frac{\lambda_1}{H}, \quad (15)$$

where γ_1 , γ_2 , λ_0 , and λ_1 are parameters to be estimated.

Table 9. Parameter estimates and fit statistics for tree-level component models (see Table 5 for model forms)

| Component model | Response variable | Parameter estimate (standard error) | | | | | Fit statistic | | |
|-----------------------|--------------------|-------------------------------------|---------------------|------------------------|---------------------|---------------------------------------|---------------|-------|-------------|
| | | $\hat{\beta}_0$ | $\hat{\beta}_1$ | $\hat{\beta}_2$ | $\hat{\beta}_3$ | $\hat{\beta}_4$ | n | rmse | R^2_{Adj} |
| Height–diameter | H | — | 0.9148 (0.001) | 0.1504 (0.002) | 1.6079 (0.012) | — | 25831 | 1.007 | 0.971 |
| Stem taper | d_h | Eqn 11 ¹ | 0.4459 H (0.005) | 85.3142 / H (4.231) | Eqn 12 ² | 0.0228 + 0.4185 / H (0.023, 0.042) | 4001 | 1.118 | 0.983 |
| Double bark thickness | DBT _{1.3} | — | 1.0511 (0.051) | 1.7910 (1.135) | 19.5889 (3.241) | — | 191 | 0.659 | 0.618 |

¹The taper model parameter $\hat{\beta}_0$ is estimated using Equation 11

²The taper model parameter $\hat{\beta}_4$ is estimated using Equation 12

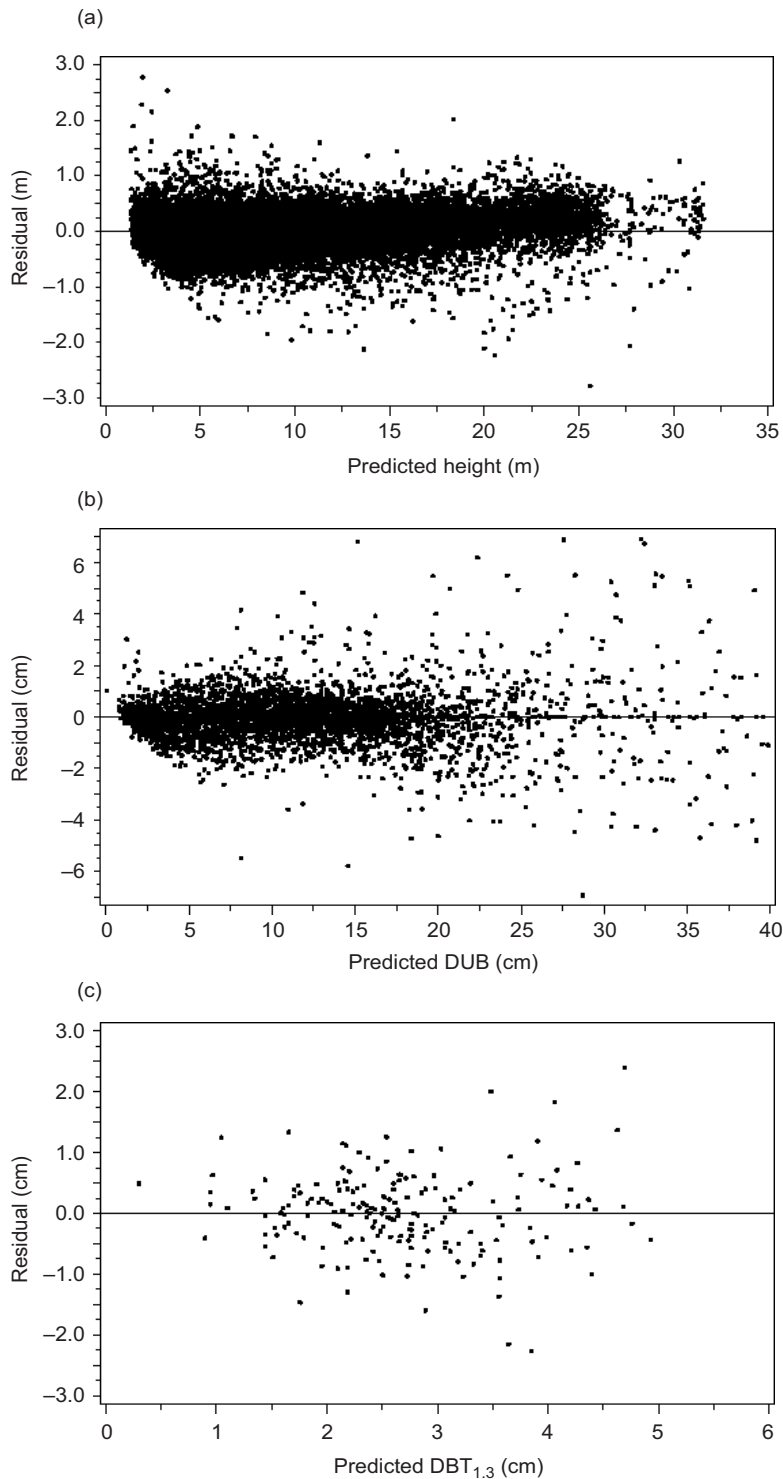


Figure 2. Regression residuals graphed against the predicted values for (a) tree height-diameter model (Equation 1, Table 5), (b) stem taper model (Equation 2, Table 5), and (c) bark thickness model (Equation 3, Table 5)

In the present study, alternative relationships for the parameters β_1 , β_2 and β_4 were firstly compared with those selected by Goodwin and Thompson (2003, i.e. Equations 13–15) using the available data. This was implemented by estimating the base model (Equation 2 in Table 5) and the relationships specified for β_0 , β_1 , β_2 , β_3 and β_4 (i.e. Equations 11–15) using the nonlinear simultaneous equations fitting procedure in the SAS/ETS

application (SAS Institute 1993). The constraint, $h_1 = 1.3$ m, and $d_1 = \text{dbhub}$ were used in all fittings. The results confirmed that Equations 13–15 were also appropriate and the parameter estimates for these relationships were:

$$\begin{aligned}\hat{\beta}_1 &= 0.4459H, \\ \hat{\beta}_2 &= \frac{85.3142}{H}, \\ \hat{\beta}_4 &= 0.02280 + \frac{0.4185}{H}.\end{aligned}$$

The resultant stem taper model had $\text{rmse} = 1.12$ cm, and $R^2_{\text{Adj}} = 0.98$ (Table 9). The residual plot is shown in Figure 2b.

In application, the parameters β_0 , β_1 , β_2 , β_3 , and β_4 will be first predicted from the observed H and dbhub of a sample tree using Equations 11–15. The predicted parameters are then applied to the taper model (Equation 2 in Table 5) for estimating the under-bark stem diameters along the stem, and corresponding sectional volumes. When the sectional height to be predicted is total height, the predicted volume will be total under-bark volume of a sample tree. To validate the model, we showed in a separate study using a sequential accuracy testing approach (Wang and Baker 2005) that the predictions of under-bark stem diameters derived from this stem taper model would have an acceptable accuracy for most expected applications.

Tree stem bark thickness model

Tree dbhub and total height are required as inputs to the developed stem taper model for predicting underbark stem diameters. Dbhub is estimated as the difference between dbhob and double bark thickness ($\text{DBT}_{1.3}$), but because the latter is not commonly measured during inventory, a bark thickness prediction model is then required. The best model found for this purpose based on the available data was:

$$\text{DBT}_{1.3} = \hat{\beta}_1 \times \exp\left(\hat{\beta}_2 - \frac{\hat{\beta}_3}{\text{dbhob}}\right), \quad (16)$$

where $\hat{\beta}_1 = 1.0511$, $\hat{\beta}_2 = 1.7910$, $\hat{\beta}_3 = 19.5889$, $R^2_{\text{Adj}} = 0.62$, and $\text{rmse} = 0.66$ cm (Table 9). The residual plot is shown in Figure 2c.

Diameter percentiles models

Quadratic mean diameter (D_q), stand basal area (BA) and age (T) were identified as the best stand variables for predicting the percentiles D_0 , D_{25} , D_{50} and D_{95} of the cumulative diameter distribution at any age. The base model selected on the basis of fit statistics and residual analysis was:

$$\hat{D}_{\text{pct}} = [\hat{\beta}_0 + \hat{\beta}_1 D_q \times T][1 - \exp((\hat{\beta}_2 + \hat{\beta}_3 \text{BA})T)], \quad (17)$$

where \hat{D}_{pct} , is the predicted value for D_0 , D_{25} , D_{50} or D_{95} .

The fit statistics and parameter estimates of the prediction models are presented in Table 8. In application, BA and N at age T are first predicted from the stand basal area and stocking projection models respectively (i.e. Models 2 and 3 respectively in Table 4). D_q is then calculated based on the predicted BA and N .

Model application

The developed stand- and tree-level component models, together with the models for predicting the four percentiles of diameter distributions can be used to construct a whole-stand distribution growth and yield model (Vanclay 1994, p. 23). This size-class growth model can be used for projecting the characteristics of plantations sampled in inventories into the future for wood flow analysis and management planning. The procedures are:

1. Estimate the site index (S) for a sample plot or site from the stand height (MDH) measured at age T y using the site index model (Equation 7).
2. Set the measured stand height, basal area and stocking, the estimate of site index and the inventory age to be the initial stand conditions (i.e. MDH₁, BA₁, N_1 and T_1) respectively for the three stand-level models (i.e. Equations 1–3 in Table 4).
3. Predict stand height, basal area and stocking at the prediction age T_2 (i.e. MDH₂, BA₂, and N_2) from the stand-level models respectively with their parameter estimates (Table 8).
4. Estimate stand volume (V_2) at T_2 using the following stand volume equation (Wong *et al.* 2000):

$$V_2 = 0.3983 \times BA_2 - 0.0661 \times MDH_2 + 0.35366 \times BA_2 \times MDH_2. \quad (18)$$

5. Estimate the diameter percentiles at age T_2 (D_0, D_{25}, D_{50} and D_{95}) using Equation 17 and their parameter estimates respectively (Table 8), where $BA = BA_2$, $T = T_2$, and $D_q = \sqrt{(40\,000/\pi) (BA_2/N_2)}$.
6. Predict the location and shape parameters of the Weibull distribution at age T_2 (a and c) using Equations 2 and 3. Negative values for a should be set to zero.
7. Solve Equation 4 for the Weibull scale parameter b (i.e. positive root of Equation 4) using the estimated a , c and D_q .
8. Predict the probabilities (f_i) of diameter occurrence by 1 cm intervals of tree dbhob as:

$$f_i = \exp \left[- \left(\frac{L_i - a}{b} \right)^c \right] - \exp \left[- \left(\frac{U_i - a}{b} \right)^c \right], \quad (19)$$

where L_i and U_i are the lower and upper limits respectively

for i th diameter class $i = 1, \dots, k$, and k is the total number of diameter classes. In application, the lower limit of the first diameter class should be set to the location parameter a (i.e. $L_1 = a$ and $U_1 = a + 1$), which corresponds to the estimated minimum tree diameter, and k should be determined with the condition of $\sum_{i=1}^k f_i = 1$.

9. Estimate the stocking for each diameter class by multiplying the estimated f_i with the stand stocking, N_2 , predicted as at Step 3.
10. Estimate the volumes for each diameter class. For this, mean volume for a tree corresponding to the mid-point of each diameter class can be determined using the developed height–diameter relationship (Equation 10) and taper model (Equation 2 in Table 5 with parameter estimates as in Table 9).
11. Reset the initial conditions (predictor variables) at age T_1 of the stand-level models to be the predicted values at age T_2 obtained in Step 3 (i.e. MDH₂, BA₂, N_2), and prediction age to be $T_2 + 1$ (if annual predictions are required), and repeat Steps 2 to 10 until the target age or prediction interval is reached.

In this procedure, the predictions from the stand-level models are used as a control, and the stand stocking, basal area and volume derived from the predicted diameter distributions are adjusted to be compatible with the stand-level predictions (Fig. 3). This approach has been widely used (e.g. Nepal and Somers 1992; Cao and Baldwin 1999; Wang and Hamilton 2003), and an appropriate algorithm and computer program is required for iterative adjustments.

Accuracy evaluation

The prediction accuracy of the stand growth models developed in the present study was evaluated using measurements from the reserved permanent plot data set described earlier. Stand (dominant) height, dominant diameter (MDD) and basal area values were calculated for every combination of plots and measurements. Volumes of individual trees were estimated using the height–diameter relationship developed in this study, and an existing tree volume equation (Wong *et al.* 1999). Stand volumes for each combination of plots and measurements were the sum of volumes of individual trees. Because stand-level models developed have the algebraic difference equation form, the calculated stand characteristics were rearranged into measurement pairs with non-decreasing ages for yield predictions. Summary statistics for the last measurement data from the 338 permanent plots used are presented in Table 10.

Table 10. Summary statistics for the last measurements of permanent sample plots ($n = 338$) used for accuracy evaluation

| Statistic | Age (y) | MDH (m) | BA (m ² ha ⁻¹) | V (m ³ ha ⁻¹) | MAI (m ³ ha ⁻¹) | S (m) |
|-----------|---------|---------|---------------------------------------|--------------------------------------|--|-------|
| Mean | 5.8 | 11.3 | 13.4 | 61.3 | 10.5 | 16.9 |
| Minimum | 4.9 | 4.6 | 2.2 | 6.3 | 1.2 | 8.0 |
| Maximum | 7.0 | 18.6 | 29.4 | 170.1 | 34.2 | 25.6 |

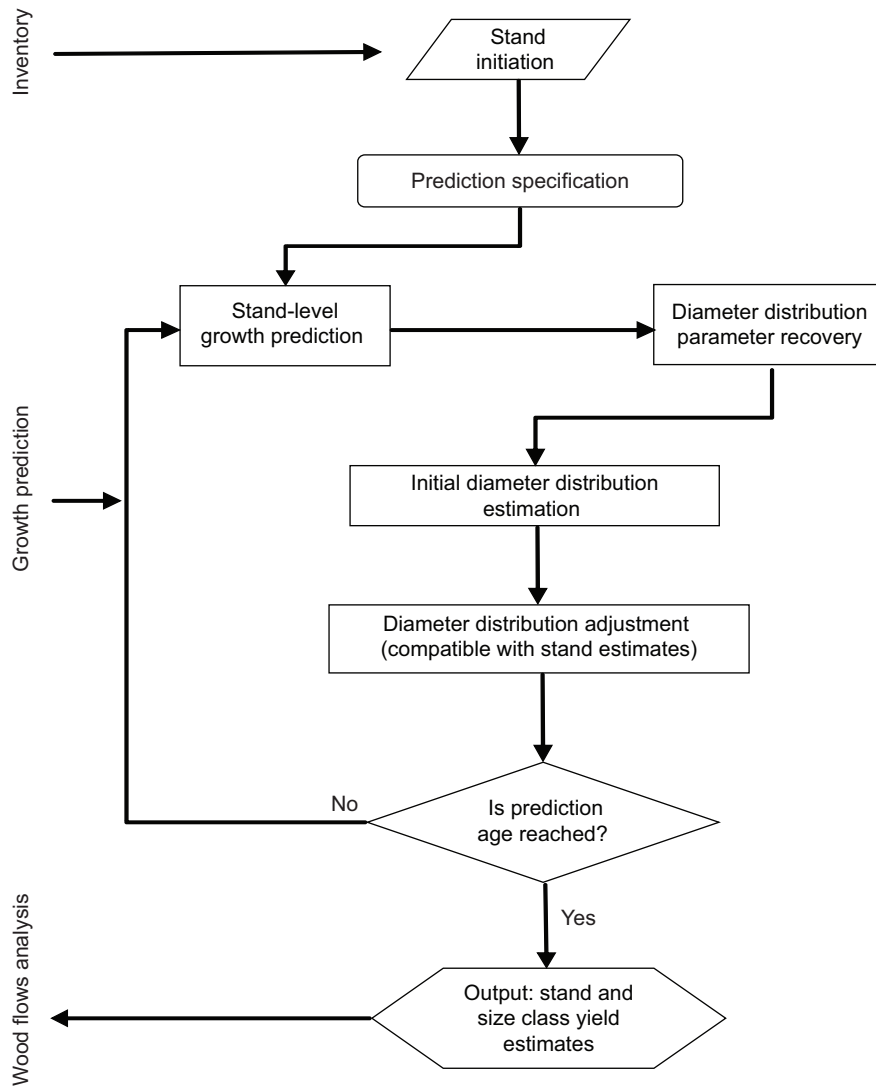


Figure 3. Flowchart illustrating application of the developed growth model

Table 11. Overall accuracy of predictions derived from stand growth models ($n = 1997$)

| Accuracy measure ¹ | Mean | Minimum | Maximum |
|---------------------------------------|--------|---------|---------|
| Stand height: | | | |
| MD (m) | -0.66 | -5.85 | 4.13 |
| MPD (%) | -7.34 | -68.72 | 28.32 |
| MSD | 2.82 | 0.05 | 33.61 |
| Stand basal area: | | | |
| MD (m ² ha ⁻¹) | 0.31 | -3.96 | 7.48 |
| MPD (%) | 1.56 | -63.53 | 45.91 |
| MSD | 2.28 | 0.05 | 33.96 |
| Stand volume: | | | |
| MD (m ³ ha ⁻¹) | 1.01 | -36.4 | 46.1 |
| MPD (%) | 1.06 | -86.52 | 56.21 |
| MSD | 115.91 | 0.04 | 607.53 |

¹MD = Mean difference between observed and predicted values

MPD = Mean percent difference between observed and predicted values

MSD = Mean squared difference between observed and predicted values

For each stand characteristic evaluated, three statistics were used to measure the prediction accuracy (Table 11):

1. Mean difference (bias) ($MD = \Sigma(y_i - \hat{y}_i) / n$), where y_i and \hat{y}_i are the measured and predicted values respectively, and n is the total number of measurement pairs used for the comparison. MD measures the overall unbiasedness of predictions.
2. Mean percent difference (MPD(%)) = $[\Sigma(y_i - \hat{y}_i) / y_i] \times 100 / n$. MPD measures the overall mean bias in a relative unit.
3. Mean squared difference (MSD = $\Sigma(y_i - \hat{y}_i)^2 / n$). MSD measures the total accuracy of prediction, which accounts for both unbiasedness and precision of prediction (Reynolds 1984).

Mean bias for predicted stand heights was relatively small (-0.7 m), mean per cent bias was about -7.3% of the observed values, and the overall accuracy, accounting for both bias and imprecision was 2.8. Similarly, mean bias in predicted stand basal areas was relatively small (0.3 m^2 ha^{-1}), and about 1.6% of the observed values with an overall accuracy of 2.3. Mean bias in predicted stand volumes was 1.0 m^3 ha^{-1} , about 1.1% of observed values. The corresponding MSD was 116; that indicates relatively high variation in predicted stand volume. However, for a prediction interval of 5 y or less, average bias in predictions should be expected to be within ± 1.0 m for stand height, ± 0.5 m^2 ha^{-1} for basal area, and ± 1.0 m^3 ha^{-1} for stand volumes, if the developed models are applied to predict future wood yields for a plantation population based on the inputs (current stand characteristics) observed in a large number of sample plots established across the population. Graphs of predicted versus observed stand height, basal area and volume for the stand-level component models applied to the validation data set are presented in Figure 4.

Discussion

The stand- and tree-level models developed here for *E. globulus* plantations are the best representation of the long-term growth measurements (yield trajectories) from the Gippsland, Central Victorian and Green Triangle regions that were made available to the present study. Predictions derived from the developed stand-level models represent the mean growth for plantations: (i) in the range of climatic (e.g. rainfall distribution patterns) and edaphic conditions (dominantly former agricultural sites) sampled in these regions, (ii) established and managed with similar silvicultural practices (planting stocking 1000–1200 trees ha^{-1} , unthinned), and (iii) for the age range represented by the data (less than about age

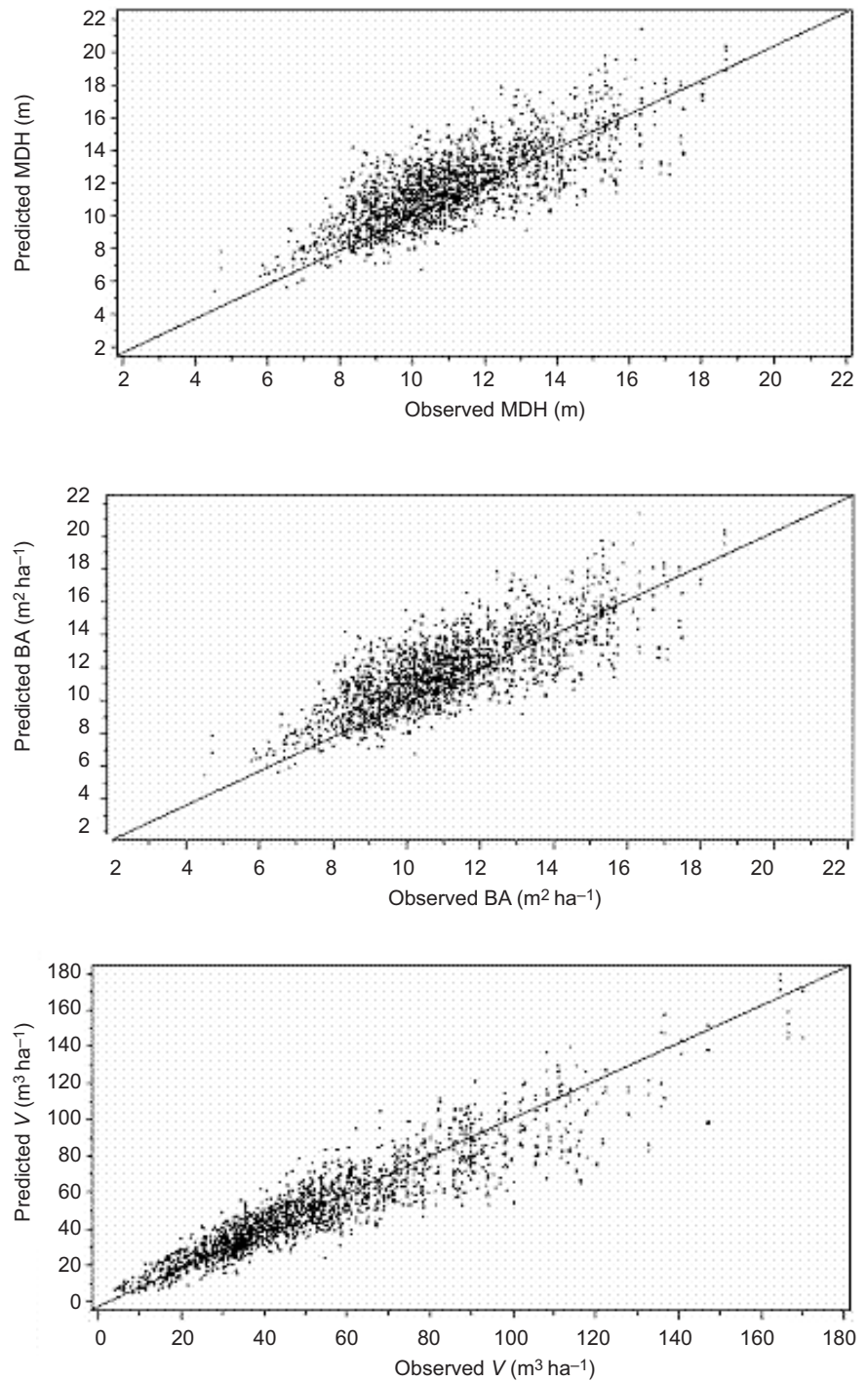


Figure 4. Predicted versus observed stand height (MDH), basal area (BA) and volume (V) for the stand-level component models applied to the validation data set

12 y), used in model selection and parameterisation. These models should be validated before being applied to plantations grown under different conditions. Wang and LeMay (1996) and Wang *et al.* (1996) developed statistical testing approaches for such applications.

The stand yields predicted from the developed models generally agreed well with observed values from the permanent sample plots, which are independent of model parameterisation. Accuracy evaluation indicated that for a prediction interval of 5 y or less,

the average biases in predictions were generally small and within 8.0% of measured stand heights, 3.0% of measured basal areas and 2.0% of measured stand volumes. Thus these models are reliable for projecting mid-rotation (i.e. 5–6 y) inventory data to rotation age (i.e. about 10 y) for wood flow analysis and strategic or management planning. Greater accuracy is expected for predictions over intervals 2–3 y from pre-harvest inventory for tactical planning of wood flows.

The stand and tree models, together with the Weibull distribution-based diameter distribution model, are useful for deriving yield estimates by size (dbhob) classes. This information is essential for analysing the structure of managed plantations and making management decisions, particularly those associated with product assortment, recovery and harvesting costs.

The models may be extended to simulate the response of *E. globulus* plantations to a range of silvicultural options for determining optimal management regimes. However, additional component models need to be developed for stand initiation under a range of silvicultural treatments (e.g. different planting densities). Also, models that can predict growth responses to different silvicultural treatments, particularly spacing and thinning, need to be developed using growth data from permanent plots in experimental trials.

The models can also be extended to incorporate the key environmental variables that are known to affect tree growth, so providing improved site-specific predictions and providing sensitivity to variation in climate. For example, Wang *et al.* (2007) used a non-linear mixed-effects modelling approach to incorporate rainfall and temperature into a stand height growth model for *E. globulus* plantations in Central Victoria.

The development of stand growth models should be undertaken as a continuous process in order to make use of new data from permanent sample plots representing different site and silvicultural conditions, and reflecting the results of tree improvement. We suggest that where there is a diversity of plantation investors, owners and managers such as there is for *E. globulus* in southern Australia, model development and validation can be undertaken most efficiently as a collaborative effort and that publication contributes generally to long-term confidence in this industry.

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Developing a carbon stocks and flows model for Australian wood products

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Summary

This paper describes the development of a model for estimating Australia's stocks and flows of carbon in harvested wood products, including estimates of atmospheric emissions. The model estimates emissions in various forms, including those from wood products contained in Australia, encompassing both domestically produced (net of exports) and imported wood products. This estimate is the basis of Australia's National Greenhouse Gas Inventory report on wood products. The model can also estimate emissions from all (and only) wood products produced in Australia, and a third variant that presumes emissions from wood products at the time of harvest.

The model represents a collaborative effort, involving relevant Commonwealth and state government agencies, industry groups and research bodies. The model uses available statistics on log flows from forest harvest and estimates of the carbon content of the various wood products processed (for example, sawn timber, plywood, pulp and paper and woodchips) to determine carbon inputs to wood products. The model uses estimates of the decay period of various classes of wood product to calculate the pool of carbon in wood products. Crosschecking with independent input data was done wherever possible to test the robustness of various input data used in the model development.

The model is built in Microsoft Excel with all rate and age parameters easily accessed and varied for sensitivity testing using the @Risk software. Wood products in use are assigned to young-, medium- and old-age pools. Simulated losses of wood products from their service life occur from each of the young-, medium- and old-age pools. Material leaving service is either transferred to bioenergy, added to landfill, recycled or emitted to the atmosphere. Losses of carbon can also occur from the landfill pool.

The recorded imports and exports of wood products are used to calculate emissions under two approaches. The first is from wood products produced in Australia (but not necessarily remaining within Australia), and the second from wood products stored in Australia (wherever they were produced). Further simulations, with and without consideration of storage and emissions from landfill, are then run for each approach. The results show that an

accounting approach that presumes emissions from wood products at harvest over-estimates emissions to the atmosphere when compared with approaches that consider the service life of wood products. The storage of wood products in landfill is also significant.

Keywords: models; forest products; stocks; lifespan; carbon; flow; greenhouse gases; Australia

Introduction

Wood product carbon emissions are included under the 1996 (Revised) Intergovernmental Panel on Climate Change (IPCC) Guidelines for the United Nations Framework Convention on Climate Change (IPCC 1997). They are reported in the Land Use, Land Use Change and Forestry part of Australia's National Greenhouse Gas Inventory (NGGI) where they arise from the service life of products. The Waste section of the NGGI reports emissions from landfill.

Under the inventory guidelines countries may elect to report harvested wood products, but only if the national stock of products is increasing. Although wood products may be reported in an NGGI, they are excluded from accounting under the Kyoto Protocol (UNFCCC 1997). This is prescribed in the Marrakech Accords (UNFCCC 2002) and the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC 2003). The Marrakech Accords defer further decisions on the accounting treatment of harvested wood products to future negotiations. Some later technical documentation has been prepared (UNFCCC 2003) and submissions on potential accounting treatments sought. The IPCC 2006 Inventory Guidelines (IPCC 2006) provide some methodological guidance, but do not specify accounting treatments. The methodological guidance expands on that of the early IPCC (Dakar) workshop (Brown *et al.* 1998) that considered potential accounting treatments.

Australia's NGGI reports emissions when (in the year of inventory) and from where (the country) they occur. Therefore, Australia's NGGI reports emissions from wood products held in Australia. Internationally, accounting options under consideration include treating the transfer of carbon in harvested wood across

national boundaries as a carbon credit (stocks increase) in the receiving country, and as a stock loss (treated as an emission) in the producing country. Other options include the producing countries monitoring and reporting emissions from harvested wood products they produce as emissions occur in other countries.

This paper focuses on developing a national wood products carbon account for Australia's NNGI, and provides contrasting outcomes for accounting treatments beyond those of when and where the emissions occur. To consider the life cycle effects of harvested wood products after their service life (that are reported as Waste under the IPCC Guidelines) the model is extended to include disposal in landfill.

Countries other than Australia report on wood products in their NNGIs (for example, USEPA 2006) or have otherwise prepared national estimates (for example, Pingoud *et al.* 2003). The input data, modelling methods and accounting frameworks used vary considerably. As developing the Australian model did not draw on these international parallels, they are not reviewed here.

A national database of domestic wood production and trade, including import and export quantities, has been kept since 1944 by the Australian Bureau of Agriculture and Resource Economics (ABARE). This consistent and detailed collection of time-series data provides a sound basis for developing a national wood products model. Jaakko Pöyry Consulting were initially engaged by the National Carbon Accounting System (NCAS) to develop a national carbon accounting model for wood products, and that work provides the forerunner model to that adapted and described here. The early model development is reported in detail in the National Carbon Accounting System Technical Reports No. 8 (Jaakko Pöyry 1999) and No. 24 (Jaakko Pöyry 2000). Updates and model refinement were subsequently undertaken by MBAC Consulting and the NCAS. Jaakko Pöyry provided a quality assurance review of the model as described here.

Approaches to carbon accounting

Accounting approaches for carbon emissions from timber harvesting and wood products reported in this paper include:

1. Presumed emissions at harvest

This approach records all domestic and exported wood and wood products and associated emissions in an Australian account, and therefore reflects the wood product produced in Australia. No wood products carbon pools develop using this approach. This is the IPCC default approach.

2. From wood products grown in Australia (wherever the product decays)

This approach accounts for all wood products and their emissions arising from wood grown in Australia, regardless of the country in which the product finally decays. Both the destination of exported raw material and wood products, and the final products that they are converted into, need to be known. This approach needs a division of all wood products grown in Australia into two categories: wood remaining in Australia, and wood exported from Australia. However, as only the destination and not the fate

of wood products exported from Australia is known, it is presumed here that the life cycle of products will be the same as if they were kept in Australia.

This assumption may not hold where products exported from Australia are used for different end-uses and are affected by different environments at their final destination. Decay rates for each country would be needed to determine the rate at which carbon is released into the atmosphere under local conditions, and these processes separately modelled. An added complication is the need to track wood products re-imported to Australia (for example, Australian woodchips exported to Japan, converted to paper, and subsequently imported by Australia). For simplicity, and because of lack of knowledge of product use and decay in other countries, decomposition of all products is treated according to Australian uses and conditions.

3. From wood products stored in Australia (wherever the source)

This approach accounts for emissions from all wood products within Australia, regardless of their country of origin. Exported wood products are accounted for by the importing country. The amount of material exported is deducted from the total production, with total imports added, to derive the amount of material available for emissions within Australia. The origin of imported wood products is irrelevant. However, Australia must monitor the total flow of imported wood products into various pools.

Model components

Information for the following components of the model has been obtained and examined:

- log flow from the forest: current annual production data were obtained by species groupings and product classes, for example, sawlogs, veneer logs, pulp logs, roundwood and other (including sleepers etc.)
- fibre flow from processing: data on the intake of raw materials to the various processing options and the output of products and by-products have been used in the model to estimate the total tonnes of carbon produced each year under various end product classes
- import and export quantities of wood products
- recycling
- entry to and decomposition in landfill
- use for bioenergy
- other losses to the atmosphere.

Life cycles, wood flows and the wood products carbon pool

Estimates of the life cycles and wood flows for each class of wood product are reported in Jaakko Pöyry (1999, 2000), and methods for estimating the existing pool of carbon in wood products proposed. Data for annual log removals are available through the Australian Forests Products Statistics published quarterly by ABARE. Data are also available through the Levies Management Unit of the Australian Department of Agriculture,

Fisheries and Forests, for the Forest and Wood Products Research and Development Corporation (FWPRDC). Relevant state forest services also publish data on log removals, and these provide a valuable crosscheck on ABARE data.

ABARE includes cypress pine in coniferous logs and does not provide separate figures for these species. The volume of cypress pine log removals was estimated by applying a conversion factor to sawnwood consumption.

Wood flow

The model develops wood flows separately for each sector of the forest products industry and these are integrated to account for cross-linkages. This is important in accounting for waste or by-products which themselves may be used as resources by other parts of the industry. In conjunction with the wood flows and the estimated life cycle of timber products, this model enables the total and future carbon pools to be estimated. Import and export data were obtained from the ABARE reports by end-use categories. Details of the flows can be found in Jaakko Pöyry (1999, 2000).

In broad terms, the parts of the model developed for each sector are similar, using:

- an estimate of raw materials input, whether of sawlogs, woodchips ex-sawmill or pulp logs
- an estimate of the products of processing, for example, 'x'% sawdust, shavings or sander dust for on-site energy generation or compost, 'y'% woodchips for other manufacturing processes, 'z'% of sawn timber products, panel products, paper, etc.
- an estimate of the fraction of products by product categories, depending on whether their expected end-use is long-term or short-term; for example, framing timber, dry dressed boards, cases and pallet stock, panel products for use in house construction, panelboards for use in furniture and cabinets, newsprint paper, writing and printing paper, etc.
- a final figure for total Australian consumption by end-use categories, converted to wood-fibre content (oven-dry weight) and to tonnes of carbon.

Treatment of bark

Bark has not been separately accounted for in this study. We regarded all bark as being a part of logging slash (harvesting residue) and accounted for under in-forest logging operations, for the following reasons:

- logs are sold with log volumes recorded on an underbark basis
- in most hardwood operations, logs are debarked in the field
- in softwood operations, some bark is lost before the logs reach the mill; most of this loss occurs during mechanised delimiting and log docking operations
- most softwood bark recovered at the mill is used for garden mulch which has decay characteristics similar to those of logging slash.

Softwood bark is a significant source of carbon, with total bark varying from about 35% of underbark log volume (not oven-dry weight) in Caribbean pine to 20% in radiata pine and hoop pine.

As the fraction of softwood bark used for energy co-generation is likely to increase, it may be reasonable to review this treatment in future.

While this approach is suitable for accounting for wood products at a continental scale, it is a general assumption that should not be applied when calculating a stand-based carbon balance. The fraction of bark removed from the site may have a significant impact on stand carbon balance.

Basic density and carbon content

Estimates of basic density and carbon content (Table 1) are relevant to all the processing options, and the choice of values has a significant bearing on the outcome. For all sawn timber, treated softwood and hardwood poles, etc., weighted basic densities for the species involved have been applied across each category. Basic density is defined as oven-dry weight divided by green volume and the values adopted are based on Ilic *et al.* (2000). A different approach was used for board products and paper, however, because these have been subjected to varying amounts of compression during manufacture: their basic densities were derived from the air-dry density of the finished products.

The carbon content of dry matter is assigned values ranging from 0.4 to 0.53 of the oven-dry (bone-dry) weight in the literature. A figure of 0.5 is used in the model: this value is commonly used elsewhere and is a median value among those of Gifford (2001).

Values for manufacturing parameters other than basic density and carbon content came from interviews with representatives of various industry associations and individual sawmilling companies. The issues addressed included:

- recoveries of green sawn timber, sawdust and chip
- sawn sizes and corresponding dressed sizes
- the range and proportions of products produced.

Weighted averages of the information received provided realistic estimates for the various species and industry sectors except hardwood sawmilling.

Wood flows from processing

Wood flows in the various wood products produced in Australia have been developed under the following species or industry headings:

- Softwood sawmilling
- Hardwood sawmilling
- Cypress sawmilling
- Plywood
- Particleboard and medium-density fibreboard (MDF)
- Pulp and paper
- Preservative-treated softwood
- Hardboard
- Hardwood poles, sleepers and miscellaneous
- Export of woodchips and logs.

Table 1. The basic densities, and moisture and carbon contents used in the model

| Property and product | Value |
|--|-------|
| Carbon fraction | |
| Softwood sawn timber: fraction of dry matter that is carbon, by weight | 0.50 |
| Particleboard: fraction of dry matter that is carbon, by weight | 0.40 |
| MDF: fraction of dry matter that is carbon, by weight | 0.40 |
| Basic density (kg m ⁻³)* | |
| Softwood sawn timber | 460 |
| Hardwood sawn timber | 630 |
| Cypress sawn timber | 600 |
| Plywood (softwood and hardwood) and veneer | 540 |
| Particleboard | 520 |
| Medium-density fibreboard (MDF) | 600 |
| Hardboard | 930 |
| Softboard | 230 |
| Pulp and paper: paper | 1000 |
| Pulp and paper: softwood | 430 |
| Pulp and paper: hardwood | 500 |
| Pulp and paper: wastepaper | 1000 |
| Pulp and paper: pulp | 1000 |
| Paper and paperboard imports and exports, on average | 1000 |
| Chips and logs for export: softwood logs | 415 |
| Chips and logs for export: hardwood logs | 630 |
| Hardwood poles, sleepers and miscellaneous | 790 |
| Moisture content of green wood (ratios) | |
| Softwood chips — weight of water : weight of wood substance | 1.10 |
| Hardwood chips — weight of water : weight of wood substance | 0.90 |

*Basic density = (mass of oven-dry wood in kg) / (volume of green wood in m³)

Softwood sawmilling

Softwood processing is very efficient, and nearly all softwood mills now have no waste. All slabs and edgings are chipped for paper pulp or panelboard feedstock, and sawdust and shavings are used for boiler fuel to provide energy for kiln drying. The destinations of sawlogs and sawn timber products were derived from representative sawmills in South Australia, Tasmania, Queensland and the ACT, and from Pine Australia. Import and export figures were derived from ABARE's Forest Products Statistics. The basic density of 415 kg m⁻³ used ('chips and logs for export: softwood logs') is from Ilic *et al.* (2000) and Gardner and Ximenes (*pers. obs.*), being a weighted average of the respective densities at harvest of radiata pine, slash pine, Caribbean pine and hoop pine.

Hardwood sawmilling

Hardwood plantation production has been included in the total hardwood removals. Most of this material is currently of pulp log quality, but more sawlogs will be harvested as the resource matures. The hardwood sawmilling sector is far more complex and varied than any of the other sectors of the industry. There are at least ten major forest species throughout the country, all having different densities and shrinkage rates, and to a great extent having different end-uses. Assumptions on the product outturn from hardwood sawmilling were based on information from the

Victorian Association of Forest Industries and a large sawmilling company running mills in Queensland, NSW and Tasmania. Data on sawlog volumes produced, imports and exports were from ABARE.

A basic density of 630 kg m⁻³ was assumed for hardwood sawlogs. This is an average of data for the following ten commonly logged hardwoods: spotted gum (*Corymbia maculata*), blackbutt (*Eucalyptus pilularis*), rose gum or flooded gum (*E. grandis*), jarrah (*E. marginata*), karri (*E. diversicolor*), mountain ash (*E. regnans*), alpine ash (*E. delegatensis*), silvertop ash (*E. sieberi*), brown barrel (*E. fastigata*) and messmate stringybark (*E. obliqua*). The basic density assumed for poles and sleepers was 790 kg m⁻³. This is an average of figures for spotted gum, ironbark, and blackbutt — the main species used. Hardwood chips have lower average density than sawlogs, poles or sleepers as they contain a wider range of species as well as younger regrowth and plantation material. An average basic density of 630 kg m⁻³ was adopted.

Cypress sawmilling

The quantity of logs removed is small and the data are included in the coniferous forest information in ABARE quarterly reports. Some cypress pine chips are used in panelboard manufacture, but the products are principally green framing, high-value flooring and dressed panelling.

Plywood (softwood and hardwood) and veneer

The Australian plywood industry is based principally on plantation-grown softwood and about 8% hardwood, both native and plantation grown. As well as plywood veneer, sliced or rotary-peeled decorative veneer is produced in small quantities for furniture, door and panel overlays. This production is not recorded separately by ABARE. Jaakko Pöyry (2000) estimated annual production to be less than 10 000 m³. Data used in the model for plywood were from ABARE and the Plywood Association of Australia.

Particleboard and medium-density fibreboard (MDF)

The characteristics of these two wood panelboards, including their density, are different, but their feedstock and end-use product categories are similar. Input is either small logs unsuited to sawmilling, or woodchips produced as a by-product of sawmilling. Most of the feedstock is from softwood plantations, although some regrowth hardwood is being used in a plant in Tasmania and some cypress pine is being used in a plant in Queensland. The industry source used for information on processing assumptions in the model was the Australian Wood Panels Association.

Pulp and paper

Plantation-grown softwood fibre provides the major resource, but hardwood fibre and recycled fibre are also important. Accounting for this sector is complicated as recycled fibre is exported and pulp is imported. While ABARE data provide some information, the Pulp and Paper Manufacturers Federation of Australia (PPMFA) provided more detailed figures. Production data in this study are derived from assumed raw material use and conversion figures rather than reported industry figures. The model-derived paper production estimates are 15% lower than the ABARE or PPMFA figures. This is because the model calculates the wood-only raw material for pulp and paper in oven-dry tonnes. The ABARE and PPMFA reported figures are in air-dry tonnes which contain about 10% moisture and 2–25% of non-wood fillers depending on the process.

A complicating factor in the assumptions on waste with the pulp and paper stream is that mills vary dramatically in their recovery according to type. Kraft pulp mills typically have a low yield of fibre (\approx 50%) whereas thermomechanical mills have a high yield (\approx 95%). The manufacture of paper from recycled material also results in a lower yield of fibre. Based on weighted inputs, a yield of 70% was adopted.

Preservative-treated softwood

Both hardwood and softwood can be treated with preservative, but only softwood has been assigned a separate category in this project. This is because treated sawn softwood has some use categories which are different to those for untreated softwood. Hardwood is usually treated so the sapwood can be protected against borer attack or decay, and its use is then the same as for untreated hardwood.

Treated softwood poles and posts have also been included with sawn softwood, but treated hardwood poles and piles have been

included with sleepers and other miscellaneous hardwood products. The information used in the model was obtained from the Timber Preservers Association of Australia.

Hardboard

Hardwood is used for feedstock; supplies are derived from pulp logs and sawmill residue.

Hardwood poles, sleepers and miscellaneous

The existing stock of hardwood transmission poles in Australia is reputed to number about 6 000 000 and production is estimated to be about 100 000 poles yearly, equivalent to about 75 000 m³ of log. Railway sleepers also represent a large resource, and although concrete sleepers are now used for all new work, timber sleepers will continue to be used to maintain secondary lines. 'Miscellaneous' includes products such as mining, fencing and landscaping timbers.

Log and woodchip exports

Export woodchips form a significant portion of the annual harvest from Australian forests. The ABARE quarterly forest products statistics report both bone-dry tonnes (BDt) of softwood chips and BDt of hardwood chips exported. The model used the ABARE-reported export figures directly in bone-dry tonnes.

Total exports of coniferous logs reported by ABARE consist of both sawlog and pulp log. New South Wales exports about 7000 m³ of short poles annually.

Lifespan of timber products (recycling and landfill)

The lifespan of wood products must be considered when ascertaining the quantity of carbon stored in timber products. We have given considerable attention to subdividing the various timber products pools into different classes based on product and decay rates. The decay rates used assume that losses of material from service will increase with product age. Therefore the entry and exit of material from production to loss from each product pool is tracked and aged according to three age classes — young, medium and old. The fraction of material lost annually from each pool may vary (for example, there may be little loss from young pools (excluding those to the medium-age class)). Material is lost at a constant rate and may be placed in landfill, recycled, used for bioenergy or lost to the atmosphere (for example, burnt with no energy capture) (Fig. 1).

For shorter-term products, the impact of the size of historic stocks is slight as recent additions to the pools are the major source of material available for loss. For long-term products, an estimate of the size of the historic pool is essential, but difficult. The size of the housing pool uses housing starts data. Other pools are also only estimates. The fraction of the pool that has stemmed from Australian-grown wood is needed to implement an approach that separately deals with imported wood products. However, this component is difficult to estimate and estimates should be treated with some caution.

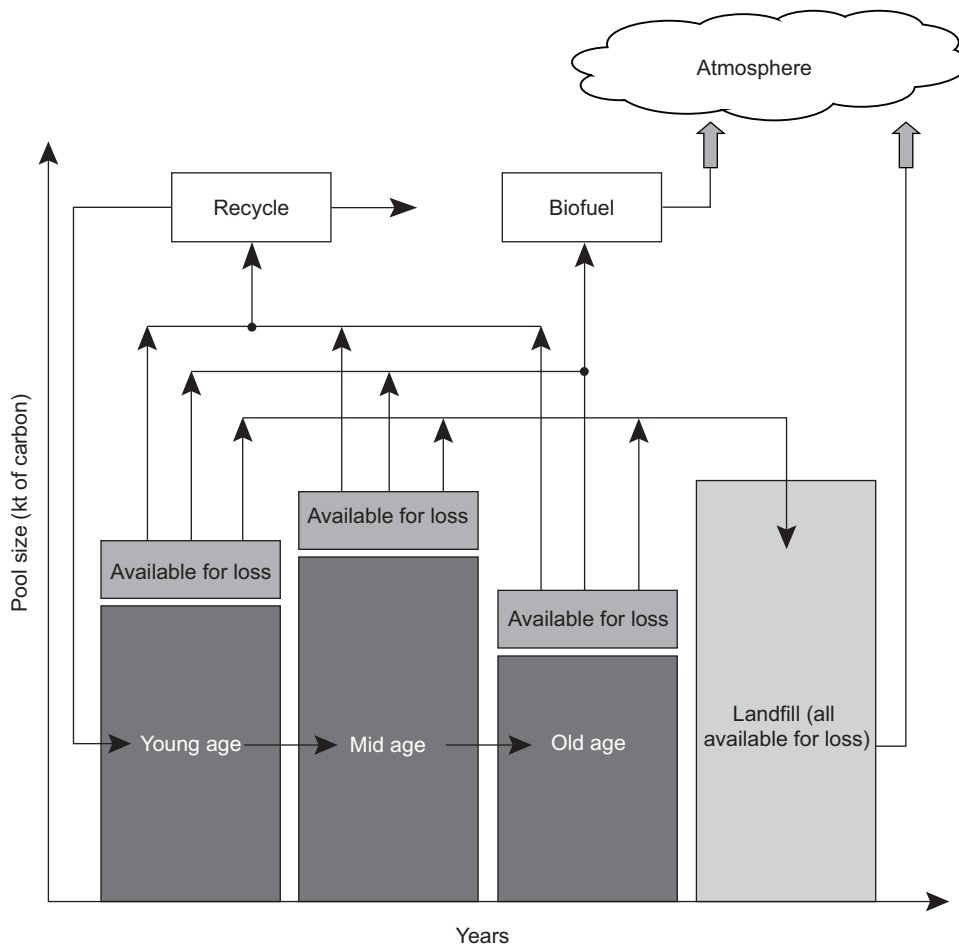


Figure 1. Major pools and flows in the wood products model

Lifespan pools assumed for the carbon model

Very short-term products — Pool 1

- Softwood — pallets and cases
- Plywood — formboard
- Paper and paper products

Age¹ (y): young = 1; medium = 2; old = 3

Short-term products — Pool 2

- Hardwood — pallets and palings
- Particleboard and MDF — shop fitting, DIY, miscellaneous
- Hardboard — packaging

Age (y): young = 3; medium = 6; old = 10

Medium-term products — Pool 3

- Plywood — other (noise barriers)
- Particleboard and MDF — kitchen and bathroom cabinets, furniture
- Preservative-treated pine — decking and palings

- Hardwood — sleepers and other miscellaneous hardwood products

Age (y): young = 10; medium = 20; old = 30

Long-term products — Pool 4

- Preservative treated pine — poles and roundwood
- Softwood — furniture
- Hardwood — poles, piles and girders

Age (y): young = 20; medium = 30; old = 50

Very long-term products — Pool 5

- Softwood — framing, dressed products (flooring, lining, mouldings)
- Cypress — green framing, dressed products (flooring, lining)
- Hardwood — green framing, dried framing, flooring and boards, furniture timber
- Plywood — structural, laminated veneer lumber (LVL), flooring, bracing, lining
- Particleboard and MDF — flooring and lining
- Hardboard — weathertex, lining, bracing, underlay
- Preservative-treated pine — sawn structural timber

Age (y): young = 30; medium = 50; old = 90

¹'Age' is the upper bound of the age class.

Table 2. The maximum fraction of each pool available for loss (that is, exposed to decomposition, see Fig. 1) and decomposition rates (annual loss as a fraction of the amount of material exposed to decomposition in each pool)

| Lifespan pool | Young | | Medium | | Old | | Landfill loss (y ⁻¹) |
|---------------|--------------------|-------------------------|--------------------|-------------------------|--------------------|-------------------------|----------------------------------|
| | Available for loss | Loss (y ⁻¹) | Available for loss | Loss (y ⁻¹) | Available for loss | Loss (y ⁻¹) | |
| 1 | 0.60 | 1.0 | 0.65 | 0.500 | 0.90 | 0.333 | 0.002 |
| 2 | 0.30 | 0.333 | 0.50 | 0.167 | 0.90 | 0.100 | 0.002 |
| 3 | 0.15 | 0.10 | 0.65 | 0.050 | 0.45 | 0.033 | 0.002 |
| 4 | 0.25 | 0.05 | 0.65 | 0.033 | 0.80 | 0.020 | 0.002 |
| 5 | 0.20 | 0.033 | 0.55 | 0.020 | 0.95 | 0.011 | 0.002 |

Table 3. Fraction of annual losses from each lifespan pool to landfill, recycling and biofuel

| Lifespan pool | Landfill | Recycling | Bioenergy |
|---------------|----------|-----------|-----------|
| 1 | 0.44 | 0.49 | 0.04 |
| 2 | 0.75 | 0.20 | 0.05 |
| 3 | 0.95 | 0.05 | 0 |
| 4 | 0.85 | 0.15 | 0 |
| 5 | 0.85 | 0.10 | 0.05 |

A specified fraction of material may be lost yearly (an exponential loss) from each age class of each product pool. The amount lost from each age class for each product pool can be capped and different fractions can be lost according to age. This feature of the model provides for 'steps' in product loss rather than using either a simple linear or exponential loss applied to a whole product pool, irrespective of the average age of the pool. If inputs vary over time the average age of products will vary, and this is represented by the amounts of material in each age class of each product pool.

Initial stock assumptions

Input data were available for the model since 1944. This had the benefit of allowing the model to establish new equilibrium pools as the input material may be 'turned-over' several times before an equilibrium stock is reached for recent years. Initial stock estimation (for 1944) is most important for Pool 5 as this material may remain in use now.

Model parameterisation

Once the data on production inputs, processing flows and initial stocks were determined other parameters needed for the model included the:

- age at which material moved from young to medium and from medium to old pools
- fraction of each age class for each product pool exposed to loss
- rate of loss from each age class in each product pool
- fraction of losses from each age class in each product pool to each of landfill, recycling, bioenergy and the atmosphere
- rate of loss from landfill.

The estimates used for the model are presented in Tables 2 and 3.

Many of the estimates are based on expert judgement. In fact, often little empirical basis or opportunity for verification of estimates exists. The maximum possible loss of carbon in wood products placed in landfill was based on research carried out by the CRC for Greenhouse Accounting (unpublished) in two landfill sites in Sydney.

To understand the impact of uncertainties, Monte Carlo analysis using the Palisade @Risk software (Palisade 1997) was applied. This approach is also able to identify model sensitivities. Through this, it is possible to identify where uncertainty in parameter estimation may be most significant for a probability distribution of expected outcomes, and to focus future data collection on areas that will best reduce uncertainties.

Model results

By integrating the carbon pools, life cycles and wood flows of wood products, the model enabled the total carbon pools and emissions to the atmosphere to be estimated. Table 4 shows the annual additions and losses and carbon pool sizes for the three accounting approaches.

Table 4 shows the significant potential of wood products to act as a store of carbon when the presumed 'emissions at harvest' result is compared with the other two accounting options. As emissions do eventually occur from stocks built up in the carbon stores, when a sufficiently large stock of carbon is emitting, estimates of emissions may exceed those from the presumed emission at harvest. When this occurs is a function of the rates of both input and decomposition (the higher the rates the earlier this will occur) and when inputs to the carbon stocks are first recorded.

Uncertainty analysis

With the consistent and comprehensive monitoring of wood production in Australia since 1944, and the confidence in this data gained through cross-verification with other datasets, little uncertainty is likely to be derived from the production data. The most likely sources of uncertainty will be the allocation to decomposition and recycling pools, and the rates of decomposition in those pools. To test the relative importance of the pool ages and decomposition rates, Monte Carlo analysis was undertaken using the @Risk add-in software (Palisade 1997) to the Excel spreadsheet wood products carbon model. The principal model parameters of interest were the decomposition rates within pools

Table 4. The flow of new material, and national carbon stock and emissions outcomes for each accounting approach

| Year | Accounting approach (kt of carbon) | | | | | | | | | | | | | | |
|------|---|------------------------------|------------------------------|--|------------------------------------|---|---|------------------------------|------------------------------|-----------------------------------|---|---|------------------------------|------------------------------|--|
| | New material, Australia (kt of carbon) | | | | | 2. 'Wood products produced in Australia' | | | | | 3. 'Wood products stored in Australia' | | | | |
| | Domestic production of new wood products | Imports of new wood products | Exports of new wood products | 1. 'Emissions at harvest' (IPCC default) | Increase due to carbon from forest | Emissions (excl. landfill, e.g. burning of waste) | Decrease due to decay (emissions incl. from landfill) | Carbon pool (excl. landfill) | Carbon pool (incl. landfill) | Increase due to new wood products | Emissions (excl. landfill, e.g. burning of waste) | Decrease due to decay (emissions incl. from landfill) | Carbon pool (excl. landfill) | Carbon pool (incl. landfill) | |
| 1990 | 4837 | 726 | 1591 | 4798 | 4798 | 480 | 691 | 66760 | 164120 | 3972 | 358 | 563 | 79399 | 181561 | |
| 1991 | 4914 | 786 | 1619 | 4804 | 4804 | 486 | 704 | 67637 | 167913 | 4082 | 362 | 572 | 80395 | 185044 | |
| 1992 | 5129 | 824 | 1708 | 5089 | 5089 | 499 | 724 | 68640 | 171914 | 4295 | 370 | 585 | 81505 | 188696 | |
| 1993 | 5369 | 827 | 1856 | 5316 | 5316 | 509 | 741 | 69811 | 176145 | 4340 | 373 | 593 | 82674 | 192426 | |
| 1994 | 5592 | 989 | 2184 | 5606 | 5606 | 528 | 766 | 71071 | 180590 | 4397 | 378 | 602 | 83848 | 196190 | |
| 1995 | 5516 | 778 | 1998 | 5478 | 5478 | 538 | 784 | 72181 | 184925 | 4297 | 383 | 614 | 84863 | 199833 | |
| 1996 | 5640 | 838 | 2137 | 5551 | 5551 | 546 | 799 | 73314 | 189341 | 4341 | 389 | 625 | 85878 | 203512 | |
| 1997 | 6136 | 910 | 2603 | 6094 | 6094 | 573 | 833 | 74661 | 194134 | 4442 | 393 | 634 | 86973 | 207295 | |
| 1998 | 6080 | 894 | 2468 | 6038 | 6038 | 581 | 849 | 76006 | 198978 | 4507 | 398 | 645 | 88071 | 211119 | |
| 1999 | 6228 | 1069 | 2621 | 6216 | 6216 | 591 | 866 | 77441 | 203971 | 4676 | 405 | 657 | 89280 | 215095 | |
| 2000 | 6852 | 944 | 3137 | 6803 | 6803 | 625 | 908 | 79039 | 209337 | 4659 | 411 | 669 | 90412 | 219038 | |
| 2001 | 7089 | 870 | 3090 | 7059 | 7059 | 647 | 939 | 80803 | 215007 | 4869 | 419 | 602 | 91691 | 223175 | |
| 2002 | 7117 | 1020 | 3485 | 7649 | 7649 | 683 | 983 | 82783 | 221116 | 5252 | 433 | 702 | 93195 | 227629 | |
| 2003 | 7262 | 1020 | 3485 | 7686 | 7686 | 707 | 1107 | 84699 | 227312 | 5297 | 443 | 718 | 94686 | 232136 | |

(for example, losses from service and landfill) and transfers (for example, to recycling, bioenergy and landfill). Monte Carlo analysis samples values from within specified ranges (probability distributions) for nominated parameters within repeated applications of the model. Probability distributions for values within ranges for each variable can be nominated, as can positive and negative correlations between variables so sampling can reflect these correlations. In this application, the nominated probability distributions were 'triangular', that is, values within the ranges sampled formed a triangular distribution around a central expected value. As there was no known correlation between variables, no correlations were specified, so value selection was random within the triangular probability distributions. The absence of specified correlations has a tendency to increase the range of possible outcomes.

The life cycle pools and the distributions of their possible values for the Monte Carlo analysis are shown in Tables 5, 6, 7 and 8. Distributions of possible outcomes were stabilised over 100 000 model iterations. The 'tornado' graphs (Figs 2 and 3) shows the relative importance of each input variable to the overall uncertainty in the model outcome.

Figure 2 shows the results of the sensitivity analysis for 'wood produced in Australia' and Figure 3 the results for 'wood stored in Australia'. The results are presented with both inclusion and exclusion of the landfill pool, and for both carbon pools and emissions.

All the tornado sensitivity graphs for both 'wood products produced in Australia' and for those 'stored in Australia' when landfill is included, and for both carbon pools and emissions (Figs 2(a), 2(c), 3(a), 3(c)) show a similar pattern. The highest sensitivity was to the fractions of Pool 1 (very short-term products) that are recycled or lost to landfill. The potential model results (Figs 2(b), 2(d), 3(b), 3(d)) show a similar large range of possible model outcomes. As noted earlier, this is in part attributable to the absence of any specified correlations between variables in the Monte Carlo analysis.

Of note is the similarity in the carbon pool results for 'wood products produced in Australia' (2(d)) and for those 'stored in Australia' (3(d)), whereas the emissions from 'wood products produced in Australia' (2(b)) are higher than the emissions from 'wood products stored in Australia' (3(b)). This reflects the proportionally great importance of Pool 1 (very short-term products) in wood product exports. It also shows that the size of carbon pools in wood products is not a direct surrogate for greenhouse gas emissions.

The sensitivity results are quite different when the landfill pool is excluded (2(e), 3(e)) — with the maximum age (retention time), Pool 1 and Pool 2 products become most important. Of note is that excluding the landfill pool significantly reduced the range of potential outcomes of the wood product pool size (Figs 2(f), 3(f)). This reflects the high sensitivity of the rates of input to landfill, which is in turn a reflection of the high retention time in landfill.

Table 5. Uncertainty ranges of pool age (y) used in the Monte Carlo analysis

| Life cycle pool | Lower bound | | | Expected value* | | | Upper bound | | |
|-----------------|-------------|--------|-----|-----------------|--------|-----|-------------|--------|-----|
| | Young | Medium | Old | Young | Medium | Old | Young | Medium | Old |
| Very short term | 0.5 | 1 | 2 | 1 | 2 | 3 | 1.5 | 3 | 4 |
| Short term | 1 | 3 | 5 | 2 | 6 | 10 | 3 | 9 | 15 |
| Medium term | 5 | 15 | 20 | 10 | 20 | 30 | 15 | 25 | 40 |
| Long term | 15 | 20 | 40 | 20 | 30 | 50 | 25 | 40 | 60 |
| Very long term | 20 | 40 | 75 | 30 | 50 | 90 | 40 | 60 | 105 |

*As assigned in the text under the heading 'Life spans for the carbon model'

Table 6. Uncertainty ranges of pool size (as fractions) exposed to decomposition used in the Monte Carlo analysis

| Age | Life cycle pool | Lower bound | Expected value (as in Table 2) | Upper bound |
|--------|-----------------|-------------|--------------------------------|-------------|
| Young | 1 | 0.500 | 0.600 | 0.700 |
| | 2 | 0.250 | 0.300 | 0.350 |
| | 3 | 0.120 | 0.150 | 0.180 |
| | 4 | 0.225 | 0.250 | 0.275 |
| | 5 | 0.175 | 0.200 | 0.225 |
| Medium | 1 | 0.550 | 0.650 | 0.750 |
| | 2 | 0.400 | 0.500 | 0.600 |
| | 3 | 0.550 | 0.650 | 0.750 |
| | 4 | 0.550 | 0.650 | 0.750 |
| | 5 | 0.450 | 0.550 | 0.650 |
| Old | 1 | 0.800 | 0.900 | 1.100 |
| | 2 | 0.800 | 0.900 | 1.100 |
| | 3 | 0.400 | 0.450 | 0.500 |
| | 4 | 0.700 | 0.800 | 0.900 |
| | 5 | 0.800 | 0.950 | 1.150 |

Table 7. Uncertainty ranges of annual decomposition rate used in the Monte Carlo analysis

| Age | Life cycle pool | Lower bound | Expected value (as in Table 2) | Upper bound |
|----------|-----------------|-------------|--------------------------------|-------------|
| Young | 1 | 2.000 | 1.000 | 0.667 |
| | 2 | 1.000 | 0.333 | 0.333 |
| | 3 | 0.200 | 0.100 | 0.067 |
| | 4 | 0.067 | 0.050 | 0.040 |
| | 5 | 0.050 | 0.033 | 0.025 |
| Medium | 1 | 1.000 | 0.500 | 0.333 |
| | 2 | 0.333 | 0.167 | 0.111 |
| | 3 | 0.067 | 0.050 | 0.040 |
| | 4 | 0.050 | 0.033 | 0.020 |
| | 5 | 0.025 | 0.020 | 0.017 |
| Old | 1 | 0.500 | 0.333 | 0.250 |
| | 2 | 0.200 | 0.100 | 0.067 |
| | 3 | 0.050 | 0.033 | 0.025 |
| | 4 | 0.025 | 0.020 | 0.017 |
| | 5 | 0.013 | 0.011 | 0.010 |
| Landfill | | 0.0015 | 0.002 | 0.0025 |

Table 8. Uncertainty ranges for destination fraction used in the Monte Carlo analysis for 'wood products produced in Australia' accounting approach

| Life cycle pool | Landfill | | | Recycle | | | Biofuel | | |
|-----------------|-------------|----------------|-------------|-------------|----------------|-------------|-------------|----------------|-------------|
| | Lower bound | Expected value | Upper bound | Lower bound | Expected value | Upper bound | Lower bound | Expected value | Upper bound |
| 1 | 0.38 | 0.44 | 0.50 | 0.45 | 0.49 | 0.53 | 0.63 | 0.04 | 0.05 |
| 2 | 0.60 | 0.75 | 0.90 | 0.18 | 0.20 | 0.22 | 0.04 | 0.05 | 0.06 |
| 3 | 0.80 | 0.95 | 1.10 | 0.40 | 0.05 | 0.06 | - | 0 | - |
| 4 | 0.70 | 0.85 | 1.00 | 0.13 | 0.15 | 0.17 | - | 0 | - |
| 5 | 0.70 | 0.85 | 1.00 | 0.09 | 0.10 | 0.11 | 0.04 | 0.05 | 0.06 |

Conclusions

With the comprehensive and consistent collections of forest production statistics since 1944 it was possible to build a robust model of carbon stocks and flows for wood products by deriving suitable conversion factors, allocating products to decomposition pools, and estimating the rates of decomposition for each pool. The benefits of a long run of wood products records is that, for all but the long-term pools, products pools have reached an equilibrium for recent years. In the longer-term pools, where this is not the case, the model will be more sensitive (more so for

stocks than emissions) to the initial conditions. As pool size is directly proportional to the emissions, it is important to note that the model is sensitive to the time when inputs to the pools begin. The longer the pools have to increase (that is, the earlier the model begins) the larger the overall carbon store that will experience the same rate of emissions.

The inclusion or exclusion of the landfill carbon store (and therefore emissions from landfill) is clearly very significant. The increase in the landfill carbon store provides a base for additional emissions. Depending on the balance of rates of emission against

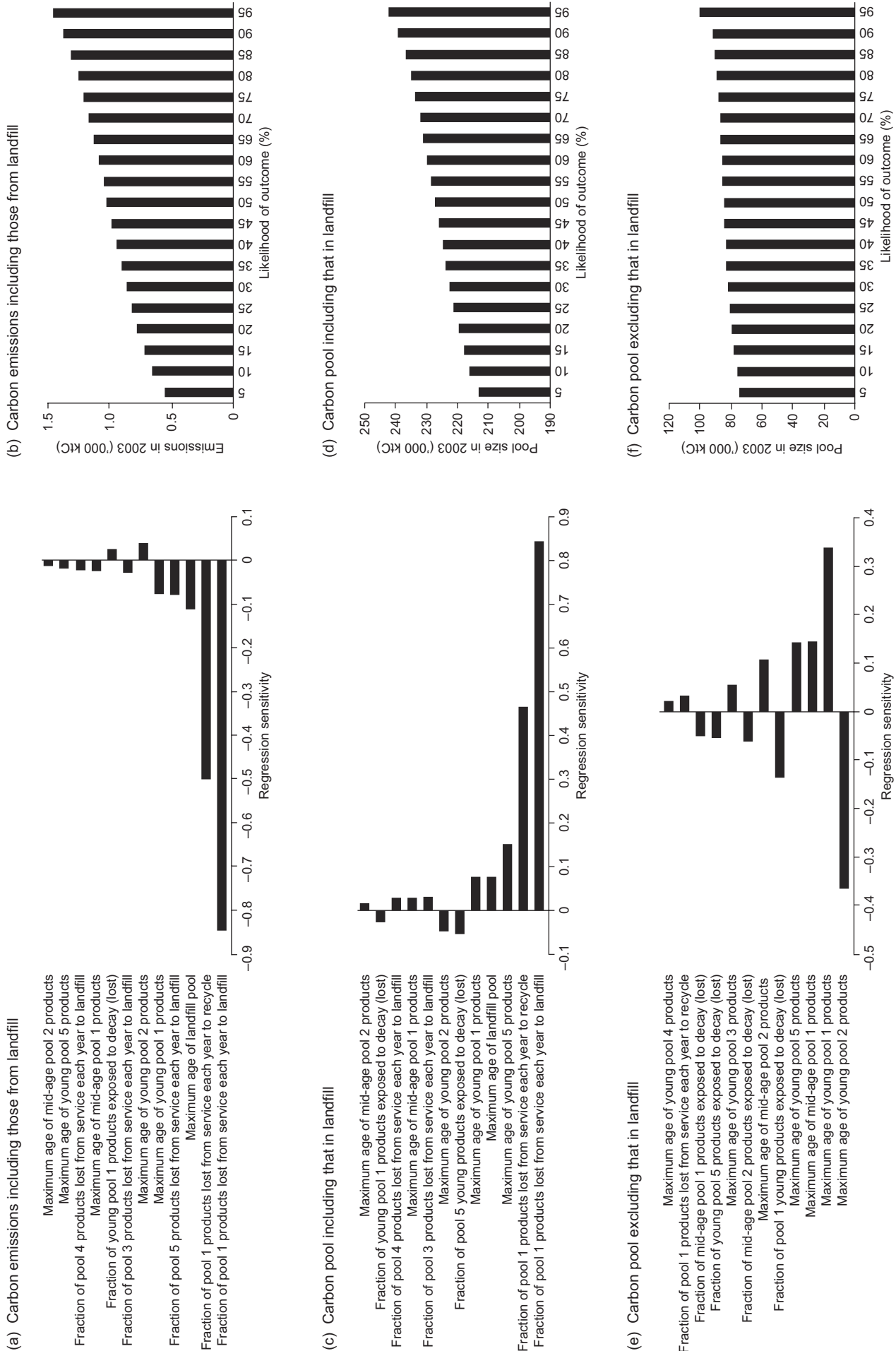


Figure 2. Results of the @Risk sensitivity analysis for the 'wood products produced in Australia' accounting approach. The tornado graphs are truncated at 12 factors. Negative sensitivity indicates a negative correlation with the output result.

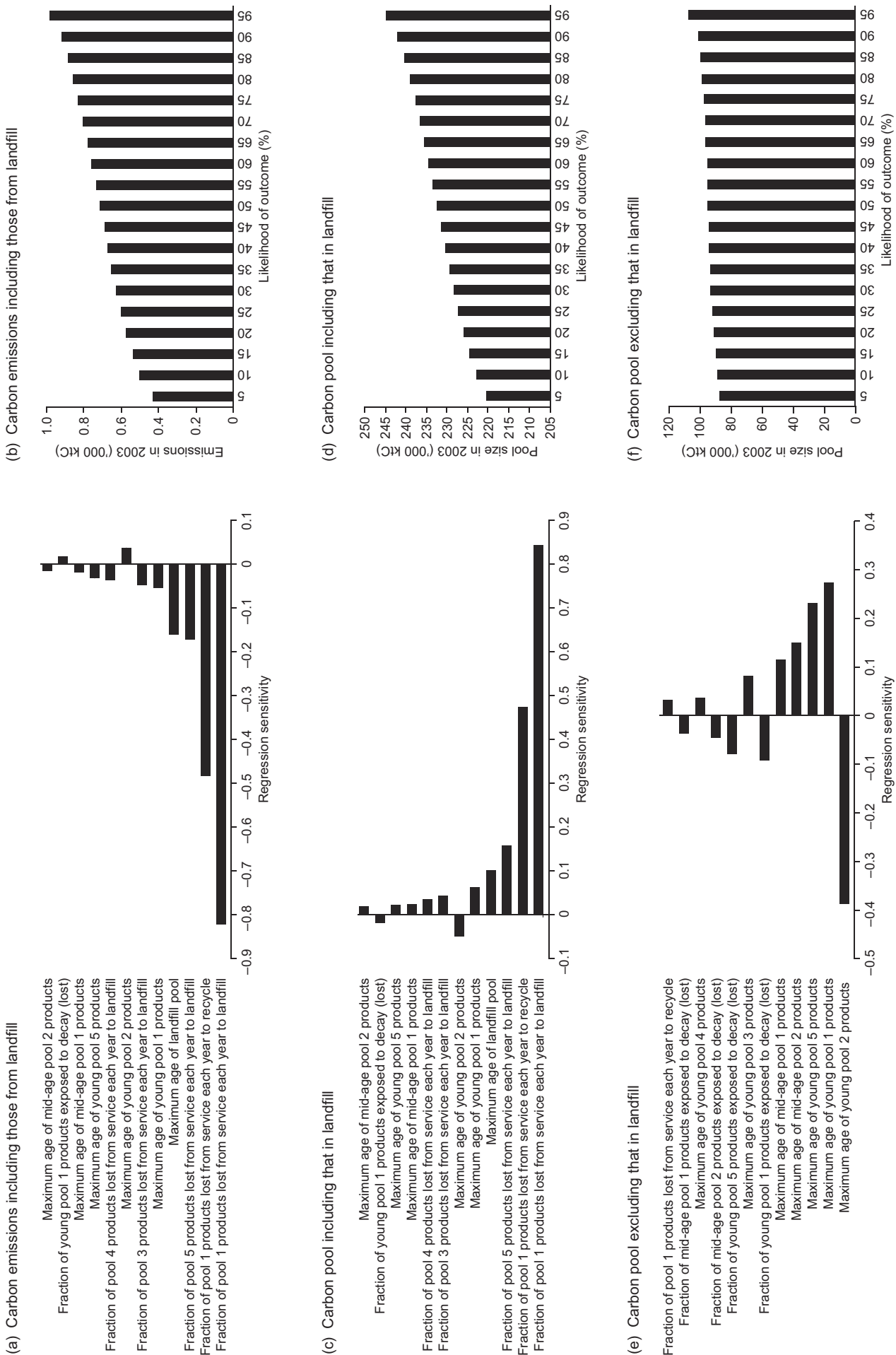


Figure 3. Results of the @Risk sensitivity analysis for the 'wood products stored in Australia' accounting approach. The tornado graphs are truncated at 12 factors. Negative sensitivity indicates a negative correlation with the output result.

the rates of input material, future annual emissions from this carbon store could potentially exceed inputs.

The emissions estimates derived in this paper consider only carbon pools and carbon pool changes (losses being considered as emissions); no corrections for global warming potentials have been applied. If the forms of gas containing carbon in emissions are considered, atmospheric emissions in the form of methane have a global warming potential (CO₂ equivalence) 21 times that of CO₂. Losses of carbon as methane would therefore be of potential significance.

The effects of the accounting approach ('emissions at harvest', 'wood products produced in Australia', or 'wood products stored in Australia') show that adopting the method that presumes emissions at harvest gives a greater emission than other approaches. This difference in outcome reflects the real-world delay in actual emissions following harvest because many wood products are stored in service for a significant time; the delay is increased when retention in landfill is also considered.

Highest emissions arise from the effects of 'wood products produced in Australia' compared with 'wood products stored in Australia'. This would be expected because Australian exports tend to be short-term (pulp and chip) products, while imports are longer-term products. The results highlight the importance of landfill as a carbon storage mechanism, and the uncertainties associated with this store. This uncertainty, and the possible effects on greenhouse gas emissions of increased methane production (though potentially captured on emission) point to clear directions for future research.

Priority areas for further research and development identified during the model development and sensitivity analysis include:

- the lifespan of timber products (both long-term products such as framing timber in housing and products with a shorter lifespan such as paper and packaging)
- the methods of final disposal of wood products, some of which (for example, landfills) may significantly extend the life of products before carbon release
- the rate and extent of decomposition of wood and paper in landfill
- the method for determining the level of carbon sequestered in housing
- the fraction of carbon that is lost as either carbon dioxide or methane.

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Predicting wood value in Queensland Caribbean pine plantations using a decision support system

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Summary

A decision support system has been developed in Queensland to evaluate how changes in silvicultural regimes affect wood quality, and specifically the graded recovery of structural timber. Models of tree growth, branch architecture and wood properties were developed from data collected in routine Caribbean pine plantations and specific silvicultural experiments. These models were incorporated in software that simulates the conversion of standing trees into logs, and the logs into boards, and generates detailed data on knot location and basic density distribution. The structural grade of each board was determined by simulating the machine stress-grading process, and the predicted graded recovery provided an indicator of wood value. The decision support system improves the basis of decision-making by simulating the performance of elite genetic material under specified silvicultural regimes and by predicting links between wood quality and general stand attributes such as stocking and length of rotation.

Keywords: plantations; management; silviculture; models; conversion; computer software; wood properties

Introduction

A decision support system (DSS) that allows managers of commercial plantations to evaluate the effect of various silvicultural regimes on the graded recovery of structural timber has been developed in Queensland by staff of Forestry Plantations Queensland (FPQ) and the Department of Primary Industries and Fisheries (DPI&F). The DSS is focussed on tropical and subtropical commercial softwoods destined for sawlog and structural timber markets, and initially has been calibrated for Caribbean pine (*Pinus caribaea* var. *hondurensis*).

The DSS provides a suite of software tools that evaluates silvicultural scenarios and simulates the effects of changes in stocking and rotation age on the branch architecture and wood properties of logs and boards destined for structural timber products. Development entailed constructing models for Caribbean pine that describe stand growth, taper, branch architecture, wood density and wood stiffness for a range of stockings and rotation ages, using data collected from specific

silvicultural experiments and routine plantations. These models are applied in conversion software¹ that uses commercial sawing patterns and specified log lengths to simulate cutting each tree into logs and then into boards. The size and location of all knots and the distribution of density in each board are outputs from the conversion software and are used in separate grading software to predict the structural Machine Graded Pine (MGP) grade of each board based on Australian Standard 1720.1 (SAA 1997). The DSS links graded recovery with stand parameters such as stocking and clearfall age to assist plantation management decision-making in relation to clonal selection and silvicultural options.

A number of similar decision support systems exist for different species. Wood quality and the location and dimension of branches can influence the recovery of timber from logs and in turn affect the grades of timber obtained from a given tree (Leban *et al.* 1999; Maguire *et al.* 1999; Pinto *et al.* 2003; Todoroki 2003). In order to understand the relationship between branching patterns, wood quality and graded recovery it has been advantageous to assess these properties at the tree and stand level, and link them to silvicultural practices in computer-based decision support systems. For example, models of wood properties such as basic density, spiral grain, ring width and mechanical properties have been developed for Norway spruce (*Picea abies*) for use in conversion software to link tree height, crown development, wood quality and branch architecture to the quality of sawn boards (Houllier *et al.* 1995; Lindström 2000). Conversion software has been developed for radiata pine (*Pinus radiata*) that links wood properties with sawing and end-use of timber (Todoroki 1996), and detailed models of branching were developed and incorporated in conversion software to determine the influence of branching on timber value (Pont *et al.* 1999).

This paper provides an overview of the decision support system developed by FPQ and DPI&F and discusses its development and potential applications.

¹In the context of this paper, 'conversion software' refers to specific software that is designed to model the process of cutting trees into logs and boards.

Components of the decision support system

The DSS consists of a suite of models and custom-built computer software tools (Fig. 1), and relies on the input of external data and models. One of the software tools called STEPS (Software Tools for Evaluating Plantation Scenarios), developed as part of the DSS, was previously described in detail by Catchpoole and Nester (2003, 2004). STEPS provides a user-friendly interface to evaluate a range of silvicultural scenarios in economic terms. The French Win-Epifn software (Leban *et al.* 1999; Meredieu *et al.* 1999) developed by the Institut Nationale de Reserches Agronomique (INRA) has been adopted as the conversion software. Win-Epifn was used to simulate the cutting of trees into logs and boards and to assign the virtual board details (dimensions, knot sizes and positions) that are used in separate board grading software. The grading software was specifically written to incorporate the Australian grading rules for Machine Graded Pine and assigns a structural grade to each board. These structural grades and the graded recovery provide an indication of wood value. The graded recovery estimates that are generated by the grading software can be returned to STEPS to enable the internal rate of return and net present value to be predicted. However, this function of the DSS has not yet been developed, as shown by the dashed line in Figure 1.

STEPS: The financial evaluation component

STEPS is a financial evaluation software tool developed using Visual Basic for Applications in Microsoft Excel[®]. It allows the economic outcomes of various silvicultural scenarios to be analysed and compared. The program takes into account growth and yield, all costs that occur over a rotation including costs associated with thinnings and pruning, and specifications of the timber products and prices applicable at thinning and clearfall. The user may provide parameters including site index, thinning age, clearfall age, pruning strategies and stocking to evaluate silvicultural scenarios by estimating internal rate of return and net present value. Options include the choice of discount rate and whether or not the net present value is calculated over one rotation or an infinite number of rotations. STEPS is currently being used by Forestry Plantations Queensland as a stand-alone

software tool to evaluate silvicultural scenarios for purposes of strategic planning. It allows the simultaneous comparison of economic and growth parameters to select optimum silvicultural regimes for specified estate areas.

Win-Epifn: The conversion software component

The French-developed conversion software called Win-Epifn[®] INRA was customised for commercially grown Caribbean pine in Queensland and was used to simulate the process of sawing trees into logs and structural timber. It requires standard inventory data (i.e. tree height, diameter, age and stocking), models of branch architecture, models of wood properties, and a selection of optimised sawing patterns that vary according to log small-end diameter. The individual board descriptions that are generated include board dimensions, the within-tree position of each board, the position and size of each knot, and the distribution of within-board density on the four sides of every board.

Branch models used in the conversion software

Considerable research has been undertaken in modelling branch architecture in *Pinus radiata* (Pont *et al.* 1999), *Picea mariana* (Lemieux *et al.* 2001) and *Picea abies* (Mäkinen *et al.* 2003). The purpose of the branch models is to characterise the relevant branch architecture for each branch in the tree, and relate this to knot size and distribution for descriptions of individual boards. The models of branch architecture predict branch diameter, branch height, branch position (orientation within the whorl and branch angle) and number of branches per whorl.

As models for *Pinus caribaea* var. *hondurensis* grown in Queensland were not available, they were developed for this project (Catchpoole *et al.* 2002) using data from a broad-scale direct thinning trial in south-eastern Queensland.

Wood property models used in the conversion software

Substantial research has been undertaken to model various wood properties in a range of species. Models for radiata pine estimate wood density distribution and spiral grain (Tian and Cown 1996),

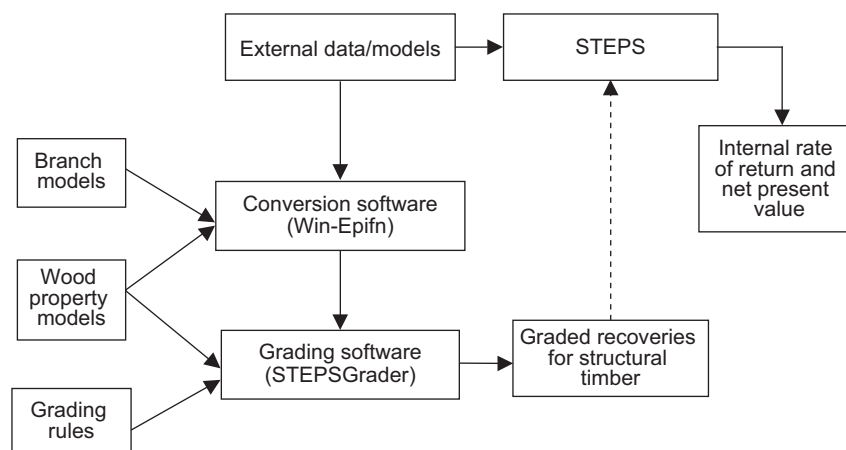


Figure 1. Structure of the decision support system

and strength and stiffness (Burdon *et al.* 2001). In Norway spruce, properties modelled include wood density distribution (Lindström 2000), spiral grain (Kliger 2002) and ring width (Saint-Andre *et al.* 2000). In Queensland, research has been undertaken to estimate genetic parameters for wood quality traits in Caribbean pine (Harding *et al.* 1991) and more recently into variation in wood properties of the interspecific slash × Caribbean pine F₁ hybrid (Harding and Copley 2000).

The models of wood properties used in this project predict within-tree distributions of basic density and ring width, and were developed from data collected from sawing studies and mechanical testing of timber from routine Caribbean pine plantations.

STEPSGrader: The grading software component

The grading software, called STEPSGrader, has been custom-built by FPQ and was developed in Microsoft Excel®. Data on wood density, ring width, knot size and knot location from the conversion software are used to predict wood stiffness (modulus of elasticity — MOE) of mechanically stress-graded pine timber. User-specified MOE thresholds and the predicted minimum MOE of a board are used in the grading software to assign MGP structural grades to each board. MGP 15 is the highest stiffness grade, and timber of this grade is of higher value to industry than grades MGP 12 and MGP 10. The standards for machine stress grading (SAASANZ 2006) were used when setting the grading rules in STEPSGrader. The grading software outputs are summarised in terms of graded recovery at the log, tree and stand level. The recovery achieved in the various structural grades can be assigned a value to provide an estimate of the total value of the wood recovered.

Development and application of the DSS

The development and application of STEPS has been described by Catchpoole and Nester (2004). This section therefore focuses on the development and application of the conversion software and the grading software components of the DSS. The conversion software is species-dependent, and customisation for a particular species is done by supplying either a suite of model parameters or a suite of detailed data files. It was decided that maximum flexibility could be achieved by customising the conversion software for Caribbean pine using data files as inputs, because this allowed independence from the software developer (INRA). The customisation process involved the following steps:

1. developing and evaluating models for tree height, diameter at breast height, height to first dead branch, height to first live branch, height to first live whorl, whorl height, number of branches per whorl, individual branch diameter and branch insertion angle (Catchpoole *et al.* 2002)
2. developing models for within-tree wood density and ring width
3. from each model listed in 1 and 2, generating files of simulated data in the format required as input by the conversion software
4. incorporating sawing patterns based on Queensland commercial pine operations.

Steps 1–3 were undertaken with minimal assistance from the software developer, INRA. Data were readily available from long-term experiments to develop the models for tree growth, branch architecture and wood properties. Developing the models and generating the input files, however, was time consuming given the limited availability of staff with mathematical and programming expertise. INRA assisted in Step 4 to ‘hardwire’ the sawing patterns into the conversion software.

Input files were created for the stocking classes of 100 stems ha⁻¹ (sph), 200 sph, 300 sph, 500 sph and 750 sph, and rotation ages ranging from 15 to 32 y. These were efficiently and automatically generated using a combination of Unix®, Maple® and Microsoft Excel® platforms. Simulations were performed for each of the input files using the conversion software. The options selected in the software to model the conversion process included cutting each tree systematically into logs up to a top diameter of 10 cm under bark, an initial stump height of 15 cm and a log length of either 490 cm or 610 cm. Each log was then virtually sawn into boards using a sawing pattern that was available in the software and varied depending on small-end diameter. The conversion software produced outputs in graphical and tabular formats at the stand, tree, log and board level. At the board level this included detailed descriptions of knot size and location on the four sides of every board, as well as knot area ratio and board density profiles. The tabular outputs were exported to other software packages for analysis, and were used in STEPSGrader where structural machine grades were assigned to each board.

These simulations have been completed and the results are undergoing validation. This has involved a thorough analysis to ensure that all tabular output from the conversion software including that on knot size and location, knot area ratio calculations, board dimensions and wood density profiles makes sense against the data provided in the input files. This check revealed that the conversion software required several modifications to adequately model Caribbean pine grown in Queensland. Win-Epifn was developed for northern-hemisphere species such as Douglas-fir and Sitka spruce; customisation for Caribbean pine required the ability to accurately model trees that produce multiple branch whorls per year and may also produce foxtails (elongated sections of stem producing no branches for several growing seasons).

Several limitations of the DSS need to be recognised when interpreting the results from STEPSGrader; these include an assumption that trees are straight and free of internal defect such as resin shake and streak. Such limitations are inherent in the conversion software, but they could have considerable effect on the graded recovery from *P. caribaea* var. *hondurensis* in circumstances where these defects are important. Because accurately modelling these defects is complex and difficult, a standard discount for downgrade due to resin defects and distortion is necessary. The cross-checking of results from the conversion and grading software and validation of the graded recoveries against actual sawmill recoveries will continue for several months.

The outputs of this DSS have many potential applications for commercial forest growers, particularly those focusing on

production of solid wood for the structural timber market. The system is sophisticated in its ability to link stand silviculture parameters with wood quality and can be used to:

- evaluate the effect of spacing and resulting branch architecture on graded recovery. This could be used simply for predicting volume distributions across structural grades, or in decision-making to determine optimum spacing to achieve a desired volume of boards of a particular structural grade
- evaluate the effects of a change in rotation age on wood quality. The models that have been developed can be confidently applied to rotations aged from 15 to 32 y, and therefore input files for the conversion software can be created for any age within this range. This allows the effects of rotation age on within-tree density, knot area ratio, stiffness and in turn graded recovery to be assessed
- provide a better understanding of the wood quality of an existing resource for the purposes of short- to medium-term planning
- evaluate individual genotypes. The models will be modified to suit the genotypes of interest, and the results of simulated sawing and grading used to choose among genotypes as an alternative to or in conjunction with selection indexes.

Conclusion

The value of recovered wood product is predicted in this decision support system by integrating data and models that describe tree growth, branch architecture, wood properties and the stiffness of timber to generate a distribution of graded timber recoveries. These graded recoveries are linked to silviculture through the tree growth, branch architecture and wood property models that are supplied for different stockings and clearfall ages. The complex suite of such models required in this decision support system is species-dependent. Customisation of the software for other species requires relevant data and capacity to develop the required models. Such a process is potentially time consuming, particularly if data need to be collected in the field. As with most decision support systems it is necessary for the user to have a good understanding of the input models and their limitations in order to be able to reliably interpret the outputs.

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Forest valuation and the AASB 141 accounting standard

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Summary

This paper examines issues relating to forest valuation using the Australian Accounting Standards Board accounting standard AASB 141 for large and medium-sized forestry entities. Current practices generally follow AASB 141:25 that states that an independent valuation of land *may* (emphasis added) be deducted from the present value of the combined asset to yield a value for the living trees (i.e. value of the biological asset), from which gains or losses relative to the previous year may be brought to account in the income statement. Such an approach distorts the income statement by gains and losses that are arbitrarily one-sided because the value of the living trees becomes a residual whose value is influenced by any movements in land value, sometimes masking the inherent productivity and value of the living trees.

The paper reviews key terminology and principles of AASB 141 and other standards, including the definitions of biological assets, non-current assets, fair value, active markets, combined assets, and highest and best use.

In the absence of an active market for medium and large forestry assets, which is generally the case in Australia and New Zealand, the estimation of fair value using the present value of expected cash flows is central to valuation. Whatever the respective form of ownership, land and living trees constitute a combined asset in which the roles are inseparable biologically. To be consistent with the use of fair value of the combined asset based on the present value of expected cash flows, the planning horizon needs to be extended to a uniform future year for the entire asset. This is to enable the optimum schedule of wood and cash flows and hence the maximum present value to be estimated.

We describe an operational method to derive the present value of the living trees (the biological asset value as rigidly defined in AASB 141) by discounting the cash flows relating solely to those living trees, in essence the current crop. Segmenting those cash flows from those used in evaluating the present value of the combined asset can do this. Assuming the going concern is viable, such that forestry is the highest and best use, the remaining issue is how to ensure that the fair value of the combined asset is properly reflected in the balance sheet. This can be done by deducting the present value of the living trees (i.e. the value of

the biological asset) from that of the combined asset (after due adjustment for land improvements). The resulting present value of 'future rotations' should then be shown as a non-current asset under 'property, plant and equipment'.

Finally, the discount rates used in forest valuations generally allow for taxation (and risk) in using a weighted average of the discount rates for equity and debt. Post-tax evaluation of cash flows is therefore recommended, rather than pre-tax, subject to avoiding double counting of any tax liabilities or debts elsewhere in the accounts.

Keywords: valuation; assets; accounting; standards; terminology; cash flow analysis; stock accounting; tenure systems; discount rates

Introduction

Corporations law prescribes that the Australian Accounting Standards Board (hereafter AASB) Standard AASB 141 'Agriculture' be used in preparing the annual financial statements required of most private and public forestry entities under that law. Accounting standards such as AASB 141 prescribe the processes to be used in 'general purpose financial reporting' and aim to meet the needs of a broad array of stakeholders by providing information for making and evaluating decisions about the allocation of scarce resources. For example, providers of resources may want to know whether the reporting entity is achieving its stated objectives in the use of resources economically and efficiently. Recipients of goods and services, and stakeholders with review and oversight responsibilities, may want to assess the ability of the reporting entity to continue in the future and whether it is making those goods and services economically and efficiently. The standards and reports are therefore not aimed simply at the valuation of the business or specific assets but at a much wider set of financial evaluations using accrual accounting and, in most cases, assuming the entity will continue as a going concern. Nevertheless, the specified processes in AASB 141 have considerable significance for the valuation of forestry assets when an 'independent valuation' is required which, as discussed later, is generally the case.

Following its decision to adopt the International Accounting Standards, the AASB adopted substantially all the International Accounting Standard (hereafter IAS) IAS 41 'Agriculture'

content and wording, except where Australian legislation had to be accommodated in AASB 141. Its application to accounting in agriculture became mandatory commencing 1 January 2005. New Zealand adopted the international standard IAS 41, commencing in 2006.

Dowling and Godfrey (2001) provide a survey and review of the accounting practices applicable to forests, among other things, at the time of introduction of the previous so-called SGARA¹ Standard (AASB 1037). Herbohn (2006) provides a later survey and review of the adoption of the SGARA Standard and implications of AASB 141. Forestry entities have encountered a number of issues in implementing the changes relating to the use of AASB 141 and these form the focus for this paper. However, the AASB 141 Standard applies to a wider array of assets than forests, including vineyards and orchards. These may also be affected by these issues but are beyond the scope of this paper.

The Association of Consulting Foresters of Australia (ACFA) has issued its interpretation of the previous AASB 1037 Standard (ACFA 2004, 2005). ACFA recognised that these interpretations did not necessarily represent the views of AASB and were subject to change as understanding evolved and as the AASB standards evolved. The introduction of the new and, in some respects, different AASB 141 necessitated revision of the ACFA forest valuation standard. This paper was intended to assist that revision, which will shortly become publicly available (ACFA 2007).

Whereas AASB 1037 required either an 'independent valuation' or a 'directors' valuation', AASB 141 does not specify either. Nevertheless, most governing boards or authorities use 'independent valuations' if financially prudent, because they reduce the risks to directors or the controlling authority. Australian Securities and Investment Commission (2006) guidelines state that an 'independent valuation' intended for publication to a section of the public and issued for a purpose regulated by the corporation law should be an objective and unbiased assessment, independent of any interested party. The aim of this paper is to examine issues pertaining to an independent valuation of a forestry asset, to indicate the problems that stem from current practices in applying AASB 141, and to recommend an operational method to overcome the issues.

The issues emerging with respect to the application of AASB 141 and, to a large extent, its forerunner AASB 1037, affect many forestry entities that are required to report according to this standard and some potentially have a major effect on financial reporting of profit or loss. Differing interpretations of the AASB 141 Standard and its forerunner AASB 1037 by relevant entities are adding to the uncertainties of valuation. Our principal focus relates to the valuation of large and medium-sized forests because, as noted in ACFA (2004), it is not appropriate to value these by simple application of the market prices to the log volumes of the living trees because an active market does not exist for such properties. Under these circumstances, the estimation of 'fair value' becomes a critical element.

Current valuation practices

Present value is currently the valuation method used by most large and medium-sized forestry entities in Australia and New Zealand (ACFA 2004, 2005 and NZIF 1999) because the market for such assets is not active (AASB 141.8) — the frequency and asset characteristics of sales are irregular — and because market-determined values or sector benchmarks are insufficient in number to provide a usable alternative. Most purchases are therefore based on an assessment of present value of expected cash flows, often across a wide array of age classes, site productivities and (sometimes) locations relative to customers. The use of present value also links to the methods typically used for the preparation of business plans, as well as sale or acquisition valuations by these entities. These assessments almost invariably value the forest as a going concern, unless it is to be broken up and sold in separate parts.

AASB 116 'Property, Plant and Equipment' has a set of 'Australian Guidance' notes attached to it that are not a formal part of that standard but include an important guiding principle (G2) that valuations of assets should be based on the 'highest and best use', the application of which to forestry assets is the subject of detailed examination in a later section. Prior to the 1990s, the issue of highest and best use did not need much further consideration by consultants as real prices for marginal farming land were relatively stable and low, or even declining as structural adjustment of farming in some areas proceeded through natural attrition.

That trend has changed, especially over the past ten years. Rural land values in a number of areas have increased, mainly reflecting competition for potential forestry land by managed investment companies in Australia (see Paton and Associates 2005) and by the apparent prosperity of dairy farming in New Zealand (see Manley 2004). These trends have highlighted a major issue for forest valuation — that of valuing the living trees in a consistent and accurate manner. Few detailed studies are available but Wilton (2005) and a Jaako Pöyry report² illustrate the issue.

Wilton's report deals with a relatively small New Zealand estate of about 415 ha of pruned radiata pine (*Pinus radiata* D.Don) planted in 1996 and 1997 (see Forest Enterprises 2007 for details). Wilton applied the last sentence of AASB 141:25 ('... the fair value of raw land and land improvements may be deducted from the fair value of the combined assets to arrive at the fair value of biological assets') in calculating the values of the living trees at the beginning and end of the period³ and then derived the gain or loss by subtraction. In the case cited, land values rose from NZ\$850 000 to \$1 325 000, an increase of NZ\$475 000, due to the increased profitability of grazing in the area. Applying these land values would imply that the value of the living trees (the

¹SGARA is an acronym for a self-generating and regenerating asset.

²Jaako Pöyry (2005) Valuation of Evergreen Forest Limited's forest assets as at 30 June 2005. Letter from W. Liley, JP Management Consulting (Asia-Pacific) Ltd, Auckland to David Sayer, Evergreen Forest Ltd, dated 10 July 2005, previously available on the then Evergreen Forest Ltd's website.

³The context of the analysis and use of rating valuations for land suggest that the duration of the period was one year.

biological asset) *declined* by NZ\$364 937 despite an increase from NZ\$2 287 554 to \$2 397 617 in the present value of the combined asset (i.e. a gain of NZ\$100 063).

The Jaako Pöyry report concerns a sequence of valuations from June 2002 to June 2005 of a much larger and more varied estate of radiata pine owned by (then) Evergreen Forests Ltd in New Zealand. In addition to the effect of falling log prices, and revisions of transport and harvest costs and of yield tables, this report noted a similar effect on the value of living trees on freehold land, when calculated according to the last sentence of AASB 141:25, due to progressively increasing land prices.

The Jaako Pöyry report goes on to argue that the land is not capable of supporting viable grazing at those increased prices and therefore attributes part of the increase in land value to speculation on long-term capital gains, a point reiterated by Liley (2002). This raises an important but peripheral issue in relation to valuation. If speculation is the primary reason for investment in land, whether carrying trees or not, then AASB 141 is not the appropriate standard for valuation of the entity — AASB 140 'Investment Property' should be applied unless, subject to certain qualifying conditions, it is owner-occupied, in which case AASB 116 'Property, Plant and Equipment' applies. If it is not the primary reason, but nevertheless a factor, the consultant and entity owner would need to make an assessment whether they believed the speculation component was likely to be realisable in assessing and valuing the highest and best use according to the principles outlined earlier.

Returning to the principal issue relating to the use of AASB 141:25 to value the living trees, the nub of our argument is that while there may be cases involving small areas of forest where AASB 141:25 can be applied appropriately, it is not generally applicable, nor need it be, noting the use of the word 'may' in the earlier quotation from AASB 141:25.

If one were to accept the deduction method, the value of living trees automatically becomes the complement of the value of the 'raw land' in the best alternative use (i.e. the residual value after deducting the land value from that of the combined asset). A referee has argued that this treatment as a residual is valid, drawing an analogy between this value and the value of equity in the balance sheet in which equity is calculated as the difference between shareholders' funds and liabilities. But that is a misleading analogy for a combined asset in which the different parts have to be valued separately. To do so would require that both shareholders' funds and liabilities be allocated to the respective parts. That brings us back to the nub of this problem because the deduction method assumes that growing trees confers no economic benefits or disbenefits, which is a one-sided distortion of the valuation of one part over the other.

The issue is one of an inconsistency in valuation method for living trees in the income statement, not a particular outcome in terms of gains or losses. Other things being equal, if real land prices were to fall, gains would arise in the value of living trees, irrespective of the production by the living trees and resultant cash flows. In a medium to large forestry entity that is a going concern, a valuation method for living trees that is captive to annual fluctuations in real land price through the application of

AASB 141:25 will be inconsistent from year to year and be inaccurate.

How should the balance sheet most appropriately reflect the fair value, given that the living trees part has to be segmented and shown separately as a 'biological asset' (previously SGARA) in the asset statement? Clarification leading to a greater consistency of approach⁴ is urgently needed.

The terminology used in AASB standards and in AASB 141, in particular, is critical to consideration of the issues relating to valuation of forestry assets. In the next section of this paper, we deal with some initial terminology and definitions, including those of biological assets, living trees, non-current assets and, most importantly, fair value. In the subsequent sections, we deal first with combined assets such as living trees and land, because that sets the scene for the principles involved in the section on the highest and best use. Successive sections then deal with valuing plantations held under single ownership of land and living trees, under forestry rights, and where land is leased. These sections provide a consistent basis for valuation of forestry assets. In the next two sections, an operational method for valuing all forms of plantation ownership is developed and its application to valuing commercial native forests considered. Sections dealing with discount rates and further concerns follow.

Terminology and definitions

In AASB 141, a *biological asset* 'is a living animal or plant'. This term replaces the so-called SGARA term of AASB 1037 but is essentially the same thing with respect to its application to forest valuation. For clarity and greater specificity, relative to other well-established forestry terminology, we have coined the term *living trees* to apply to the biological asset (previously SGARA) involved in a forest. The other major component of a forestry asset is land, which is a specific *non-current asset* (see definition in AASB 101) under the Property, Plant and Equipment Standard (AASB 116), as are other forms of property, plant and equipment.

'Fair value' is defined in AASB 141.8 as follows:

Fair value 'is the amount for which an asset could be exchanged, or a liability settled, between knowledgeable, willing parties in an arm's length transaction'.

If an active market does not exist, as is generally the case for many forestry entities, AASB 141.18 specifies the following methods that are to be used wherever market-determined prices and benchmarks are available for the forest or other biological asset, in its present condition:

18. If an active market does not exist, an entity uses one or more of the following, when available, in determining fair value:

⁴The Productivity Commission (2005) report *Financial Performance of Government Trading Enterprises* cites three of the five Australian state forestry enterprises that use present value, another two that use an immediate liquidation approach, one current cost, and one historical cost, all ostensibly under AASB 1037. Herbohn's (2006) survey suggests a somewhat greater acceptance of present value among commercial forestry entities under AASB 1037, albeit subject to a number of qualifications.

- (a) the most recent market transaction price, provided that there has not been a significant change in economic circumstances between the date of that transaction and the reporting date;
- (b) market prices for similar assets with adjustment to reflect differences; and
- (c) sector benchmarks such as the value of an orchard expressed per export tray, bushel, or hectare, and the value of cattle expressed per kilogram of meat.

For many forestry and other biological assets no active market for the asset exists *and* market-determined prices or sector benchmarks may not exist — for example, many medium and large forestry assets spanning large areas and varied age-classes. Hence AASB 141.20–22 specify:

20. In some circumstances, market-determined prices or values may not be available for a biological asset in its present condition. In these circumstances, an entity uses the present value of expected net cash flows from the asset discounted at a current market-determined pre-tax rate in determining fair value.

21. The objective of a calculation of the present value of expected net cash flows is to determine the fair value of a biological asset in its present location and condition. An entity considers this in determining an appropriate discount rate to be used and in estimating expected net cash flows. The present condition of a biological asset excludes any increases in value from additional biological transformation and future activities of the entity, such as those related to enhancing the future biological transformation, harvesting, and selling.

22. An entity does not include any cash flows for financing the assets, taxation, or re-establishing biological assets after harvest (for example, the cost of replanting trees in a plantation forest after harvest).

The issue of valuation based on estimates of present value has been a matter of debate outside and within the International Accounting Board (see IAS 141: Basis for Conclusions, especially pp. 5–7), especially in relation to biological assets and ‘financial instruments’ that include a wide range of items from cash and trade receivables, to interest and currency options, swaps and other financial derivatives. This debate is partly due to the uncertainty attached to the future values of forestry assets (e.g. volumes harvested and their prices) and financial instruments but also in some cases to reservations held about the use of market-determined prices. The recently approved section 48A of AASB139 ‘Financial Instruments: Recognition and Measurement’ provides a useful basis for elaborating on the key conditions for estimating fair value of financial instruments using the present value of expected cash flows. These conditions appear to us to apply equally well to forestry investments:

48A. The best evidence of fair value is quoted prices in an active market. If the market for a financial instrument is not active, an entity establishes fair value by using a valuation technique. The objective of using a valuation technique is to establish what the transaction price would have been on the measurement date in an arm’s length exchange motivated by normal business considerations. Valuation techniques include using recent arm’s length market transactions between knowledgeable, willing parties, if available, reference to the current fair value of another instrument that is substantially the same, discounted cash flow analysis and option pricing models.

If there is a valuation technique commonly used by market participants to price the instrument and that technique has been demonstrated to provide reliable estimates of prices obtained in actual market transactions, the entity uses that technique. The chosen valuation technique makes maximum use of market inputs and relies as little as possible on entity specific inputs. It incorporates all factors that market participants would consider in setting a price and is consistent with accepted economic methodologies for pricing financial instruments.

Periodically, an entity calibrates the valuation technique and tests it for validity using prices from any observable current market transactions in the same instrument (i.e. without modification or repackaging) or based on any available observable market data.

AASB 141.24 acknowledges that, in some cases, cost may approximate fair value, one of the specific examples being that of an immature plantation. AASB 141.18–24 outlines, but does not specifically prescribe, a hierarchy among the methods to be used where an active market does not exist because, as the international Accounting Standards Board puts it in the discussion of the IAS 41 (IASB 2005), ‘... a detailed hierarchy would not provide sufficient flexibility to appropriately deal with all the circumstances that may arise ...’. Even so, the IAS 41 discussion makes it clear that whatever method is used, account must be taken of all available market-determined prices and values. The ACFA Standard for valuing forests prescribes the reporting of such comparative information in independent valuations.

The estimation of the present value of forestry assets is further complicated by the fact that they are effectively ‘combined assets’.

Combined assets

Regardless of the ownership of the living trees (the biological asset) and land on which they stand, forests represent a combined asset in the sense that the trees cannot exist without the land. This has major implications for the valuation of forestry assets. AASB 141.25 recognises that forestry and other biological assets may be combined assets and states:

25. Biological assets are often physically attached to land (for example, trees in a plantation forest). There may be no separate market for biological assets that are attached to the land but an active market may exist for the combined assets, that is, for the biological assets, raw land, and land improvements, as a package. An entity may use information regarding the combined assets to determine fair value for the biological assets. For example, the fair value of raw land and land improvements may be deducted from the fair value of the combined assets to arrive at the fair value of biological assets.

In the case of large and medium-sized forestry entities (other than those involving a ‘forestry right’ restricted solely to the current living trees), the planning horizon for expected cash flows from the going concern needs to be set to the same future year (i.e. planning horizon) across all stands. If the planning horizon is not set to the same future year across all age classes, it is not possible to optimise the future wood flows (and hence net revenues to the combined asset) with industry demands and future development, as is typically used in business planning and in evaluation of purchase prices. To do otherwise, in a plantation

estate with a range of age classes up to that of final harvest, would lead to a progressively diminishing wood flows over time as the wood supply from intermediate thinnings progressively ceases, as a result of no replanting after final harvest.

The methods used for business planning and the evaluation of purchase (or sales) price for large and medium forestry entities are well established. The forest is divided into a set of stands (generally according to age, site productivity and location) for which inventory estimates are available as to the current characteristics. Computer-based models founded on empirical data and subject to field checking are used to forecast stand growth, mortality and the expected yields by log assortment classes at any given age. These are embedded in mathematical programming or simulation models that optimise the present value mathematically or iteratively by matching the possible future wood flows of the array of different log assortments against industry demands and future development over a fixed planning horizon. The length of that horizon varies from 10 to 50 y (or more) according to the predominant log assortments (e.g. pulpwood versus sawlog), growth rate of the species concerned, stand treatment (pruning, thinning etc.) and legal requirements (e.g. sustainable yield). The individual stand computations may extend beyond the planning horizon to the year of final harvest of the current crop or infinite series thereof (after Faustmann) and then discounted back to the planning horizon, or there may be an assumption of liquidation at the end of the horizon. In either case, the present or terminal value of the combined asset in the stand at the end of the planning horizon is effectively included as revenue at that time.

Assuming fair value is calculated on the above basis, the present value of the living trees can be calculated from the same cash flow data by segmenting those data to include only those costs and revenues relating to living trees at the time of the valuation. To put this another way, the fair value of the biological asset is based on a present value calculation for the current crop of living trees.

AASB 141.26 requires that the change in fair value of the living trees must be included in the profit or loss for the relevant period, whereas the changes in the values of non-current assets are not. Land improvements (buildings etc.) that do not have living trees but are potentially saleable separately from the combined asset of land and living trees can be valued independently of the combined asset.

The issue taken up in the next section is how to address the principle of valuing according to highest and best use, a principle which underpins all forestry valuations of a combined asset.

Valuing highest and best use

From the accounting standard's perspective for a going concern, the valuation of an asset is based on the premise of using the highest and best use as the benchmark, as the Australian Guidance Note G2 to AASB 116 sets out:

... The fair value of an asset is determined by reference to its highest and best use, that is, the use of the asset that is physically possible, legally permissible, financially feasible, and which results in the highest value ...

The independent valuation of land normally rests on appraisals based on market evidence by professionally qualified valuers. This is clearly a component relevant to the determination of highest and best use. When dealing with the value of a combined asset such as land and living trees, however, it is not the only consideration.

The appropriate comparison in determining the highest and best use is between the present value of the combined asset and that of the best alternative use or uses of the separate components. Among other things, the present value of the best alternative use depends on when it would be most opportune to harvest or remove the living trees, less the cost of rehabilitating the site, which varies considerably depending on age and the fair value of the land. If all the trees were very young, immediate clearing of living trees may be appropriate. For large estates, progressive harvesting of age classes over a number of years may be needed in order to best realise the potential value of the living trees. Thus, assuming there is no legal or other barrier to the opportunity to change uses (see AASB 116.G2), the present value of the best alternative use is the optimum discounted salvage value of the living trees *less* the costs of rehabilitation *plus* the value of the land in the best alternative use, as and when that land is expected to become available.

If the present value of the combined asset exceeds or equals that of the best alternative use, the highest and best use is to maintain the combined asset and value it accordingly. If less, the present value of the alternative use is the appropriate valuation. Having established how the principle of highest and best use might best be applied, we now turn to examine how valuation practices might be framed consistently across all forms of ownership but avoiding the difficulties posed by AASB 141.25. We will confine our initial analysis to that of plantation estates where the entity owns both land and living trees. We later address ownership under forestry rights (legal ownership of living trees but not the land) and leased land before describing the operational method, its application to commercial native forests and the choice of discount rate.

Single ownership of land and living trees

The problem relates to the general application of the wording of AASB 141.25 that '... the fair value of raw land and land improvements may be deducted from the fair value of the combined assets to arrive at the fair value of biological assets' by consultants undertaking independent valuations. The underlying issue is that living trees and similar long-lived plant crops are seldom separable physically from the land until final harvest without incurring a considerable decrease in product value. Separating them into the respective values of the living trees (the biological asset) and 'raw land' (the non-current asset), and then treating the two components as though they are independent, is confounding the principle that the combined asset should be valued on a fair value basis in its highest and best use, consistent with the valuation of other property and assets.

Clearly, a separate complementary entry of the present value of 'future rotations' is needed to ensure the values of land and living trees sum to the fair value of the combined asset (after appropriate separate recognition of land improvements). This is the only mechanism that can ensure that the calculation of the biological

asset value plus the present value of future rotations is consistent with the fair value of the combined asset as determined by present value calculation.

As noted earlier, land improvements (e.g. buildings) that are separable should continue to be valued independently of the present value calculations and shown separately as non-current assets under property, plant and equipment on the balance sheet.

Forestry rights

In managing a forestry right involving an existing large or medium-sized plantation, the entity uses both land and living trees as a combined asset, notwithstanding the different ownership of land and living trees. In arm's length transactions between knowledgeable and willing parties, the purchase price for a forestry right is almost invariably based on the present value of the expected cash flows. The same method also generally forms the basis for later annual valuations.

If the forestry right covers only the harvest life of the youngest living trees, then the present value of the living trees is simply confined to the living trees. Any harvest of future crops subsequent to the harvest life of the initial set of living trees confers no value because the valuation of a biological asset is restricted to the living trees. The subsequent crop may, of course, confer costs if replanting is a legal requirement of the forestry right, but that will have been factored in calculating the price to be paid for the forestry right.

If the duration of the forestry right extends beyond the harvest life of the youngest living trees, the present value of future rotations should be accounted for as in the preceding section. The proposed method of valuation for forestry rights is therefore consistent with that proposed for single ownership of land and living trees.

Leased land

Under AASB 117.15, because land has an indefinite life and title does not normally transfer to the lessee at the end of the lease, it is treated as an operational lease and expensed⁵, unlike buildings which may be treated as a finance lease or an operating lease, depending on the conditions on the lease. Similarly, leases in which the lessor effectively retains much of the risks and benefits pertaining to the land, such as certain types of sharing and joint venture⁶ arrangements, are treated as operating leases. These do not appear as assets or liabilities in the balance sheet of the lessee because the lessee does not effectively own the assets. For these, the minimum annual lease payments are recognised as a direct expense, as are contingent rents⁷. Thus, it is appropriate to value

the present value of the living trees (i.e. biological asset) and that of the present value of future rotations (if applicable) in the same manner as above.

Many of the questions posed to the ACFA Forest Valuation Sub-Committee about the interpretation of AASB 141 relate to the forest value being perceived to be different on leased land to that on owned land because of the practices adopted to date.

We now detail an operational method for valuation of forestry assets that is consistent across all types of ownership, based on the principles developed in the preceding sections.

Operational method

The following method conforms to the provisions of AASB 141 and the analogy with AASB 139.48A noted earlier and provides a more appropriate and accurate valuation method for medium to large forestry entities where no active market for the forestry asset exists. The choice of the discount rate to be used is taken up in a later section.

1. Optimise the present value of the combined asset by mathematical programming or simulation to determine the best schedule of wood flows over an extended uniform planning horizon for both current and future tree crops and the present value thereof (i.e. the fair value of the combined asset).
2. Segment those cash flows in (1) that relate solely to the living trees at the time of valuation and calculate their present value (i.e. the value of the biological asset, as defined in the AASB 141 standard). This value is used to calculate the annual change in value of the living trees which goes to the income statement and thus to profit or loss.
3. Determine the value of land improvements from independent data to the above and bring to account as a non-current asset under property, plant and equipment.
4. Deduct the value of land improvements from the present value of the combined asset (i.e. No. 1 above) to derive the present value of living trees plus future rotations.
5. Deduct the value of the living trees (i.e. No. 2) from the present value of the adjusted value of the combined asset (i.e. No. 4) and bring to account this present value of future rotations as a non-current asset under property, plant and equipment.
6. Where the land is owned by the reporting entity, periodic revaluations of land in the best alternative use should be disclosed in notes to these estimates but not shown as a non-current asset under property, plant and equipment, to avoid double counting of assets.

Native and other forests

In principle, the valuation of medium to large-sized commercial⁸ native forest entities using even-aged silviculture is exactly the

⁵We acknowledge the assistance of an anonymous referee in clarifying this point.

⁶Joint venture in forestry practice sometimes involves complete control by the lessee and therefore does not qualify as a 'joint venture' under AASB 131 but in some cases control is shared jointly.

⁷Contingent rent is that portion of lease payments that is not fixed in amount but is based on the future amount of a factor that changes with the passage of time (e.g. percentage of future sales, amount of future use, future price indices, future market rates of interest) — see AASB 117.

⁸AASB 141 is limited to 'Agricultural activity' which is defined as 'the management by an entity of the biological transformation of biological assets for sale, into agricultural produce, or into additional biological assets.' While there may be some ambiguity inherent in the last phrase, the intent of the definition is clearly to exclude non-commercial forest uses, among others.

same as that recommended above, although the planning horizon may be much longer.

For a medium- to large-sized native forest entity in which uneven-aged forests are harvested under selection, gap or group selection silviculture, the present value would be calculated over successive cutting cycles to a fixed and long-distant planning horizon, but the process is otherwise similar in principle.

The accounting treatment of coppice rotations following the first or later rotations of coppicing species is nominally more complicated because the coppice remains a 'biological asset' after harvesting and thus the value of the living trees (the biological asset or SGARA) is tied to the number of coppice rotations expected until the coppice is removed and new seedlings are planted. In all other respects, the recommended method holds for coppice.

A number of other lesser issues arise in the interpretation of the provisions of AASB 141 and these are taken up in ACFA (2007). However, one issue concerning the choice of discount rate is of greater importance and demands review here.

Discount rates

AASB 141.20 states that a 'current market-determined pre-tax rate be used' in determining the fair value through an analysis of the present value of expected cash flows. Nevertheless, some uncertainty appears to exist among standard-makers as to the appropriate approach regarding pre-tax or post-tax discount rates because, in discussing general principles on fair value measurement, the IASB (2006) discussion paper notes that '... after-tax cash flows should be discounted using an after-tax discount rate'.

Any due diligence concerning sale or purchase of a forest asset is normally carried out on a post-tax basis. Most valuers of forests use some variant of the weighted average cost of capital across both debt and equity in such valuations and in annual financial valuations. In doing so, taxation is implicitly recognised, as the differences between discount rates relating to debt versus those relating to equity are clearly not solely a matter of risk, but rather of both risk and taxation treatment. A generic sector approach to the treatment of cash flows net of taxation based on present and expected future rates of taxation would be appropriate to the evaluation of the fair value of the combined asset. Fair value measurement is an evaluation made in the hypothetical setting of a transaction between a willing buyer and a willing seller and does not recognise the taxation circumstances of the particular entity. However, pre-tax is presently the mandated basis for determination of the fair value of the biological asset.

The argument has been made that if taxation rates are stable, the AASB 141 Standard reference to pre-tax is of no consequence because the effects would be the same for successive valuations and thus be cancelled out in the calculation of gains and losses and the consequent impact on the income statement. This is not so. The discount rate plays a pivotal role in determining the optimum set of future wood flows in the planning models described earlier. The wood flows or resulting expected cash flows will differ between evaluations of present value using pre-tax and post-tax discount rates. Furthermore, the present value

of expected cash flows over the relatively long planning horizons that typify most forestry investments is very sensitive to the value of the discount rate.

The post-tax approach outlined above for an independent valuation needs to be distinguished from the pre-tax approach generally used in the preparation of an entity's financial report. The latter is necessary because financing and related tax considerations may affect deferred tax assets or deferred tax liabilities. In our view, however, an independent valuation of the living trees and future rotations should consider sector or generic financing considerations consistent with the assumptions underlying the post-tax discount rate. These considerations may differ from those used by the entity. The valuer's approach on these matters should always be guided by the need for an objective and unbiased assessment of fair value in the context of the sector or generic class of investment.

As noted earlier, the choice of discount rate is critical to the estimation of fair value using a present-value approach. The use of a pre-tax discount rate may result in a material underestimate of fair value using a present-value approach. Hence an independent valuation should be based on a post-tax discount rate and post-tax cash flows.

We recommend that post-tax discount rates be applied to post-tax cash flows when estimating the fair value of a medium to large forestry going concern based on a present net value approach.

Future changes to standard

The method outlined above is pragmatic in nature because of the need to adhere to existing accounting standards. We have therefore sought to adhere to the AASB 141 Standard and to provide a consistent and accurate basis of valuation, not just of the living trees (the value of the biological asset or SGARA) but also for the other components of the combined asset: one that can be applied to all types of forests and ownerships.

Two possible changes to AASB 141 would alleviate further concerns we have about its use in forest valuation:

1. Recognition and materiality of future crops⁹

Under AASB 141, the focus placed on valuing the living trees (the biological asset) is presumably because they are assets for which 'future economic benefits will eventuate' and 'can be measured reliably', whereas those associated with future crops are not viewed as having those properties. Yet in assessing the present value of a going concern of a medium or large forestry entity, one has to make a whole array of predictions of future growth, mortality, prices and costs over a long period. A one-year-old stand of trees is recognised but, for a going concern, is it materially different from one which is yet to be planted the year following the current final harvest? The assumptions made regarding future values of living trees are no different to those

⁹Thanks are due to another anonymous referee for assistance in clarifying this section.

for subsequent crops and the discrimination therefore seems arbitrary and does not match established practice in estimating fair value for purposes other than general-purpose financial reporting.

This benign neglect of future crops in the AASB 141 Standard has other implications that are undesirable. Many consultants simply assume that future crops are present value neutral — implying that they contribute no material (see AASB 1038) value. In our experience, while the values of future crops on some specific areas may not be material, others can be materially positive or negative. Manley's (2002) survey of effective discount rates used in New Zealand valuations shows an increasing trend with stand age for valuations involving predominantly immature forest compared with those for predominantly mature forest. This indicates that many predominantly immature or 'greenfield' plantations could not pass the economic test set by the choice of discount rate for mature plantations — a point that is explicitly made by Colley (2002) and based on valuations carried out by his company, and Liley (2002). This suggests to us that consultants are factoring in differences in risk for the two situations in ways that are inappropriate to the valuation of both.

The IASB's (2006) *Fair Value Measurement: Discussion Paper* suggests that a hierarchy may be established regarding the reliability of input data used in present calculations and also notes that techniques such as stochastic modelling and certainty equivalents are suitable options for the recognition of risks, in addition to the widely used risk-adjusted discount rate. These changes might, if approved, enable recognition of the value of future crops in a manner different to that proposed here, while maintaining consistency with the value of the combined asset.

2. Unrealised gains or losses

When calculated according to AASB 141, the value of the biological asset does not reflect only the value of the living trees — it also reflects the inherent contribution of the land to the time of final harvest because the biological asset is inseparable from it over that period. True, whatever the contribution of the land, it is netted out in calculating the annual gains or losses to be brought to account in the income statement and profit or loss, which provides some comfort for the resulting estimate. However, Ferguson and Houghton (1996), Dowling and Godfrey (2001), the Productivity Commission (2005) and Herbohn (2006), among others, have expressed concerns because the annual change in the values of the biological asset is not a realised value in the context of a going concern, yet it is treated as one by incorporating it in the income statement. This creates two potential problems for users of these financial statements:

1. '... users may develop unrealistic expectations of distributable profits, creating pressure for entities to declare and pay dividends, when no funds are available' (Herbohn 2006)
2. an increased volatility of earnings (Dowling and Godfrey 2001).

Mindful of the potential for misinterpretation, Forestry Plantations Queensland, a government trading enterprise, has created a special 'Plantation Growing Timber Unrealised Revenue Reserve' to show the annual changes in value of the biological asset. This

ensures that any such gains shown in the income statement and profit or loss are clearly understood *not* to be available for distribution. We recognise that current practice accords with current accounting trends to try to 'mark to market' all values in the balance sheet and support that goal. That is a different matter, however, to protecting the unsuspecting stakeholder from confusing an as-yet unrealisable value with a realisable value. Valuation would be better based on the present value of the combined asset, with the annual change brought to account solely in an appropriately labelled unrealised reserve under non-current assets.

Acknowledgements

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The senior author is a non-executive director of two plantation entities and a former chair of another. Both authors have been consultants to various plantation and native forest entities. However, the views expressed in this paper are solely those of the authors.

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Short communication

Pheromone and volatile lures for detecting the European house borer (*Hylotrupes bajulus*) and a manual sampling method

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Summary

We evaluated commercially available cross-vane traps ('Intercept'), loaded with either synthetic pheromone or a combination of (+)- α -pinene and (-)-verbenone in terms of their ability to detect European house borer (*Hylotrupes bajulus*, 'EHB'), and compared their effectiveness with a manual search method. We employed pairs of traps at 45 sites, 28 of which had previously been identified as infested using manual search methods. In a four-month trapping period, a total of only six female adult EHB were detected from three sites, all of which had previously been identified during the manual survey. We suggest that the general sedentary behaviour of the beetle and its tendency to reinfest the same individual host tree limits the probability of it being intercepted by chemical lure traps in the field. Although labour-intensive, manual search methods remain the most reliable means of identifying local EHB infestations.

Keywords: trapping; attractants; pheromone traps; insect pests; wood borers; Coleoptera; *Hylotrupes bajulus*

Introduction

European house borer (*Hylotrupes bajulus* L., Cerambycidae) (EHB) is a native of northern Africa, but is now widespread, with a range which includes Europe, North and South America, South Africa, Asia Minor, China and Russia (Dürr 1954; Duffy 1968). EHB is a pest of seasoned softwood, with larvae having a developmental stage of up to a decade. Adults are capable of reinfesting the same host timber and do not require an adult diet. The flight season occurs in the warmer months (Dürr 1957). The species was detected in New South Wales, Queensland and Victoria in the 1950s following the importation of prefabricated houses from Europe. This incursion was eradicated about 20 y later.

Beginning in January 2004, EHB was detected in several dead pine trees throughout a 75 km × 35 km region surrounding Perth,

Western Australia (31°57'S, 115°52'E). This is the first record of EHB in Western Australia. These initial detections were made by the sighting of distinct oval exit-holes (about 5–10 mm long, running with the grain), and subsequent splitting of timber samples to obtain larvae. To improve our surveillance capability, we investigated the use of chemical lures and cross-vane traps during the EHB flight season of 2004. Much research has been undertaken to test the attractiveness of sex pheromones and monoterpenoids to EHB (Fettköther *et al.* 1995, 2000; Reddy *et al.* 2005a,b) within laboratory or similar enclosed conditions. Here we present results of the first test of the ability of these chemicals to attract wild EHB in the field.

Materials and methods

Upon initial discovery of EHB in Western Australia in January 2004, we found that the exit holes of newly emergent adult beetles had a distinct shape and alignment: a hole of 5–10 mm long and 2–4 mm wide, running with the wood grain. Consequently all dead pine trees (*Pinus pinaster* Aiton and *P. radiata* D. Don) within the general Perth area (and subsequently more widely) were manually surveyed. Where likely exit holes were sighted, dead trees were dissected. This involved cutting sections of branch or trunk which contained exit holes into bolts 300–500 mm long which were then split into sections 10 mm in diameter. All larvae present were identified using Duffy's monographs (1957, 1963). While exit holes were identified prior to the trapping, tree dissection occurred after trapping unless otherwise stated (below).

In mid-November 2004, 45 pairs of cross-vane traps ('Intercept', IPM Technologies, Oregon, USA) were placed in the field, covering an area 70 km (N–S) × 35 km (E–W) around the Perth area. The cross-vane trap has been shown to be more effective than other trap designs for trapping woodborers (McIntosh *et al.* 2001). Twenty-three pairs were placed in sites known to be infested with EHB, based on the survey method described above.

In these sites, traps were placed within 20 m of infested material. Eighteen pairs were placed at sites not found to be infested by previous manual surveys. The remaining four pairs were placed at sites that had been infested but were cleared of all material known to be infested before or during the trapping period. Traps were placed with the lures 1.2 m above ground.

The pheromone-based trap consisted of a synthetic pheromone lure based on pheromone isolated from male EHB (3R-hydroxy-6-2Kt, Fettköther *et al.* 1995, 2000), which has been shown to attract male and female beetles in laboratory and glasshouse trials (Fettköther *et al.* 2000; Reddy *et al.* 2005a,b). The other trap consisted of a host-plant volatile lure, which contained both an (+)- α -pinene and (-)-verbenone lure. Verbenone is a constituent of EHB larval frass known to attract and stimulate ovipositioning in EHB females (Evans and Higgs 1975; Fettköther *et al.* 2000). α -pinene effectively attracts EHB under laboratory conditions (Fettköther *et al.* 2000; Reddy *et al.* 2005b) and is often used in trapping programs for wood-boring beetles (e.g. Byers *et al.* 1989; McIntosh *et al.* 2001; USDA-APHIS-PPQ 2003). Release rates were α -pinene, 300 mg day⁻¹; verbenone, 1.5 mg day⁻¹; OHB pheromone 3 mg day⁻¹. The traps forming each pair were no less than 10 m apart, as recommended by Bashford (2003).

The sampling period was between November 2004 and March 2005, during the beetle's flight season. Lures were replaced at the end of two months and traps were serviced every two weeks. Adult EHB were identified using Bense's key (1995).

Results

A total of six adult EHB, all females, were trapped with chemical lures at three sites. Four were caught in a single pheromone trap, and one individual was captured in each of two host-plant volatile traps. All three of these sites were found to be EHB-infested, following dissection of dead pine wood. Chemical lures did not detect EHB at the other 20 sites known to be infested, nor did they detect any new sites of infestation.

Based on emergence from laboratory-housed timber, female: male ratio was 0.602 (97/161, $n = 258$). The EHB pheromone trap had, as expected, a clear bias towards detection of females ($P = (0.602)^4 = 0.020$). Although verbenone may select towards the sampling of females, the low trapping number ($n = 6$) means we cannot comment further on any potential bias.

Discussion

Although the pheromones and monoterpenoids used in this study have previously demonstrated attractiveness to EHB adults (Fettköther *et al.* 1995, 2000; Reddy *et al.* 2005a,b), we have performed the first test of such chemicals in field conditions with wild beetles. The numbers of beetles caught in chemical traps during the sampling period were very low compared to other similar trapping regimes for other beetle species (e.g. Byers *et al.* 1989; Turchin and Odendaal 1996; de Groot and Nott 2001, 2004; McIntosh *et al.* 2001). We believe that this is due to infrequent long-distance flight by female EHB and the high frequency with which adult EHB reinfest the same host timber. Fettköther *et al.* (2000) have described the beetle as having 'a very sedentary behaviour using already successful breeding sites'

and therefore adult flight is not always essential. We therefore suggest that the probability of intercepting the beetle in flight is limited.

The range of effectiveness of lures is also an important issue, as all previous EHB-luring trials have been performed with the release of beetles only a few metres from the lures, and effectiveness has been recognised as decreasing significantly after only 3.5 m (Reddy *et al.* 2005a). Given the density of conspecifics and potential host trees, and the suitability of the current host tree in an infested pine plantation, for example, any chemical trap needs to compete with substantial chemical noise not present in laboratory trials. The combination of both male sex pheromones and monoterpenes has recently been shown to be more attractive to female adults than pheromones or plant volatiles alone (Reddy *et al.* 2005a).

Apart from manual surveys of wood from which wood-boring beetles have emerged, chemical lures and flight intercept traps are the only means of early detection of colonising beetles. Although manual surveys are labour intensive, our results show that they are effective in the detection of EHB-infested sites when the beetle is well established in a region. Manual survey methods also have the advantage that they can be carried out during the entire year — not just during the flight season. Given that EHB spends most of its lifetime as larvae, the likelihood of detection at this life-cycle stage is particularly high.

As we did not employ control traps (i.e. traps without any chemical lure) in this study, we cannot quantify precisely the effectiveness of the chemical lures versus the trap itself. However, given that all six adults trapped were females, we suggest that the trapping is not due simply to beetles colliding with the trap panes during flight, particularly given that male:female ratios in the population at large are male-biased and that males are responsible for discovery of new hosts (Fettköther *et al.* 2000). Although the number of sampled individuals is very low ($n = 6$), complete dominance by female beetles is statistically significant. Although the small size of this sample is undesirable, this was a direct consequence of the ineffectiveness of the trapping regime.

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Book reviews

Terania Creek: Rainforest Wars

Nigel Turvey

Glass House Books, Carindale, Queensland

190 pages, ISBN 9781876819354, ISBN 1 876819 35 9, Softcover \$28

For many readers of this journal, the names Terania Creek, the Nightcap and the Washpool recall images of confusing confrontations between loggers, ‘hippies’ and police that appeared on their TV screens around 1980. For northern NSW foresters of the time, they are names associated with a perception of the beginning of the end of professionalism in forestry when the best intent and practice of the professionals could be overturned and negated by the political whims of born-again conservationists. In scenes that have been repeated again and again throughout Australia, it is not surprising that foresters who have gone through the experience have ended up cynical, shell-shocked and weary and not a little confused as to how this could have happened in their quiet neck of the woods and what they could have done to prevent it.

In 1990 Ian Watson wrote about the events of Terania Creek, among the first forest confrontations to attract the media’s attention (Watson 1990). He interviewed mostly timber industry workers and conservationists, and analysed the battle as one between the middle-class intellectual values of the latter and the working-class utilitarian values of the former. Many of his interviews were conducted only a few years after the events, so the passion and immediacy are evident. Through his quotes he gives a graphic account of the strong feelings of the antagonists.

Sixteen years later we have another account of the events, this time by a forester educated in Ireland but who has spent most of his professional life in Australia. Nigel Turvey is probably better known as a forest soils scientist than an historian, but in this slim volume he brings his considerable research skills to bear on demystifying the Terania Creek conflict and subsequent events which ended in the banning of rainforest logging in New South Wales. Like Ian Watson, he interviewed a wide range of participants, including foresters, policemen and politicians. He has reviewed and referenced an impressive array of documentation. His account is easy to read and is broken down somewhat thematically but more or less chronologically. In places he disconcertingly drops threads and then picks them up in a later chapter, resulting in a need to repeat details to restore the context.

Turvey begins by briefly setting the scene — the mystique of the primeval rainforest and the confusion over what the public perceives as ‘rainforest’. He unfolds the saga from the decision to selectively log in 1979 a 77-ha compartment in Terania Creek which happened to be adjacent to the farm recently acquired by the Nicholsons to escape the city. The confrontations in the bush are recounted from the perspectives of the various players, as are the behind-the-scenes manoeuvring by both sides to keep the media engaged and sympathetic to their respective views,

despite the competing news events such as the Lindy Chamberlain case.

The judicial inquiry set up in 1979 by Premier Wran following his call to halt logging in Terania Creek receives a less comprehensive treatment by Turvey. Ross Florence (*pers. comm.*) notes that ‘there were 116 hearing days and 170 organisations/persons granted leave to appear — yet his account of the hearings focuses almost entirely on the stripping of Len Webb’s credibility’.

Turvey gives a plausible account of the split in the NSW Cabinet between those supporting the jobs of the timber workers and those opposed to logging the rainforest, including the pivotal role played by Premier Wran’s wife. Wran announced in 1982 a permanent ban on rainforest logging in NSW and began a process of moving state forest lands into national parks. To date almost a million hectares have been transferred by this political solution.

In the main, Turvey’s account is balanced and factual, without negating the importance of emotions and feelings in the ‘war’. Importantly for readers of this journal he pays particular attention to the role of foresters and the Forestry Commission and the impact the conflict had on both. The public saw foresters as aligned with the timber industry (they all wore hard hats on the TV) which stood in dogged opposition to the saviours of the last remaining remnants of the rainforest, and the urban sentiment swung towards the latter. In his final chapter entitled ‘Lessons and Landscapes’, Nigel places some of the blame on the poor communication and ‘hubris’ of the foresters and sawmillers.

This is a book which should be read by any who wonder why the forestry profession has suffered ‘the slings and arrows of outrageous fortune’, who wonder how and why political decisions are made in forest conflicts and who have a desire to understand what really was happening in the far north-east of New South Wales around 1980. The book is well presented with some interesting photographs, including one of an attractive protester wearing a policeman’s cap while giving the owner a scalp massage. A classic indeed!

Reference

Watson, I. (1990) *Fighting over the Forests*. Allen & Unwin, Sydney, 173 pp.

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The Forest Certification Handbook

Ruth Nussbaum and Markku Simula

Earthscan, London

Second edition 2005, hardback, 288 pages, ISBN 1844071235 / 9781844071234

£35.96 from the Earthscan shop, <http://shop.earthscan.co.uk/?&v=2>

This book is titled a 'handbook' and, as it notes on page 1, 'is not designed to be read from cover to cover, but rather to be used as a reference book that provides information on whichever aspect of certification is of interest to a particular reader at a particular time'. This second edition appeared ten years after the first, marking a decade in which forest certification moved from fringe to mainstream in forest policy, but remains little — if any — less contested.

The handbook remains a valuable sourcebook for those who are considering, or need to engage with, forest certification. In the Australian case, that's now many more than those working in forestry a decade ago, with a total of about 15 certificates issued under the Australian Forestry Standard (AFS) and Forest Stewardship Council schemes, totalling around 5.7 and 0.5 million ha, respectively. More than 100 000 ha of forest are now certified in each jurisdiction other than the ACT, NSW and the NT — illustrating the relevance of forest certification to many Australian forest managers, as well as to forest policy.

The Forest Certification Handbook is in four parts: '1. How forest certification schemes work'; '2. Forest certification in practice'; '3. Existing forest certification schemes'; and '4. Forest certification in context'. Australian readers are likely to find Parts 1, 2 and 4 most useful; Part 3 appears somewhat dated (even allowing for the delay in this review, for which the reviewer is regrettably and apologetically responsible), and doesn't address — for example — the AFS. The authors each have extensive direct certification experience, in businesses built largely around the certification industry, and they do a thorough job of outlining the mechanics, the politics and the potential and limitations of forest certification.

The handbook is probably most valuable for those who are new to forest certification, or those who feel the need for a broader view of the certification arena than can be elicited from more specific scheme-focused information or most academic critiques. The handbook is studiously non-partisan in terms of certification schemes, although strongly pro-certification as a policy instrument. It does, however, recognise and discuss the limitations of certification. The sections discussing 'new applications of forest certification' — to carbon and other environmental services markets — are timely in the Australian context, as elsewhere.

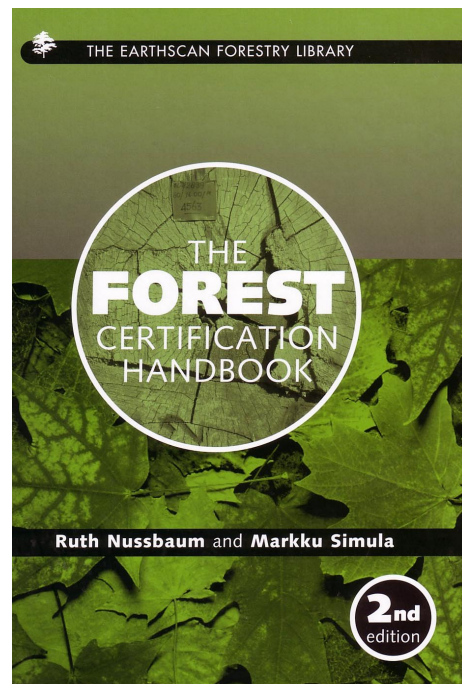
While Parts 1 and 2, in particular, are likely to remain quite durable because of their focus on process; a next edition could usefully shift the Part 3 content to a form that is more easily kept current, such as a website. While the introductory chapter and Part 4 will age somewhat in terms of detail, the overall discussion of policy and operating contexts is constructed in such a way as to remain valuable.

In summary, like many handbooks, *The Forest Certification Handbook* should find a place in the libraries of forest policy and management organisations in both the public and private sectors, and of individuals whose work causes them to engage with forest certification.

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Australian Forestry

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