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Low-rainfall eucalypts as a potential plantation resource in south-eastern Australia for sawn appearance products

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Summary

Four eucalypt species were evaluated for their potential to produce sawn appearance products when grown in the low rainfall (400–600 mm y^{-1}) region of south-eastern Australia. The species were selected on the basis of their suitability for the region and the availability of sawlogs in existing plantations. The sampled trees were about 40 y-old with a minimum diameter at breast height over bark of 30 cm. A butt log 3.1 m long was harvested from ten or eleven trees of each of the following species: *Eucalyptus astringens* (Maiden) Maiden (brown mallet), *E. cladocalyx* F.Muell. (sugar gum), *E. leucoxylon* F.Muell. (yellow gum) and *E. occidentalis* Endl. (flat-topped yate). The logs were back-sawn with a conventional sawing system to produce boards mostly of 100 mm x 40 mm (nominal) cross-section.

The recovery of green boards that met high-value appearance grades was poor. The recovery of select grade or better boards ranged from only 0.9% of log volume for *E. leucoxylon* to 8.1% for *E. astringens*. The poor recoveries were mostly attributable to the small diameter of logs and the lack of silvicultural treatment in the stands from which they were cut.

The results highlight the difficulties of growing high-value sawlogs in this region, without suitable silviculture. At best, given the expected long rotations, the economics of growing high-value sawlogs are likely to be marginal, and profitability will depend on other land management benefits provided by the trees. Improved genetic stock and appropriate silviculture will be critical if green recoveries (select grade and better) of at least 30–35% are to be achieved. Green recoveries of this magnitude are likely to be required for a viable sawn timber industry to be established in this region.

Use of a conservative air-drying schedule resulted in little drying degrade, surface checking being the main drying defect observed. Given the level of surface checking found, in the absence of other defects 85% of boards would still have made select grade or better. Nevertheless, careful drying practices will be required to minimise surface checking in back-sawn boards of each of these species.

Keywords: forest plantations; sawnwood; yields; productivity; dry conditions; arid climate; amelioration of forest sites; *Eucalyptus*

Introduction

There are various reasons for farmers and regional communities to establish plantations in the low-rainfall (400–600 mm y^{-1}) regions of south-eastern Australia. Primary amongst these is the need to improve agricultural systems and ameliorate serious broad-scale environmental degradation, such as dryland salinity. Other considerations include provision of wind-breaks and stock shelter, enhancing local and regional aesthetics, and increasing biodiversity.

In the study region, uncertainty about the wood quality and processing characteristics of candidate species is a major constraint to plantation establishment. This study provides data on the recovery of green appearance-grade products from four eucalypt species in existing plantations (grown with minimal management) to evaluate their potential to produce solid-wood appearance products. Basic observations on the drying properties of these species are also reported.

Materials and methods

Species selection

An initial survey of 30–60-y-old plantations in the predominantly winter rainfall region (400–600 mm y^{-1}) of south-eastern Australia assessed basic growth characteristics (growth rate, tree form, and site and climate suitability) and identified species with at least 20 trees (to allow some freedom to select the 10–11 trees to be evaluated) meeting the following criteria for the sawmill study:

- about 40 y-old
- a minimum diameter at breast height over bark (DBHOB) of 30 cm
- a clean, straight bole to height of at least 3.5 m (sufficient to harvest a butt log 3.1 m long).

Diameters were measured with a diameter tape, tree height with a Suunto clinometer and 30 m tape, and the point basal area with a factor 1 or 2 wedge depending on size and distribution of surrounding stems. Table 1 summarises the plantation and log information for each of the four species sampled. All the plantations were located north of Horsham in western Victoria (<450 mm y^{-1} rainfall) and harvesting was carried out in February 2000.

Table 1. Summary of species and log details: mean (and standard error in parentheses)

Details	Species			
	E. occidentalis	*E. cladocalyx*	*E. leucoxylon*	*E. astringens*
Plantation	Barrett	Wail	Wail	Glen Lee
Latitude	36°25'S	36°31'S	36°30'S	36°16'S
Longitude	142°19'E	142°05'E	142°04'E	141°50'E
Age at harvest (y)	42	29	44	41
No. trees	11	10	11	11
DBHOB (cm)	41.3 (2.3)	35.1 (0.8)	36.5 (1.2)	34.6 (1.2)
Range	30.1–52.9	31.0–39.0	30.5–44.5	30.9–45.2
Tree height (m)	20.8 (0.5)	19.3 (0.4)	21.2 (0.8)	18.0 (0.5)
Range	18.3–23.0	17.2–21.6	17.2–25.2	16.1–21.3
Point basal area (m^2 ha^{-1})	20.8 (1.0)	22.1 (1.7)	17.8 (0.9)	17.0 (1.6)
Large-end diameter (cm)	38.7 (0.9)	31.6 (1.0)	35.8 (1.2)	36.1 (1.5)
Small-end diameter (cm)	33.6 (0.7)	26.6 (0.5)	28.8 (0.8)	30.0 (1.0)
Log volume‡ (m^3)	0.330 (0.013)	0.209 (0.010)	0.259 (0.016)	0.272 (0.019)
Taper (cm m^{-1})	1.6 (0.1)	1.6 (0.2)	2.2 (0.2)	2.0 (0.3)
Large-end sapwood width (mm)	16.7 (0.7)	19.3 (1.4)	21.6 (1.6)	15.9 (0.8)
Small-end sapwood width (mm)	17.9 (0.6)	21.0 (1.5)	19.9 (0.7)	15.2 (0.8)

‡Log volume calculated using Smalian's formula from the large- and small-end diameters.

Log preparation and sawing

Immediately upon cross-cutting and trimming to length, the ends of all logs were coated with a wax emulsion ('PARACOL' 855N: Hercules Chemicals Australia) to prevent end-drying and checking. After transport to the sawmill the logs were stored, with the bark left on, under water spray. In the days preceding sawing, logs were debarked and, after ends were trimmed square, measured for length. End diameters and sapwood width were measured on the longest and perpendicular axes. Log taper was calculated as the difference between the large- and small-end diameters divided by the log length. Sawing was conducted at the Timber Industry Training Centre, Creswick, using a conventional back-sawing strategy. A sizing carriage and 72-inch-diameter 'Salem' vertical band-saw were used for primary log breakdown. A Grey one-man circular-saw bench was used for re-sawing and sizing boards to dimension. The sawing strategy involved cutting a central cant 105 mm wide that was aligned with the north–south orientation of the logs in the plantation (Fig. 1). Boards 43 mm thick were taper sawn from the cant and wings, and smaller-dimension products were also cut where possible. To enable the sawyer to identify the north–south axis of the logs, three lines of different colours were applied to the large end of each log to indicate the north, south and west axes respectively. The lines later enabled the relative positions of the boards in the log to be determined (the paint can be seen on ends of boards in Fig. 2b).

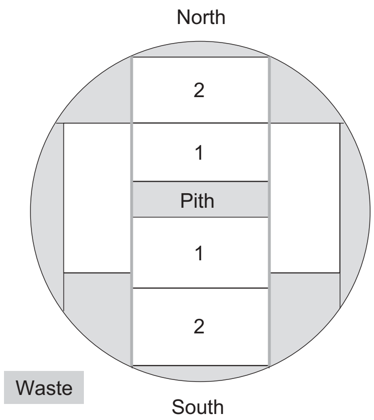

Figure 1. Basic sawing pattern (view of small end). A central cant, 105 mm wide (indicated by light lines), was cut in the north–south alignment and then boards 43 mm thick were taper sawn.

Green grading and recovery calculations

All boards were visually graded to CSIRO appearance-grading rules (Waugh and Rozsa 1991). The grades and a brief description of the uses of each grade are provided in Table 2. Boards were notionally docked where an upgrade of two grades could be achieved within the length restrictions listed in Table 2.

Green recoveries were determined using nominal board sizes and notional docked lengths. The nominal board sizes were 100 mm x 40 mm, 100 mm x 25 mm, 100 mm x 12 mm, 70 mm x 40 mm, 70 mm x 25 mm, 70 mm x 12 mm, 50 mm x 40 mm and 50 mm x 25 mm. Log volumes were calculated using Smalian's formula. To simplify the interpretation of the green grade recoveries, the following measures of recovery were calculated:

- sawn recovery — total recovery of all products plus reject, as a percentage of log volume. This is an indicator of the efficiencies of the sawing systems and strategies used rather than of the quality of wood sawn.
- product recovery — recovery of all sawn products less reject, as a percentage of log volume. Cutting grades (Table 2) were allotted to polishing and moulding grades.
- target recovery — recovery of cover grade and better, as a percentage of log volume. Products 100 mm x 12 mm or 50 mm x 25 mm in size and less than 1.8 m in length were rejected, as they are not sizes preferred by industry.

Table 2. Brief description of CSIRO-developed appearance grades (Waugh and Rozsa 1991)

Grade	Brief description of uses
Polishing	Wood used for highly decorative purposes. Graded on all faces and used for high-value furniture, wood turning and trim items. Minimum length 1.8 m.
Moulding	Also used for highly decorative purposes. Graded on all faces and used for furniture and trimmings. Minimum length 1.8 m.
Select	Graded on the best face and both edges. Examples of uses are lining boards, strip flooring and shelving. Minimum length 2.4 m.
Standard	Graded on the best face. Example uses are lining boards and strip flooring. Minimum length 2.4 m.
Utility	Graded on the best face. Example uses are industrial shelving, strip flooring, and industrial lining boards. Minimum length 2.4 m.
Cutting grade 1	Short lengths equivalent to polishing grade cut from lower-grade boards. Minimum length 1.2 m.
Cutting grade 2	Short lengths equivalent to moulding grade cut from lower-grade boards. Minimum length 1.2 m.
Cover	Graded on the worst defect. Stiffness is of prime importance as the products are used for strength within furniture. Not strictly a structural product because the tolerances for machining and distortion are finer than specified for structural products. Minimum length 2.4 m.
Case	Graded on the worst defect. Used for low-grade pallets or chipped if price is not right. Minimum length 2.4 m.
Reject	No use as solid wood; possible use as fuel wood or chips

- select recovery — recovery of select grade and better, as a percentage of log volume. The same restrictions on product dimensions apply as for the target recovery.

Lyctid-susceptible sapwood is not permitted, or at best is restricted to the limits for wane, in the CSIRO appearance-grading rules. *E. astringens* is known to have lyctid-resistant sapwood (Bootle 1985), while *E. cladocalyx* and *E. leucoxylon* are known to have lyctid-susceptible sapwood (Standards Australia 2000). The susceptibility of *E. occidentalis* is unknown, but it may be resistant as it is closely related to *E. astringens*. Regardless, in this study it was assumed for all species that even if the sapwood was susceptible, it would be chemically treated and thus permissible. Without treatment the recoveries for *E. cladocalyx* and *E. leucoxylon*, and possibly *E. occidentalis*, would be further reduced.

Drying

No drying schedules for back-sawn material of these species, 40 mm thick, were given in Rozsa and Mills (1991). To minimise drying degrade, all boards in the present study were dried conservatively under mild conditions of controlled air-drying. Boards 40 mm thick were deliberately targeted for the drying study, as drying problems are more pronounced in such thick boards. If these boards can be dried successfully, it should be possible to dry thinner boards with less degrade and in a shorter time.

To monitor drying rates and degrade, one sample board was prepared from each of the trees in the study. In each case, the board selected for sampling was from the north–south cant (Fig. 1); preferably from the outer heartwood. The sample boards were 600 mm long and cut from the butt end of the board. A section 20 mm long was cut for determination of moisture content (MC) accordance with the oven-dry (OD) method outlined in AS/NZS 1080.1:1997 (Standards Australia 1997). At the completion of drying, additional sections were cut from the middle of the sample boards to determine final MC and to re-estimate more accurately the OD weight of these boards. The boards from each species were kept separate in four discrete stacks; the sample boards were distributed across two layers within each species stack (Fig. 2). The stacks were arranged in two pairs, one member of each pair being on top of the other.

Prior to the sample boards being cut, all boards were left block stacked and wrapped in plastic for six weeks. When the sample boards were prepared the boards were stickered out and the stacks re-covered with plastic. After a further 11 weeks the plastic was removed from the long sides of the stacks and replaced with hessian. After a further five weeks the hessian was removed from the long sides of the stacks. The stacks then were placed in front of a drying fan-wall to improve uniformity of drying. The fan-

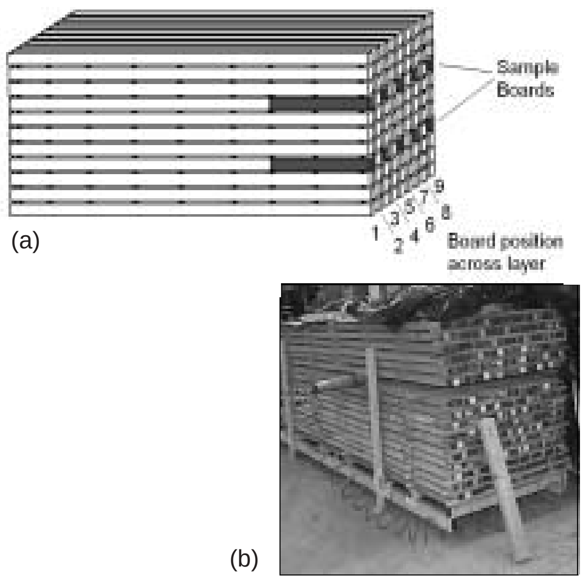

Figure 2. (a) Diagram of placement of sample boards: boards from each species were placed in two layers. (b) A sample board of *E. astringens* removed from stack for weighing.

Table 3. Comparison of log features (log volume, small-end diameter (SED) and taper) and the various green recovery figures from this study (400–600 mm y^{-1}) with those from the butt logs only in the Washusen *et al*. (2000) study (580–750 mm y^{-1}) (Rk = rank)

Species	Count	Log volume		SED		Taper		Sawn recovery		Product recovery		Target recovery		Select recovery	
(location, age)		Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk
	Rainfall zone: 400–600 mm y^{-1}														
E. cladocalyx (Wail, 29 y)	10	0.209	9	26.6	10	1.59	6	40.0	7	32.0	5	18.1	8	1.0	9
E. astringens (Glen Lee, 41 y)	11	0.272	6	30.0	7	1.96	3	39.9	8	32.5	4	22.9	6	8.1	5
E. leucoxylon (Wail, 44 y)	11	0.259	8	28.8	8	2.25	1	35.9	10	22.0	10	7.4	10	0.9	10
E. occidentalis (Barrett, 42 y)	11	0.330	2	33.6	3	1.63	5	43.0	3	26.4	9	14.0	9	5.2	8
Combined	43	0.269		29.8		1.86		39.7		28.1		17.7		3.9	
	Rainfall zone: 580–750 mm y^{-1}														
E. cladocalyx (Earlston, 40 y)	5	0.304	4	33.2	4	1.54	7	43.3	2	35.1	2	32.6	2	20.6	2
E. cladocalyx (Bandiana, 36 y)	5	0.297	5	32.4	5	1.82	4	42.8	5	34.5	3	29.6	4	18.9	3
E. globulus (Oxley, 15 y)	10	0.208	10	27.5	9	1.30	9	42.9	4	27.0	8	20.6	7	6.5	7
C. maculata (Lake Hume, 40 y)	10	0.411	1	38.1	1	2.17	2	44.1	1	39.4	1	37.0	1	28.0	1
E. sideroxylon (Lake Hume, 40 y)	5	0.314	3	34.2	2	1.39	8	42.2	6	31.0	6	30.6	3	13.7	4
E. sideroxylon (Tarrawingee, 26 y)	5	0.264	7	31.5	6	1.06	10	36.0	9	27.9	7	25.0	5	8.0	6
Combined	40	0.302		32.8		1.59		42.3		32.7		29.1		16.3	

wall monitored ambient conditions to draw air through the stacks (<0.5 m s^{-1}) when the temperature was <30°C and relative humidity >60%. At all times the top and ends of the stack remained covered with plastic.

Steam reconditioning was applied for 6 hours when the average board MCs were about 15–18%. At this stage, an electrical moisture meter ('Delmhorst' RC1C) was used to check that core MCs were below 25%. After reconditioning, the boards were kiln-dried to 10% MC. The final drying schedules took 2 weeks, with conditions set at 60/50°C (dry bulb/wet bulb) for 7 days, equalised at 70/50°C for 4 days and finally conditioned at 70/65°C for 2–3 days. Air flow through the kiln was 1–1.5 m s^{-1}. The steam reconditioning and final drying were undertaken in a pilot-scale kiln with a capacity of 4 m^3.

Results and discussion

Recovery of green appearance products

Table 3 shows the various recoveries for each species. For comparison, the equivalent recoveries, from the butt logs only, have been extracted from the study by Washusen *et al.* (2000) and included in this table. One difference in grading between the two studies was that sapwood was graded as wane in the Washusen *et al.* study. This was mostly due to the strong colour difference between heartwood and sapwood in *E. sideroxylon*, which usually makes sapwood unsuitable in appearance products. The recoveries for the other species in the Washusen *et al.* study, which have lighter colours and less contrast between heartwood and sapwood, would be slightly higher than shown in this table if the assumption used in this study had been applied; that is, that the sapwood would be chemically treated against lyctid borer.

Table 3 clearly shows that the recovery of appearance products in the present study was poor compared with that in the Washusen *et al.* study. This is partly due to the smaller diameter and greater taper of the logs sawn in this study. This is most apparent with *E. cladocalyx*, where the small-diameter logs had much lower recovery of the higher-quality grades (mostly due to wane and pith, as shown in Fig. 3) than was obtained from the larger logs sampled by Washusen *et al.* (2000).

The obvious exception is *E. occidentalis*, which had the second-largest logs of either study with only average taper. While it had the third-greatest recovery of sawn products, the recovery of target and select grade products was very poor. This was mostly due to extensive decay columns from large dead knots that were not apparent in the standing trees. Figure 3 shows that decay was in fact the major cause of boards being rejected for most species in this study. Wane, pith and green knots were the other main grade-limiting defects, restricting a high proportion of the boards to the lower-value products of cover grade, case grade or reject grade. Termite galleries were a problem only with *E. leucoxylon*.

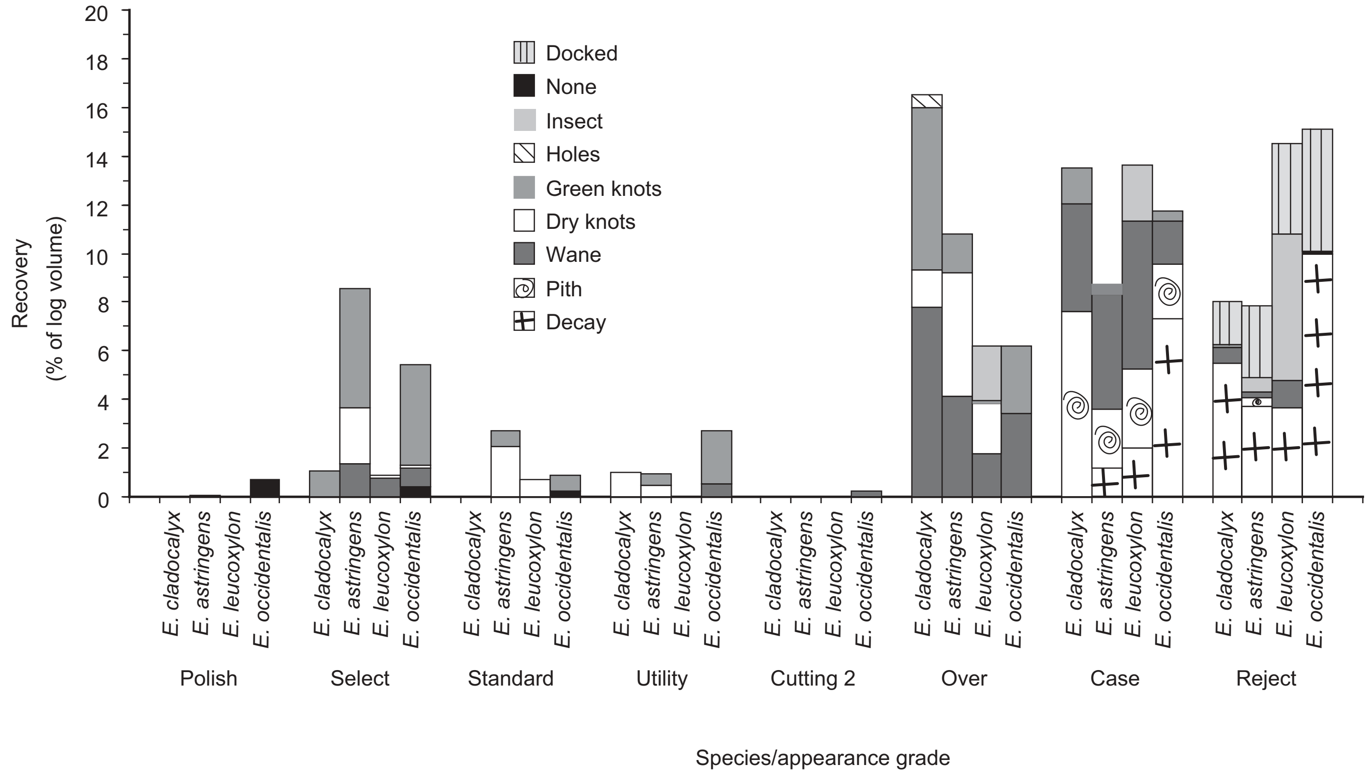

Figure 3. Grade-limiting defects and consequent recovery of appearance grades for each species

Intuitively, small-end diameter (SED) has an effect on recovery of appearance grades, as anything that increases the corewood zone (pith, juvenile wood and inner knotty zone) will significantly reduce the proportion of outer clear mature wood that can be sawn into high-grade products. Figure 4 shows, by position in the central cant (Fig. 1), the proportion (fraction of volume) of boards that met the target grade criteria (cover grade or better). As expected, the fraction of boards that meet the target grade criteria clearly increases with the distance of the origin of the board from the pith. The yields in positions 1 and 2 are notably low for *E. leucoxylon* and *E. occidentalis*. *Eucalyptus leucoxylon* had the poorest form; wandering or irregular pith is likely to be the main problem with this species.

Efforts to minimise the amount of irregular pith, and knotty and decaying corewood, through genetic improvement, silviculture and mechanical pruning will be important for these two species in particular if recoveries are to be improved.

Work on improving characteristics such as stem form and branching is already being undertaken by the Australian Low Rainfall Tree Improvement Group (ALRTIG). Early provenance testing with *E. occidentalis* suggests that significant improvements in form and height to crown break should be readily achieved through selection of appropriate seed (Chris Harwood, CSIRO Forestry and Forest Products, *pers. comm.*).

Drying rate and degrade

Figure 5 shows the mean MC of the sample boards for each species during drying. While *E. cladocalyx* started out with the highest mean MC, it also dried most rapidly. The opposite situation occurred with *E. astringens*, which started with the lowest mean MC but dried most slowly. The drying rates shown in this figure are likely to reflect both the inherent drying properties of each species and the position of the species in the two composite stacks. Boards of *E. cladocalyx* were at the top of its stack while *E. astringens* boards were at the bottom of its stack, closer to the colder moister air that settles at ground level.

While wrapped in plastic and hessian, only minor surface checking occurred, toward the ends of the boards. After the hessian was removed, some small fine checks became evident, especially in *E. occidentalis*. New checks continued to be initiated and existing checks lengthened over the following three months. Checks mostly occurred on boards that were on the edge of the stacks or on boards that came from positions close to the pith.

Cross cuts made through the sample boards at the conclusion of drying revealed only two or three boards with any internal checks. In these cases, the checks were restricted either to material from close to the pith or within localised areas with unusual patterns (wide or non-concentric) of growth rings. Distortion was a minor problem, being mostly isolated occurrences of spring.

Despite the conservative drying conditions, some fine surface checking remained on some boards of all species after they were machined to 90 mm x 35 mm. Table 4 shows how surface checking would have limited the grades of the boards in the absence of all other defects. About 75% of boards had no surface checking, while most boards with surface checks would still meet the criteria for select to utility grade. Overall, surface checking was the grade-limiting defect for about 12% of the boards. Boards of *E. cladocalyx* had the worst instances of surface checking, but

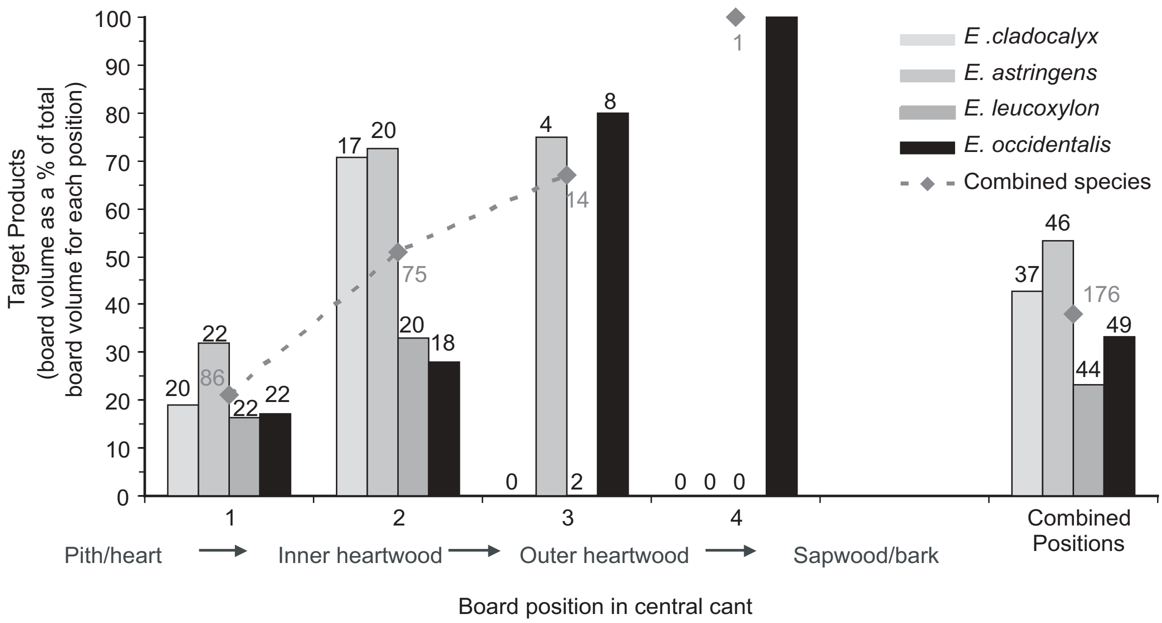

Figure 4. Volume of target products (cover grade and better) expressed as a percentage of the volume of all boards for each board position from the north-south cant only. Numbers above columns indicate the total number of boards recovered from each position. Numbers on the y-axis indicate the position of boards on the log cross-section (Fig. 1).

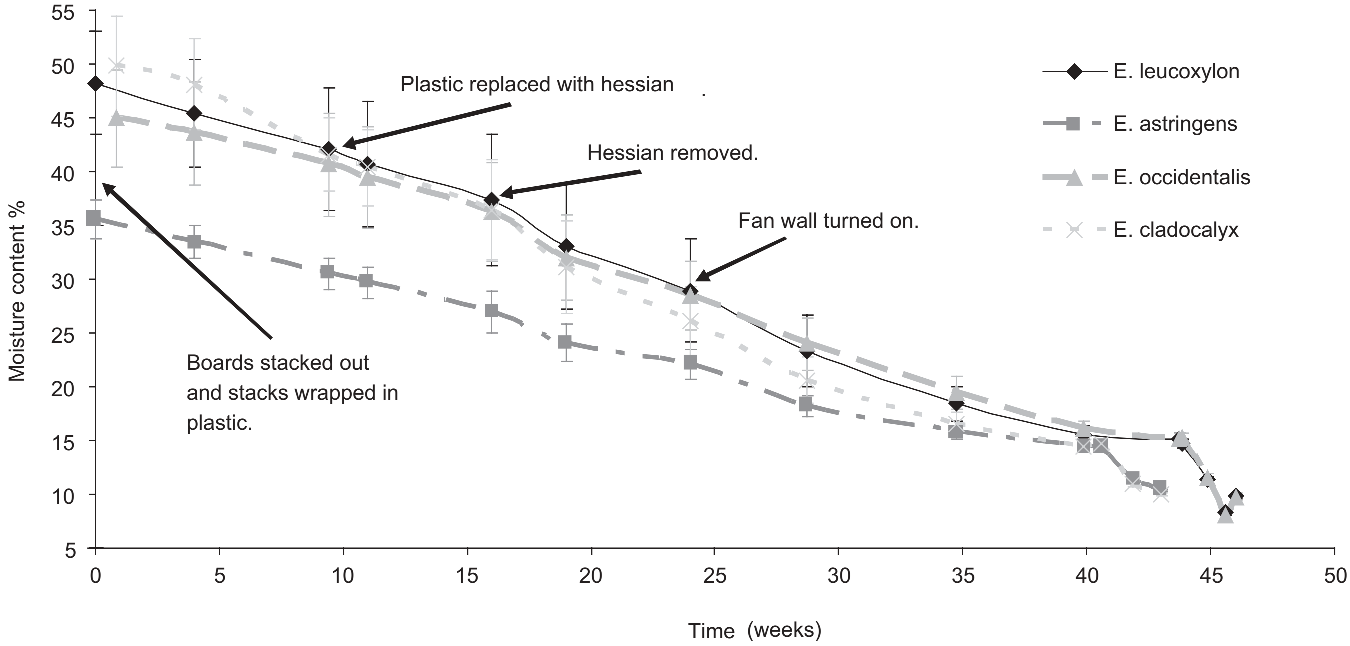

Figure 5. Mean moisture content of the sample boards for each species over time during drying; error bars show 95% confidence intervals for the mean sample board

Table 4. The appearance grades (% of boards) the boards would have achieved if all defects other than surface checks had been ignored. The final two columns show the number of boards where surface checking was the grade-limiting defect. Sample boards are included in this table.

Species	Appearance grade (%)					Count	Grade-limiting defect	
	Polish	Select	Standard	Utility	Cover		Number	Fraction (%)
E. cladocalyx	67	6	0	28	0	54	2	4
E. astringens	70	18	0	12	0	74	14	19
E. leucoxylon	93	5	2	0	0	59	3	5
E. occidentalis	69	12	1	13	4	98	14	14
Combined (%)	74	11	1	13	1	100	33	12
Combined (count)	211	31	2	37	4	285		

these were rarely the grade-limiting defect — probably because of the high percentage of these boards with pith and green knots (Fig. 3) due to the small diameter of the logs. Boards of *E. leucoxylon* had the lowest incidence of surface checking, with 93% of them being check free.

Conclusions

The recovery of appearance products from the four species sampled was poor compared with the recovery from other species in a similar study by Washusen *et al*. (2000). The main inherent defects contributing to the poor recovery were decay, green knots, dead knots, wane and pith. The impact of these defects was significant, confining a high proportion of sawn boards to the low-value grades of cover and case, as well as causing a similarly high proportion of boards to be rejected. These defects were a result of the poor form and small diameter of the logs sawn (with the exception of larger-diameter *E. occidentalis* logs).

Despite the conservative air drying, surface checking still occurred in all species, although internal checking and distortion problems were negligible. In most cases the surface checks appeared to be fine, long and deep. Some of the surface checks were removed in the machining process, but in the absence of all other defects about 15% of the boards would have been limited to select grade or lower by checking. Pre-drying could possibly bring the drying time for 43 mm back-sawn boards to 60–120 days with acceptable levels of surface checking. This observation is partly based on the previous experience of drying from green a number of medium- to high-density species (including *E. cladocalyx*) evaluated by Washusen *et al*. (1998). Drying problems and times should also be significantly less when drying thinner products.

Despite the poor result in this study, *E. cladocalyx* shows good potential in the lower-rainfall zone as it appears to have comparatively better growth rates (Anderson 2000; Stewart *et al*. 2000) than other species considered for the low-rainfall region, and recoveries from older, larger trees were promising (Washusen *et al*. 2000). The potential of *E. occidentalis* and *E. astringens* also appears to be good, provided that stem form and branching characteristics can be significantly improved. *Eucalyptus leucoxylon* appears to have little potential for high-value solid wood products unless its form can be significantly improved, and it might be considered only on sites unsuitable for the other species. In its favour, *E. leucoxylon* did have the least surface checking during drying.

At best, given the expected long rotations, the economics of growing high-value sawlogs in the low-rainfall region are likely to be marginal, and overall merit of planting candidate species will depend on other land management benefits. A detailed evaluation of the economics of growing these species in the low-rainfall region has not been attempted here. Nevertheless, it is felt that a viable sawing industry based on such a resource would need to achieve green recoveries of target products (cover grade or better) of at least 35–40% of log volume, and recovery of appearance products (select grade or better) of at least 30–35% of log volume. To achieve these figures, trees will probably need to be at least 40 cm DBHOB to maximise the volume of clear outer heartwood. Recent work (Washusen, unpublished) suggests that it may be possible to recover 35% of log volume as polish and moulding grades from large-diameter ($\geq$40 cm) pruned trees, providing that drying degrade can be minimised. An ability to cut out defects and produce shorter boards would also help to achieve these levels of recovery.

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Projecting native forest inventory estimates from public to private tenures

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Summary

Inventory information on privately managed forest areas tends to be more variable and less available than for equivalent publicly managed forests. This paper reports on an examination of the timber volume on Tasmanian private and public native forests and demonstrates that the differences between tenures in terms of total (entire stem) volume (m^3 ha^{-1}) are significant but relatively small. The paper also demonstrates that information from public forest inventories may be used to generate auxiliary information that can improve the efficiency of sampling on equivalent private forests. Regression and variable probability sampling using auxiliary information generated from public forest inventories can reduce the need for establishing sample points in private forests to only 25% of that required under simple random sampling for a given level of precision.

Keywords: forest inventories; volume determination; sampling; tenure systems; Tasmania

Introduction

The intensity of sampling across the forests of Australia is very irregular. Public service authorities managing commercial forest plantations tend to implement intensive sampling regimes with up to 1 sample point per 4 ha, while using a lower intensity (e.g. 100 plots / stratum) in their commercial native forest areas. Where inventories exist, sampling intensities on privately managed plantations and native forests tend to be much lower than in the equivalent publicly managed areas. This varying level of sampling and resulting quality of information creates difficulties when national or regional estimates of forest values are required. Often values derived from publicly managed forests are subjectively scaled down and applied to the privately managed forests. Resource Assessment Commission (1991, Appendix F.3.3), for example, scaled down the commercial timber volume available from private forests to as little as 10% of that available from public forests on the basis of subjective estimates by experienced forest managers. Industry and regional planning requires much better information as the privately managed resource becomes more important in areas like south-eastern Queensland. A subjective approach is also no longer sufficient, either to meet Australia's international reporting obligations (e.g. Montreal Indicators and Kyoto Protocol), or to demonstrate sustainability under Regional Forest Agreements.

This paper compares inventory estimates of entire (gross) tree volume across tenure boundaries and outlines the potential to use inventory information from publicly managed forests to predict information on privately managed forests.

Data

Forestry Tasmania maintains an extensive and reliable aerial photograph database of all native forests in Tasmania, both publicly and privately managed. These photographs are interpreted, and forests are classified into polygons (PI Types) delineating patches of relatively uniform forest. Each patch is described according to the broad species group of the forest, average crown height and density, etc. The minimum patch size ranges from 2 ha to 10 ha. Stone (1998) details this typing process for Tasmania. Tasmania is divided into 25 Inventory Areas (IA), and for State Forest sampling purposes the PI Types are grouped into Forest Classes by similar condition, height and crown density of the eucalypt component, and potential growth. Fixed-area plots (about 0.2 ha) are randomly placed within the gross State Forest (i.e. public forestland) area of each Forest Class. The DBH of all commercial trees over 10 cm is measured and a systematic sample of trees is also selected for measurement of height and bark thickness to allow the derivation of height : diameter relationships and bark thickness models. Tree shape, volume and growth are modelled from the data collected.

In 1982, Forestry Tasmania undertook an inventory over privately managed forests using their standard measurement techniques and models. However, plots were not randomly placed within each of the Forest Classes on the private lands. Instead, plots were subjectively selected to cover PI Types not adequately covered on public forestland or where there was an *a priori* expectation that there was a significant difference between public and private forests of a common Forest Class. This inventory data was used to model the Entire Stem Volume (ESV m^3 ha^{-1}) as at 1990.

For the current analysis, Forestry Tasmania provided the estimated ESV for sample plots on public forestland by IA, Forest Class and PI Type as at 1990. Types and IA that did not include samples for each tenure were excluded from analysis (Table 1). Each Forest Class is aggregated from up to 40 PI Types, but these PI Types were not all represented within both tenures. In total, 934 plots (96 private and 838 public) were available for analysis.

Table 1. Number of sample points by inventory area, type and tenure

Inventory Area	Tenure	Forest Class															
		5	6	7	8	9	10	12	19	21	26	31	32	34	35	37	40
4	Private	1			1										1		2
	Public	1			1										15		2
5	Private			3	4	23		2	3								
	Public			5	2	8		1	3								
7	Private				1	2	2	2	5	1		1	3				
	Public				23	28	2	2	29	21		2	12				
8	Private		1	1	5	1			2	1		3	3			2	
	Public		13	32	8	11			11	11		2	5			5	
10	Private								3								
	Public								5								
11	Private				1	2	1										
	Public				7	10	3										
13	Private					1	1		1	1							
	Public					10	2		50	6							
14	Private		1			2	2										
	Public		13			129	39										
15	Private								1								
	Public								169								
19	Private													1			
	Public													30			
21	Private										1			1			
	Public										12			98			

The ESV range is high, varying from 0 to 1500 m^3 ha^{-1} (Fig. 1). Three potential outliers with ESV exceeding 1200 m^3 ha^{-1} were retained for all analyses as there were no compelling reasons for excluding them.

Analysis and results

The unbalanced and sparse nature of the data made it impossible to undertake an ANOVA with Tenure, Forest Class and IA as

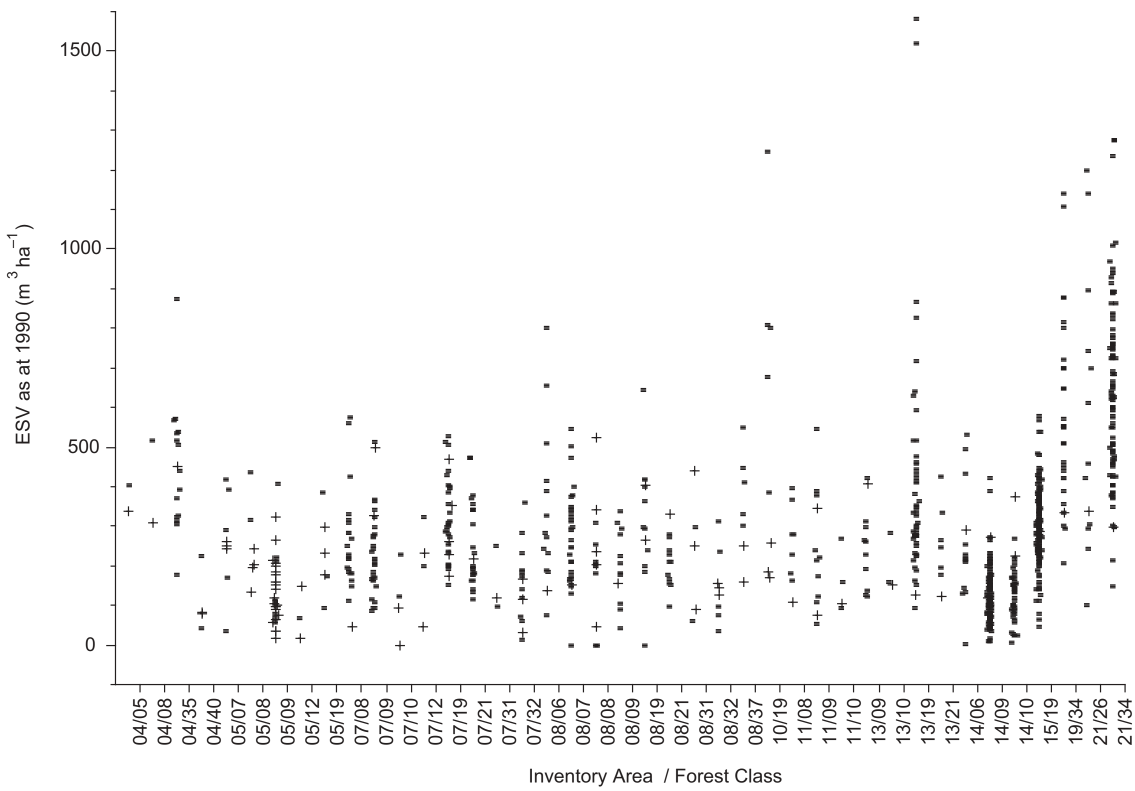

Figure 1. Plot of Entire Stem Volume (m^3 ha^{-1}) against Inventory Area and Forest Class for private (+) and public (■) forest samples

Table 2: ANOVA statistics for √ESV as dependent variable with tenure and Area / Class as independent variables

Source	DF	Sum of squares	*F* ratio	Prob > *F*
Tenure	1	164.59	10.90	0.0010
Area / Class	40	2306.19	3.81	<0.0001
Tenure x Area / Class	40	1107.75	1.83	0.0014
Error	850	12832.2		
Total	931	16410.73		<0.0001

(interacting) independent variables. However, as there appeared to be an interaction between IA and Forest Class a new variable (*Area / Class*) was defined as the combination of IA and Forest Class. A square root transformation of ESV was also necessary for further statistical analysis to meet assumptions about homogeneity of errors.

An analysis of variance (Table 2) found that the square root of ESV was dependent on Area / Class ($F = 3.81$; $P < 0.0001$), and the tenure x Area / Class interaction ($F = 1.83$; $P = 0.0014$).

Although tenure was a significant factor ($P < 0.001$) and on average public forest had a greater ESV than private forest, the significant tenure x Area / Class interaction term indicates that the difference in ESV between privately managed forest and the public forest was not consistent for all Area / Classes. Figure 2 shows that in some Forest Classes, the ESV on private tenure was greater than on public tenure.

Disaggregating Forest Classes into their original PI Types allowed the samples to be classified into condition (cutover, burnt, not recently disturbed) and the stand height and crown density of the mature eucalypt component. The ordinal height and density classes were then allocated average class heights and densities to create continuous numerical values. Analysis of variance (Table 3) indicates that the interaction between tenure and IA remains

Table 3. ANOVA statistics for √ESV as dependent with Tenure, IA and Condition as nominal variables and the stand height and density of the mature eucalypt component as continuous variables

Source	DF	Sum of squares	*F* ratio	Prob > *F*
Tenure	1	87.78	5.87	0.0156
Condition	2	271.51	9.08	0.0001
Height	1	1063.33	71.12	<0.0001
Density	1	570.32	38.14	<0.0001
IA	9	186.16	1.38	0.1909
IA x Tenure	9	285.96	2.12	0.0252
Error	900	13456.13		
Total	923	15921.19		<0.0001

Table 4: ANOVA statistics for reduced model with √ESV as the dependent variable and the stand height and density of the mature eucalypt component as continuous variables

Source	DF	Sum of squares	*F* ratio	Prob > *F*
Height	1	6370.97	384.13	<0.0001
Height^2	1	236.88	14.28	0.0002
Density	1	1848.18	111.43	<0.0001
Error	920	15258.38		
Total	923	23714.41		<0.0001

significant ($F = 2.12$; $P = 0.0252$). However, height and density alone explain almost as much of the error as the model that includes condition, tenure and IA (Table 4).

A linear regression model using height and density was fitted using only the public forest data ($R^2 = 0.52$):

$$\sqrt{ESV} = 5.983 + (0.02327 \times height) + (0.006819 \times height^2) + (0.07682 \times density) + E \qquad (1)$$

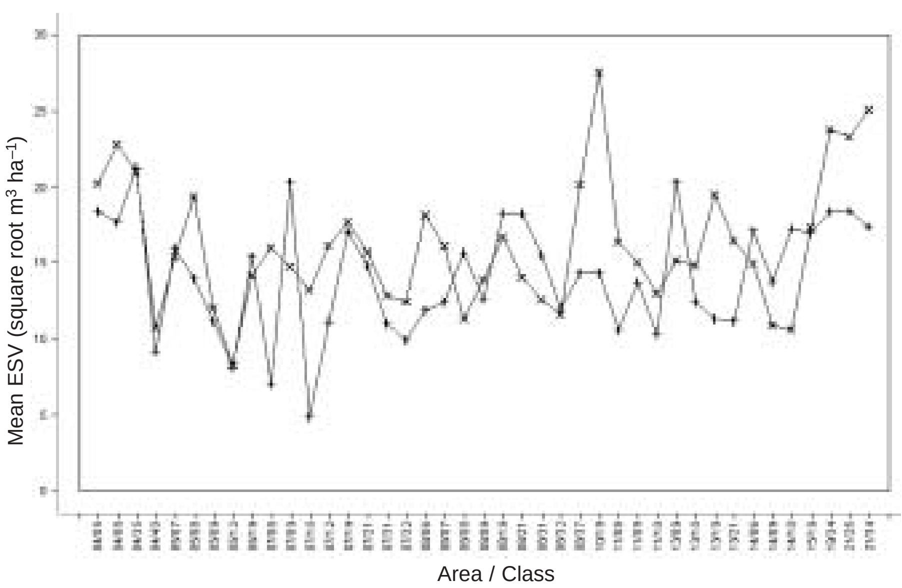

Figure 2. Entire Stem Volume (ESV; square root of $m^3\,ha^{-1}$) for public (x) and private (+) tenures for each Area / Class, with least square mean values connected

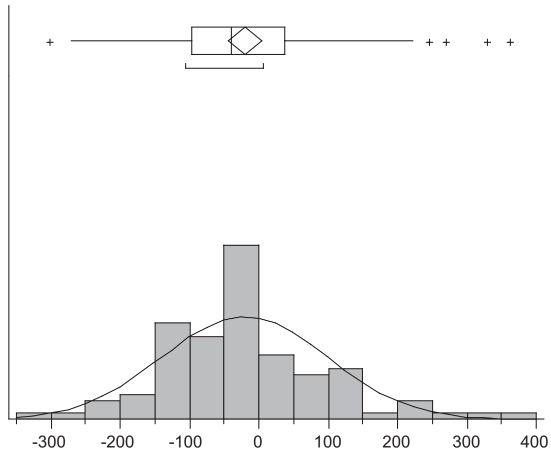

Figure 3. Quantile box plot and frequency distribution for errors in predicting private forest ESV, using model parameters fitted from public forest data. The central box in the quantile plot contains 50% of the observations with 25% extending above and below the box. The median location bisects the box with a horizontal line. The mean and standard errors form a diamond within the box, while the horizontal 'whiskers' contain all data within 1.5 times the interquartile range.

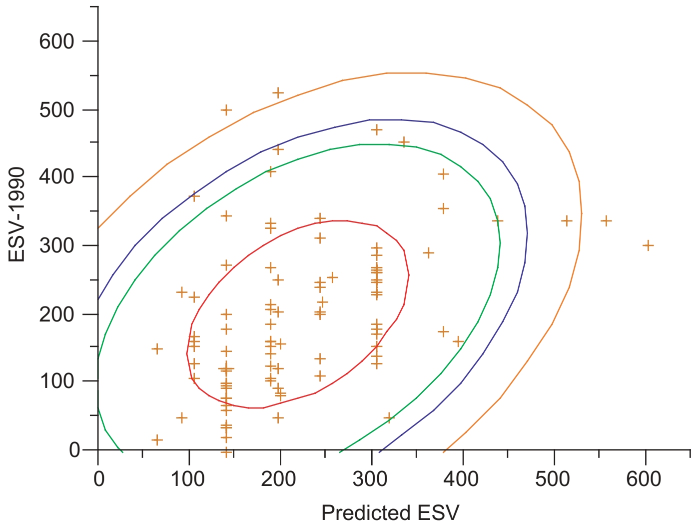

Figure 4. ESV measured in private forest compared to ESV predicted from the public forest model, with normal density ellipses (50%, 90%, 95%, 99%)

where ESV denotes the predicted entire stem volume (m^3 ha^{-1}), 'height' denotes the mean height of the dominant eucalypt component within the PI Type, 'density' denotes the mean stand crown density within the PI Type, and E denotes the error term (which is tested for homogeneity and normal distribution). The standard errors of the regression coefficients are 2.12, 0.0124, 0.00231 and 0.00779, respectively.

This equation was used to predict the $\sqrt{}$ESV for the privately-managed forests, which was transformed to normal units. The difference between the observed and predicted ESV (error distribution) for the private forest predictions was slightly skewed with a mean error of –19.6 m^3 ha^{-1} (std error = 12.2 m^3 ha^{-1}), which is not significantly different from 0 (P = 0.05) (Figs 3, 4).

Discussion

Tenure appears to be a statistically significant effect for ESV of the native forests in Tasmania. However, with a few exceptions, the effect is relatively small and is not consistent across IA or Forest Classes. This small difference is in contrast to the large differences in standing wood volume reported by the Resources Assessment Commission (1991) between private and public managed forests in Tasmania (81 m^3 ha^{-1} and over 179 m^3 ha^{-1} respectively for wet eucalypt forests). Within a given height and density class, it is likely that management history will be different between privately and publicly managed forests — different grazing, fire and timber improvement regimes are to be expected. These differences may have a major impact on merchantability (merchantable volume) by introducing defects, damage or poor form without affecting the total volume. The interaction between tenure and Area / Class (Table 2) may be the result of different combinations of PI Type within Forest Classes for the two tenures.

Over 50% (R^2 = 0.52) of the total variation in ESV was explained by the simple height and density model. Introduction of the condition and location parameters increased the explanatory value to 58%: much greater than the explanatory value of the model developed in Hamilton and Brack (1999) for public native forests in Victoria. The Hamilton and Brack model used aerial photograph classification of tree cover, crown form, height and species composition, with elevation and a location index to predict merchantable volume (net D+ sawlogs m^3 ha^{-1}), but explained less than 20% of the variation (R^2 = 0.185). This low but significant R^2 may be due to their dependent variable being merchantable volume rather than total volume, and to the practice of using point samples (BAF = 3.0) to determine the on-ground volume. The point samples are likely to introduce more variability into the samples than the 0.2 ha plots used for the Tasmanian model.

Hamilton and Brack (1999) demonstrate that even the low explanatory power of their model is enough to improve the estimation of net volume when compared to a traditional (stratified random) sampling approach. The simple model developed from Tasmanian public forest data has much more explanatory power, and predicted the total volume of the private forest samples with a mean error that was not significantly different to 0 (P = 0.05) (Fig. 3). However, forest managers would be justifiably concerned about extrapolating estimates from one type of forest to another — especially if an ANOVA indicated that there were missing terms in the model (i.e. Table 3 indicates Tenure, IA and Condition are statistically significant (P < 0.05) and should be included in a model). This concern may be alleviated by either testing and 'proving' the extrapolation of the public forest model to a new population or using the model estimates as auxiliary variables in a two-phase or variable probability sampling scheme.

Brack and Marshall (1990, 1998) outline a sequential sampling approach that allows model predictions to be efficiently tested for applicability to a new population. The ESV for a relatively small number of random points within the private forest estate could be compared with the predictions from the model derived from public forest data. A series of disagreements (i.e. the predictions are significantly different or not usefully close to the ESV found at the sample point) would quickly indicate that the public forest model is inadequate and should not be used in privately managed forests. Brack and Marshall (1990) concluded that, depending on the error levels acceptable to the user, as few as three sample points could accept or reject a model as useful. If the test proves that the model is inadequate, the proposed approach allows the sample data to be reused to help determine an unbiased estimate of the new population without recourse to the invalidated model.

Two-phase sampling (ratio and regression sampling) is a powerful sampling approach that assumes a linear relationship between an auxiliary variable (e.g. ESV predicted by a model that uses aerial photography) and the dependent variable of interest (e.g. ESV measured on ground plots). Conditions such as whether the relationship goes through the origin and how the variance changes with increasing auxiliary value magnitude will determine what type of two-phase sampling is appropriate statistically. A relatively small number of points within the private forest estate could be chosen to parameterise an equation that relates the predicted ESV with the measured ESV, which can then be used to estimate the mean ESV measured on the ground from the mean of all the predicted ESV. Figure 4 indicates that the relationship between predicted and measured ESV of private land goes near the origin and the variance is approximately homogenous, which makes Regression Sampling most appropriate (Schreuder *et al.* 1993).

Alternatively, a probability proportional to prediction (3P) sampling frame requires only that the auxiliary variable be positively correlated to the dependent variable to provide an efficient estimate of the total volume. That is, 3P does not require the relationship between ESV predicted and measured on the ground to be linear or meet other normal regression assumptions, but simply that larger predicted ESV stands are generally associated with larger on-ground measurements of ESV. Again, Figure 4 confirms this positive relationship.

To simulate the efficiencies of these three potential sampling frames, samples were taken from the private forest data and used to predict the total volume from the 'estate' of 96 private sample plots. Samples were taken randomly (Control), systematically (Regression) and with variable probability (3P). The results (see Fig. 5) are based on 30 simulations of 10 samples for 3P and the Control. The Regression simulations ordered the plots by the auxiliary variable and systematically, beginning with each of the first 10 plots, selected every ninth plot to generate 10 sample regression lines.

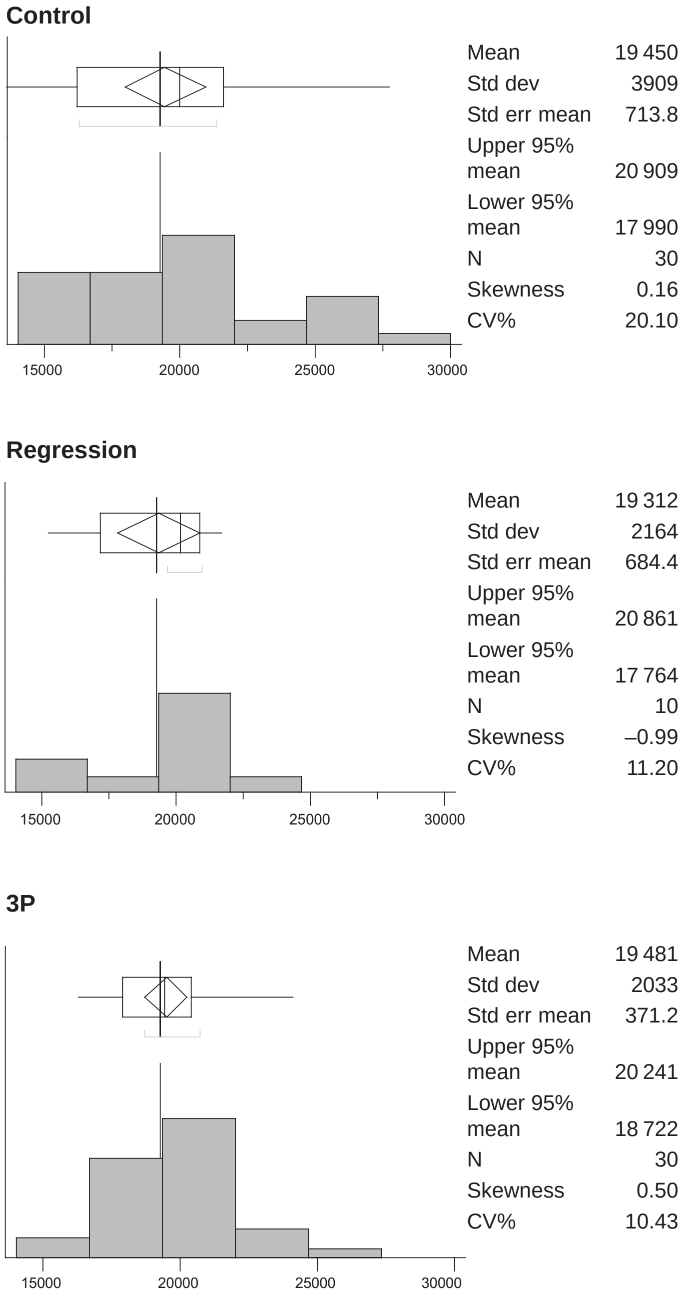

Figure 5. Distribution of estimated total ESV for the 96 private forest plots using three sampling frames. Observed total ESV (19 300 m^3) is marked by the vertical line.

The central box in the quantile plot contains 50% of the observations with 25% extending above and below the box. The median location bisects the box with a horizontal line. The mean and standard errors form a diamond within the box, while the horizontal 'whiskers' contain all data within 1.5 times the interquartile range.

The Control was unbiased, but simulated total ESV ranged from 12 600 to 27 700 m^3 (about ± 40% of the observed total), with a Coefficient of Variation (CV) of more than 20%. This relatively poor level of precision is expected due to the small sample size and the high variation of the ESV measured on the individual ground plots (CV ≈ 60%). The observed range of estimated values agrees with the expected sampling error (E%) (P = 0.05) for 10 randomly-chosen samples over a population with a CV of about 60%:

$$E\% = \frac{CV\% \times t_{0.05,\,9}}{\sqrt{n}} = \frac{60\% \times 2.26}{3.16} = 43\% \,. \qquad (2)$$

The regression samples were also unbiased and estimated total ESV ranged from 15 200 to 21 600 m^3 (about ±15% of the observed total) with a CV only slightly more than half the Control. This improved precision is not surprising because the possible lines that can be drawn through systematically selected sample plots can not vary too far from the 'true' line that represents the relationship of predicted against observed ESV for all the plots. If tenure were not a significant factor in predicting ESV from aerial photography then the 'true' line relating ground measurements with predictions would have a slope of 1.0 and an intercept of 0. However, the intercepts for the regression model were significantly greater than 0 and the slopes were significantly less than 1.0 ($P < 0.05$), which indicates that individual plots with a small predicted ESV were underestimated, while plots with a large predicted ESV were overestimated by the model developed from the public forest data (Fig. 4). A deviation from the 1:1 relationship is in agreement with the earlier ANOVA (Table 3) that indicates tenure does have a significant influence on ESV. Note however that despite deviation from the public forest model predictions, the regression sample estimates of the total ESV are precise and unbiased (Fig. 5). An alternative two-phase sample approach could re-parameterise equation 1 for private tenure, i.e. use the public forest data simply to define the best equation form, then sample within the private forest to estimate the coefficients. However, a sample size much greater than 10 systematically selected plots would be needed to reliably estimate the coefficients and attempts to do so with only 10 samples resulted in imprecise, biased and illogical estimates.

The 3P estimates of total ESV ranged from 16 200 to 24 900 m^3 (about ±20% of the observed total) with a CV marginally smaller than the regression. As with regression sampling, the 3P estimates were unbiased even though the predicted ESV used as the auxiliary variable was biased.

The distributions for all three sampling frame simulations were centred on the mean and not significantly skewed. However, the variation in the Control sampling frame was much greater than in the frames that used the model predictions as auxiliary data. Equation (2) indicates that halving of the CV for regression and 3P sampling when compared to that for the Control means that only one quarter as many samples would be required to achieve any given level of sampling precision. However both regression and 3P samples require the auxiliary variable to be available for all points in the forest, which is possible in the Tasmanian situation because of the aerial photography and interpretation carried out over the entire forested estate. Satellite imagery or existing maps potentially provide other sources of auxiliary data that could lead to similar improvements in the CV for modelled estimates. Figure 5 demonstrates that regression or 3P frames can utilise even biased auxiliary information like model predictions different populations to predict the ESV without significant bias.

Conclusion

Private forests have significantly different standing volume to public forests of equivalent eucalypt height and density in Tasmania. With few exceptions, however, the difference is small and there are situations where the differences in standing volume are positive as well as negative. There is no evidence in this study to support the Resource Assessment Commission (1991) average estimate of private forest containing less than 50% of the standing volume in public forests.

Statistical relationships derived from well-sampled public forests can be used to generate auxiliary information about private forests. Providing the auxiliary data cover all the private forest area and there is a positive correlation with a variable of real interest (like biomass or volume), this information can be used in appropriately designed multi-phase or variable probability sampling approaches to substantially reduce sample size, as compared to simple random sampling, to achieve any given level of precision. Biases that may be introduced by extrapolating from public to private forests can be corrected by regression sampling approaches. Variable probability sampling systems will also be able to use a biased model to produce auxiliary variables without resulting in a biased estimate of the population total.

Acknowledgements

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Wood density and shrinkage of five-year-old *Eucalyptus camaldulensis* x *E. globulus* hybrids: preliminary assessment

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Summary

Trees of *Eucalyptus camaldulensis* x *E. globulus* subsp. *globulus* hybrids growing at Pinjarra, Western Australia, were harvested for assessment of wood fibre and wood properties of sawn timber. Trees were 5-y-old at the time of felling. Wood density was in the medium range: mean green density was 980 kg m^{-3}, basic density was 507 kg m^{-3} and air-dry density was 653 kg m^{-3}. Green moisture content was 94%. Tangential shrinkage before reconditioning was greater than the shrinkage of mature *E. camaldulensis* or 13-y-old *E. globulus*. Radial shrinkage of the hybrid wood at 4.9% was similar to that of mature *E. camaldulensis* but less than that reported from 13-y-old *E. globulus*. The wood of *E. camaldulensis* x *E. globulus* has potential for value-added purposes; no problems were identified with sawmilling, drying and sanding.

Keywords: wood properties; quality; density; shrinkage; moisture content; hybrids; *Eucalyptus camaldulensis*; *Eucalyptus globulus*

Introduction

Hybrid eucalypts are being developed for industrial plantations with the aim of producing lines that show hybrid vigour, improved tolerance to biotic and abiotic stresses, or ability to grow under conditions marginal or unsuitable for high-value species such as *Eucalyptus globulus* (Griffin *et al*. 2000). Hybrid eucalypts generally have an overall morphology intermediate between that of the parent species with few traits being dominant, but some traits may be closer to those of one parent than the other (Pryor 1954; Pilipenka 1969; Tibbits 1988; Meddings *et al*. 2003). Wood properties have moderately high heritability (Zobel and van Buitjenen 1989) and have also been shown in hybrids to be generally intermediate between the parents. Wood density and radial shrinkage are traits for which most hybrids appear intermediate (Siarot 1991; Malan 1993, 2000; Verryn 2000) although it is sometimes difficult to make comparisons given data from trees of different ages. There are as yet no examples of useful heterosis in wood properties where the hybrid value is better than that of the best parent. Li *et al*. (1997) reported quantitative trait loci (QTLs) in two linkage groups that affected wood density in *E. grandis*.

Eucalyptus camaldulensis x *E. globulus* subsp. *globulus* hybrids were made with the objective of producing trees that have commercial yields of wood or pulp when grown on saline land (Meddings *et al*. 2001, 2003). The literature indicates that for *E. camaldulensis* and *E. globulus* up to 5.5 y old there is little difference between the wood properties of trees grown on saline and non-saline land, although there was a tendency towards greater density on saline sites (Clark *et al*. 1998; Catchpoole *et al*. 2000).

There are no reports of wood properties of this hybrid, although three clones of *E. globulus* subsp. *maidenii* x *E. camaldulensis* in Morocco were reported to have a high wood density (Table 1). Those trees were considered natural hybrids and their exact parentage was unknown. As a preliminary indication of the wood properties of the *E. camaldulensis* x *E. globulus* hybrids, we report here on the harvesting and assessment of wood density and shrinkage properties of 5-y-old hybrids growing on non-saline land.

Materials and methods

Plant material and field site

Hybrids were produced by fertilising flowers of *E. camaldulensis* growing in a plantation at Kwinana, Western Australia (32°15'S, 115°45'E), with pollen from *E. globulus*. The *E. camaldulensis* were clones from progenies of trees from Broken Hill, NSW (85), and Erudina, South Australia (87), respectively, and the pollen was collected from *E. globulus* subsp. *globulus* progenies from King Island, Tasmania (K). There was a high proportion of abnormal seedlings amongst the progeny and these were excluded from subsequent plantings (Meddings *et al*. 2003). Trees were planted in July 1995 on the coastal plain near Pinjarra (32°35'S, 115°50'E), 87 km S of Perth, which has an annual rainfall of about 948 mm. Many trees in a 4-y-old *E. globulus* plantation on the planting site had died during the summer of 1993/94, which was exceptionally dry. The few remaining *E. globulus* trees were removed and burned, land was ripped and mounded and herbicides applied to suppress weeds. The hybrid trees were planted 3 m apart in rows 4 m apart. Each tree was planted with two 50 g DAP fertiliser tablets (Bailey's) and no further fertiliser was applied.

Harvesting

The two hybrid families used in the present trial on average were 10.5 m high after 5 y. Two trees with above-average growth and form were selected from each of the families for felling and assessment of wood properties (Table 2). These were coded as 85xK and 87xK.

Table 1. Wood properties of some *Eucalyptus* species and their hybrids

Species and hybrids	Age (y)	Basic density (kg m^{-3})	Air-dry density (kg m^{-3})	Radial shrinkage (%)	Reference
E. camaldulensis	12		600–870	6.8	Van Vuuren *et al*. (1978); Dyer (1962); both cited in Malan (1993)
	14	512			Ona *et al*. (1996)
	Mature	710	913	8.9	Kingston and Risdon (1961)
	Mature?		960		Banks (1954)
	Mature		Up to 960		Poynton (1979) cited in Malan (1993)
E. globulus	3.5	520			Catchpoole *et al*. (2000)
	13	538	737	8.5	Moore *et al*. (1996)
	14	596			Ona *et al.* (1996)
	17–23	561	790	14.4	Kingston and Risdon (1961)
	Mature	681	900	7.7	Kingston and Risdon (1961)
	Mature?		600		Banks (1954)
E. maidenii	Mature?		620		Banks (1954)
E. maidenii x *E. camaldulensis*	≥3		911		Fechtal and El Abid (1995)

Table 2. Details of trees harvested for wood density and shrinkage assessments

Hybrid line	Log number	Height (m)	Merchantable* height (m)	DBH (cm)	Stem form
Hybrid 85xK	2 W	10.9	6.0	24.0	Good — 1st branch at 2.6 m
Hybrid 85xK	14 O	11.1	7.0	25.3	Good — single trunk
Hybrid 87xK	6 K	12.5	6.6	20.8	Moderate — 1st fork at 2.5 m
Hybrid 87xK	13 A	13.7	9.0	28.7	Good — 1st branch at 2 m

* merchantable height = height to trunk diameter under bark of 8 cm

Trees were felled and samples collected in October 2000. The diameter at breast height (DBH), total height and 'merchantable' height (i.e. to a minimum of 8 cm diameter under bark) were measured. Sample logs from the four hybrid trees (varying in length from 60 to 149 cm) were transferred to the Forest Products Commission Timber Technology mill at Harvey, Western Australia. Three of the trees produced both butt and crown logs, while the remaining tree produced only a butt log.

Milling and assessment

The logs were sawn on a 'Woodmizer' portable bandsaw. Matched specimens would normally be cut from each side of the heart, but this was not possible in all cases due to some checking and internal defects. Where log quality permitted, a plank 28 mm thick was milled from bark to bark through the heart. The plank was then sawn into sections 28 mm wide to prepare specimens for assessment of wood density. The density specimens with growth rings parallel to one edge were also used to estimate tangential and radial shrinkage.

The sections were docked to lengths of 200 mm and sanded on four sides using a belt sander, to give a smooth, consistent surface, and specimen dimensions of about 25 mm x 25 mm. The properties measured were green density (green mass / green volume), basic density (oven dry mass / green volume), and air-dry density (air-dry mass / air dry volume). Lines were drawn across the tangential and radial faces in the centre of the specimens to ensure that the dimensions were measured in the same positions each time. The specimens were then immersed in water for 24 h to reduce moisture variation prior to taking measurements.

In assessing wood density and shrinkage, measurements of mass, length, width and thickness were taken every two days and recorded while the specimens were air-drying on a wire mesh sheet. Mass was measured on a balance accurate to 0.01 g. The dimensional measurements were taken with a Vernier calipers accurate to 0.03 mm. When equilibrium moisture content of about 12% was reached, the specimens were oven-dried at 103°C to constant weight.

Results and discussion

Despite some checking upon arrival at Timber Technology and the presence of internal defects, sawing the logs on the Woodmizer presented no problems. Growth stresses were not evident; this could be attributed to stress release caused by some checking prior to milling. The slabs from which the specimens were later prepared were quite knotty and cracked, and, as explained previously, it was not possible to prepare a complete set of defect-free specimens.

The density specimens dried at a uniform rate, although collapse was evident in some. In a commercial operation using this timber, a steam treatment at about 18% MC would be necessary to recover the wood. Values for moisture content, green density, basic density

Table 3. Moisture content, green density, basic density and air-dry density of *E. camaldulensis* x *E. globulus* wood

Tree	Log no.	No. of samples	Mean moisture content (%)	Mean green density (kg m^{-3})	Mean basic density (kg m^{-3})	Mean air-dry density (kg m^{-3})
Hybrid	6 K Crown	2	97	975	555	648
87xK	6 K Butt	4	101	995	497	685
	13 A Crown	4	86	986	532	666
	13 A Butt	11	91 (9)	979 (33)	513 (26)	649 (49)
Hybrid	14 O Butt	5	106 (8)	996 (34)	483 (18)	622 (15)
85xK	2 W Crown	2	85	944	509	649
	2 W Butt	2	87	952	510	677
Weighted mean			94 (10)	980 (34)	507 (28)	653 (45)

The values in brackets denote the standard deviation (given only for five or more samples).

Table 4. Tangential, radial and longitudinal shrinkage of *E. camaldulensis* x *E. globulus* wood

Tree	Log no.	No. of samples	Mean tangential shrinkage (%)	Mean radial shrinkage (%)	Mean longitudinal shrinkage (%)
Hybrid 87xK	6 K Crown	1	12.7	6.5	0.6
	6 K Butt	2	8.5	6.7	0.7
	13 A Crown	2	9.3	3.0	0.5 (0.3)
	13 A Butt	6	7.4 (4.4)	5.2 (2.9)	0.4 (0.3)
Hybrid 85xK	14 O Butt	5	12.3 (2.2)	4.2 (1.8)	0.3 (0.2)
	2 W Crown	2	NS	NS	0.2
	2 W Butt	2	NS	NS	0.3
Weighted mean			9.6 (3.8)	4.9 (2.3)	0.4 (0.3)

*Values in brackets denote the standard deviation where there are five or more samples.
NS = 'not suitable'. Specimens did not have growth rings orientated parallel to the face because initial milling could not be done through the heart.

Table 5. Comparisons of density and shrinkage of wood of *E. camaldulensis* x *E. globulus* hybrids and parent species

Species	Green density (kg m^{-3})	Basic density (kg m^{-3})	Air-dry density (kg m^{-3})	Tangential shrinkage* (%)	Radial shrinkage* (%)
E. camaldulensis x *E. globulus* subsp. *globulus* (5 y old)	980	507	653	9.6	4.9
E. globulus subsp. *maidenii* x *E. camaldulensis* (≥3 y old)[1]				911	
E. camaldulensis (mature)[2]		710	913	8.9	4.4
E. globulus (13 y old)[3]	1040	538	737	8.5**	6.9**

[1]Fechtal and El Abid (1995); [2]Kingston and Risdon (1961); [3]Moore *et al*. (1996)
*Before reconditioning
**Based on backsawn boards and not small specimens

and air-dry density are given in Table 3, and for tangential, radial and longitudinal shrinkage in Table 4.

The wood density measurements from this assessment are compared with published data for a mature *E. camaldulensis*, plantation-grown *E. globulus* and a natural hybrid of the reciprocal cross (Table 5). The 5-y-old hybrid timber had lower basic and air-dry density than samples from either mature *E. camaldulensis* or plantation-grown *E. globulus*. The young age is most likely the reason for this difference; density is expected to increase as the trees age, particularly as the female parent (*E. camaldulensis*) is a high-density species. It is interesting to note that in the natural hybrid in which *E. globulus* subsp. *maidenii* was used as a female parent with *E. camaldulensis* pollen, the wood of the hybrid trees was of high density, similar to that of *E. camaldulensis*.

Shrinkage measurements (Table 5) indicate that the tangential shrinkage of the hybrid was greater than of mature *E. camaldulensis* or 13-y-old *E. globulus*, while radial shrinkage of the hybrid was slightly more than that of the *E. camaldulensis* parent, but 2% less than that of the *E. globulus* parent. It is expected that under normal growing conditions all wood properties of the hybrid will improve with age.

Overall assessment of the timber properties and processing behaviour of the hybrids indicated that there were no problems with saw milling, drying or sanding. The wood of *E. camaldulensis* x *E. globulus* has potential for value-added purposes. Further tests of wood properties of older trees will be necessary, using plantations where clonal replicates can be tested and where trees are growing in both saline and non-saline conditions.

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Processing 17-year-old Tasmanian blue gum sawlogs grown at wide spacing

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Summary

Large areas of Tasmanian blue gum (*Eucalyptus globulus* Labill. subsp. *globulus*) have been planted in the south-west of Western Australia. This resource is principally planted on farmland for pulp and paper manufacture, but a small proportion has been managed for sawlogs. In this study a sample of logs from a 17-y-old Tasmanian blue gum stand grown on an ex-bush site, and thinned and pruned at an early age, was processed into sawn timber. Mean sawlog small-end-diameter-under-bark was 39.3–45.6 cm. The recovery of appearance-grade boards, based on log volume, was 30%, and another 2.4% could be used as filler laminates in panels or panel products. Mean air-dry density was estimated to be 680 kg m^{-3}, similar to the density found in other studies, but lower than the density of mature trees. Recovery and wood quality are compared with those obtained in other studies conducted in Western Australia and the eastern States. The development of a new eucalypt sawlog industry on cleared private land is discussed.

Keywords: forest plantations; silviculture; fertilizers; sawmilling; drying; recovery; outturn; wood utilization; wood properties; wood density; quality; wood defects; *Eucalyptus globulus*

Introduction

The timber of Tasmanian blue gum (*Eucalyptus globulus* Labill. subsp. *globulus*) has been used for general construction, pulp and paper, rayon, flooring and furniture. If preservative-treated it can be used for posts, poles, sleepers and fence posts. The species has generally been used as a green structural timber because of the timber's susceptibility to surface checking, collapse and warping, particularly when backsawn (Boland *et al*. 1984).

Currently there are about 200 000 ha of Tasmanian blue gum plantations in the south-west of Western Australia on ex-pasture land, established mainly as a source of woodchips for pulp and paper manufacture. Almost 60% of the total resource has been planted since 1995 (Department of Fisheries, Agriculture and Forestry — Australia 2001). Some of this resource could be allocated to other end uses, for example sawn timber, medium-density fibreboard or veneer.

There are an estimated 1080 ha of eucalypts planted and managed for sawlogs on privately-owned land in Western Australia, of which 640 ha or 60% is Tasmanian blue gum. A further estimated area of 100 ha or 9% of the privately-grown eucalypts that are managed for sawlogs consists of Sydney blue gum (*Eucalyptus saligna* Sm.) (Hingston 2000). The areas available for sawlog production could be increased by managing already established stands for sawlogs, using appropriate pruning and thinning schedules, thereby increasing the area of trees potentially yielding a sawlog crop (Hingston 2002).

Farm forestry research in Western Australia started in the mid-1970s, and investigated the growing of pine sawlogs at wide spacing. Similar trials with eucalypts began in the early 1980s. Many of the trees in these trials have reached a size suitable for milling and assessment of their utilisation potential. These studies contribute to the development of commercial tree crops that can be used by farmers to provide a range of benefits, such as land protection, salinity control, shade and shelter, and income from timber.

In 1994 a sawmilling study was conducted at the CALM Centre for Timber Technology (CTT) and a veneering trial at Wesfi's Victoria Park plant, using 13-y-old Tasmanian blue gum (Moore *et al*. 1996).

This paper reports a further sawmilling study begun in October 1998, using trees from an adjoining stand. On-farm milling equipment was used to break down the logs in the field, followed by re-sawing resultant flitches with a conventional bandsaw. The purpose of the study was to assess graded recovery of 17-y-old Tasmanian blue gum timber milled from pruned trees grown at wide spacing on ex-pasture land.

As density is the best single predictor of strength and hardness, and these properties have not been assessed for blue gum grown in Western Australian plantations, we also took the opportunity to evaluate density.

Materials and methods

Stand management history and study aims

The five Tasmanian blue gum trees used in this study came from a study site in Vasse Plantation, about 20 km south-west of Busselton. The trial had been established on an ex-bush site in 1981. At the same time, pasture was established to build up soil fertility and to graze cattle. Six different eucalypt species were planted in 7-row belts at 3 m x 2 m spacing (1666 trees ha^{-1} within the tree belt). The slower-growing, forked and crooked trees were

Table 1. History of the Tasmanian blue gums growing at Vasse, Western Australia

Year	Operation	Fertiliser application
0	Trees planted at 3 m x 2 m spacing in belts of 7 rows (1666 trees ha^{-1})*	Aerial application of 416 kg ha^{-1} Super Copper Zinc Molybdenum No. 1 applied with pasture establishment; 100 g Agras No. 1 (18% N, 7.6% P, 17% S, 0.06% Zn) applied to each tree at planting
1		480 kg ha^{-1} of Super Copper Zinc Molybdenum applied to increase pasture and tree growth
3	Culled to 675 trees ha^{-1}*. Crop trees pruned to 50% of tree height (about 2.5 m).	200 kg ha^{-1} of superphosphate applied annually in years 3 to 10
5	Culled to 220 trees ha^{-1}*. Crop trees pruned to 50% of tree height (about 6.0 m).	See above for year 3
8	Crop trees pruned to 50% of tree height (about 10.0 m)	See above for year 3
11		240 kg ha^{-1} of superphosphate (9% P) applied
13	55 trees harvested for milling and veneer study (Moore et al. 1996)	150 kg ha^{-1} of superphosphate (9% P) applied
15 and 16		200 kg ha^{-1} of super potash (3:1) applied to the pasture strips only
17	5 trees harvested for this milling study	

The annual applications of fertiliser were to increase pasture growth, but would have also benefited the trees.
* tree density within the tree belt.

culled at 3, 5 and 8 y of age to allow the remaining widely-spaced crop trees to grow with less competition. The final stocking was 220 trees ha^{-1}. The trees were pruned at age 3 y to 2.5 m, then at age 5 y and 8 y to about 6 m and 10 m respectively. Cattle were introduced at year 3 to graze the pasture. The history of silvicultural treatment and fertiliser application is given in Table 1.

The stand parameters for the five trees prior to felling the trees in October 1998 were:

- Stand density: 220 stems ha^{-1} (within the tree belt)
- Stand mean height: 24.4 m
- Stand mean dbhob: 45.9 cm
- Stand basal area (over bark): 37.6 m^2 ha^{-1} (within the tree belt)
- Total tree volume: 306 m^3 ha^{-1} (within the tree belt)
- Mean annual increment (volume over bark): 17.8 m^3 ha^{-1} (within the tree belt)

For the five sample trees:

- Total merchantable volume (to 10 cm dbhob): 10.5 m^3
- Sawlog volume to 7.5 m: 6.35 m^3
- Pulpwood volume: 4.20 m^3.

Logging

Five dominant trees were randomly selected for this study. After felling, each tree was docked into logs 2.5 m long; the logs were marked with a branding hammer to identify tree number and butt, mid and crown logs, then end-sealed with 'Mobilcer' log end sealer. The logs were taken only from the pruned section of the trees. Although the crown section was not used for sawlogs, it was assumed to be pulpwood and the volume was calculated.

Log measurement and yield

After felling, tree height and merchantable height (to 7.5 m) were measured, together with log lengths, and small and large-end diameters under bark. Any major log defects, for example large knots, branches or sweep, were recorded. Log volumes were determined using Smalian's formula (Carron 1968).

Milling — log breakdown

The logs were milled on site in October 1998, using a 'Woodmizer' portable bandsaw with a thin (2.5–3 mm) kerf. Logs were broken down into flitches using a back-sawing pattern, which involved cutting on one side of the log, then on the opposite side (at 180° to the first cut), then backsawing the remainder of the log. Dimensioned flitches were cut to about a quarter of the log diameter or until log degrade was encountered, then logs were turned 180° and further flitches were cut on the opposite side of the log. The effect of growth stresses (bow and spring) was monitored during log breakdown. This cutting pattern is similar to one used by CSIRO for fast-grown eucalypt sawlogs >45 cm mid-diameter (Waugh 1998), although Waugh recommended turning the logs 90°, not 180°.

This pattern, combined with cutting the logs to short lengths (2.5 m), helped to minimise the effects of any growth stresses in the logs. The resultant flitches had minimal bow and spring following milling. Each flitch was cut parallel to the bark, that is 'taper sawn'. This allowed the shorter-length products and residue to come from the lower-quality knotty core region of the log, rather than from the more valuable clear wood on the outer parts of the log.

The logs were cut into flitches 25 mm, 38 mm and 50 mm thick which were identified with a log number, block stacked by log, strapped and taken to the Centre for Timber Technology (CTT) in Harvey for re-sawing. During transport the flitches were covered with a tarpaulin to reduce drying.

Milling — re-sawing and docking

At CTT, flitches were stored in a shed with open ends for about two weeks before re-sawing into backsawn boards with a 'Jonsereds' band re-saw. The following widths were cut from each

Table 2. Drying schedule for Tasmanian blue gum boards 25 mm or 38 mm thick, and 50 mm thick

Drying stage	MC at change (%)		DBT (°C)		WBD (°C)		RH (%)		EMC (%)		Air velocity (m sec^{-1})	
	25/38 mm	50 mm	25/38 mm	50 mm	25/38 mm	50 mm	25/38 mm	50 mm	25/38 mm	50 mm	25/38 mm	50 mm
1	Green		30	20	1.5	1.0	89	91	19.6	20.9	0.5	0.5
2	60	60	30	25	2.0	1.5	86	88	18.0	19.3	0.5	0.5
3	45	45	40	30	3.0	2.0	82	86	16.0	18.0	0.5	0.5
4	35	35	45	40	4.5	3.0	78	82	14.2	16.0	0.5	0.5
5	30	30	50	45	5.0	4.5	75	78	12.8	14.2	0.5	0.5
6	25	25	50	50	8.0	5.0	62	75	9.9	12.8	0.5	0.5
7	20	20	55	50	10.0	8.0	57	62	8.6	9.9	0.5	0.5
8	15	15	60	60	15.0	15.0	43	43	6.4	6.4	0.5	0.5
9	12	12	60	60	5.0	5.0	77	77	12.7	12.7	0.5	0.5

MC = moisture content; DBT = dry bulb temperature; WBD = wet bulb depression, i.e. the difference between the dry bulb and wet bulb readings; RH = relative humidity; EMC = equilibrium moisture content.

of the different flitch thicknesses: 50 mm, 75 mm, 100 mm, 125 mm or 140 mm. Priority was given to boards 100 mm, 125 mm or 140 mm wide, as these sizes are commonly used by Western Australian furniture manufacturers. At the docking saw, boards were trimmed to 1.2 m, 1.5 m, 1.8 m, 2.1 m or 2.4 m. The aim of docking was to produce the longest possible lengths free of faults, for example brittle heart, decay, excessive knots, kino, wane and end splits. Boards from each log were identified and individually tallied, which allowed recovery from individual logs to be calculated.

Boards were then treated with log end-sealer to reduce end splitting, and block stacked ready for dipping.

Dipping for *Lyctus* borer attack

The sapwood of Tasmanian blue gum is susceptible to *Lyctus* borer attack (Bootle 1983). To prevent attack, the timber was dipped in a 4.5% borax solution immediately after block stacking. After draining the excess liquid, the timber was covered completely with a plastic tarpaulin to prevent drying and to facilitate diffusion of the preservative throughout the sapwood. The timber remained block stacked for several months in a controlled high-humidity environment, before strip stacking and drying by solar kiln. The recommended diffusion time is 28 days, but the timber remained blocked stacked for several months until kiln space was available.

Strip stacking and kiln drying

The timber was strip stacked into stacks 2.4 m long for drying, using standard 19 mm pine strippers. Standard 800 kg weights (400 kg m^{-2}) were placed on top of each stack to minimise cupping or twisting during drying. Sample boards located throughout the stacks were used to monitor moisture content.

Timber of all sizes was dried using the commercial drying schedules for marri (*Corymbia calophylla* (Lindl.) K.D.Hill and L.A.S.Johnson). These schedules (Glossop and Bishop 1996) recommend increasingly severe drying conditions as moisture content of the timber decreases. Table 2 gives the drying schedules for 25 mm or 38 mm boards, and 50 mm boards.

Collapse recovery steaming

After kiln drying, cell collapse was observed in some 50 mm boards. To recover cell collapse, a steam re-conditioning treatment with the wet and dry bulb temperatures set at 97°C was applied for 8 h. To restrain the timbers from twisting, concrete weights of 3.7 t were placed on top of the bundles. A visual assessment of the timber after steaming indicated that the boards had recovered from the cell collapse.

Table 3. Tree dimensions and sawlog and pulpwood yield for the five 17-y-old Tasmanian blue gum trees assessed

Tree no.	Dbhob (cm)	Total height (m)	Pruned height (m)	Sawlog, pulpwood and merchantable volume (m^3)					
				Butt log	Mid log	Crown log	Total sawlog	Pulpwood	Total merchantable
1	60.6	26.5	10.5	0.65	0.51	0.43	1.59	0.92	2.51
2	55.6	25.5	10.0	0.57	0.41	0.37	1.35	0.88	2.23
3	56.4	23.6	9.1	0.46	0.30	0.24	1.00	1.04	2.04
4	52.2	24.0	10.2	0.61	0.34	0.29	1.25	0.62	1.87
5	52.0	22.3	9.5	0.48	0.36	0.32	1.16	0.74	1.90
Mean	55.4	24.4	9.9	0.55 (43.6)[a]	0.38 (30.3)[a]	0.33 (26.1)[a]	1.27 (60.2)[b]	0.84 (39.8)[b]	2.11

[a] mean volume in each sawlog category as a percentage of mean total sawlog volume, and
[b] mean volume of (total) sawlog and pulpwood as a percentage of mean (total) merchantable volume for all trees

Dressing and grading

After kiln drying and reconditioning, boards were pre-dressed and graded into appearance- or core-grade timber. Appearance grades were based on the WA Industry Standard (FIFWA 1992) and core grade or laminated panel core grade (CALM 1989). The core-grade boards are structurally sound and suitable for filler laminates in panels or panel products to be used without further manufacture. Boards were graded and docked to lengths ranging from 0.9 m to 2.4 m (in increments of 0.3 m), with some 2.5 m lengths, aiming at producing longer lengths in a lower grade rather than shorter lengths of a higher grade. Reasons for downgrade, rejection or docking were recorded.

Lengths as short as 0.9 m were permitted because a survey of ten furniture manufacturers in Western Australia found that while the maximum length of solid jarrah (*E. marginata* Donn ex Sm.) timber required was 2.2 m, 84% of lengths were less than 1.0 m (Challis 1989).

Harris Wood Machining of Busselton dressed a 1 m^3 sample of timber into floor boards 12 mm and 19 mm thick. Wood quality and machining properties were noted. Another sample was given to 12 woodworking students at the South-West Regional College of TAFE to assess the quality of the timber.

Air-dry density

After kiln drying to 12% moisture content, 23 Tasmanian blue gum boards were randomly selected for assessment of air-dry density. The air-dry volume was calculated after measuring the width and thickness of each board with Vernier calipers, and the length with a lineal tape measure. Mass was determined using digital scales to an accuracy of 0.01 g.

Results and discussion

Log yields and stand management

Table 3 gives the tree dimensions, and sawlog and pulpwood yields, for the five trees assessed in this study. The mean sawlog and pulpwood yields were 1.27 m^3 per tree and 0.84 m^3 per tree respectively, with sawlogs making 60.2% and pulpwood 39.8% of the merchantable tree volume to a 7.5 cm diameter limit. Four trees produced a higher proportion of sawlogs than pulpwood; tree 3 had 49% of its volume as sawlogs and 51% as pulpwood.

Moore *et al*. (1996) estimated a mean sawlog and pulpwood yield of 0.96 m^3 per tree and 0.36 m^3 per tree, respectively, at 13 y, giving a total merchantable volume of 1.32 m^3 per tree. The sawlog component was 73% and pulpwood 27% of merchantable volume. As would be expected, the sawlog and pulpwood yields were greater at age 17 y than those reported for 13 y. Any further comparison is unwarranted as the trees in the earlier study were grown in a different stand and at a mean stocking of 135 stems ha^{-1}, whereas stocking in this study was 220 stems ha^{-1}.

Knots and other branch defects

The reasons for downgrading the finished boards, and percentage (based on board volume) downgraded for each log class, are shown in Figure 1 for 25 mm and 38 mm boards, and in Figure 2 for 50 mm boards. In the mid and crown logs, knots and the combination of knot and checks were the major reason for downgrading boards. For example, in the 25 mm and 38 mm boards the fraction downgraded from Prime Grade to Standard Grade was 3% for mid logs and 5.1% for crown logs. The fraction downgraded from appearance grade to Core Grade or below was 8.4% for mid logs and 14.9% for crown logs. For the 50 mm boards, knots did not result in any mid-log boards being downgraded from Prime Grade

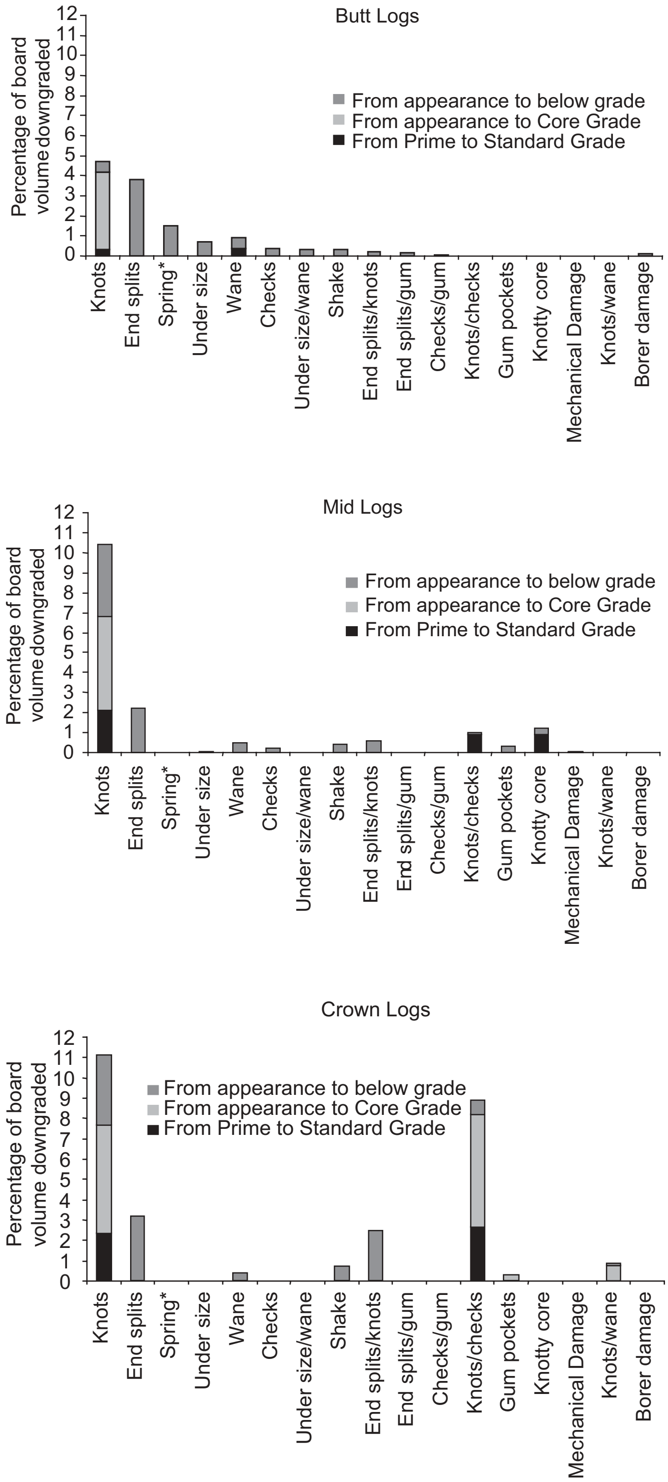

Figure 1. Reasons for downgrading 25 mm and 38 mm Tasmanian blue gum boards and percentages (based on board volume) downgraded for each log class

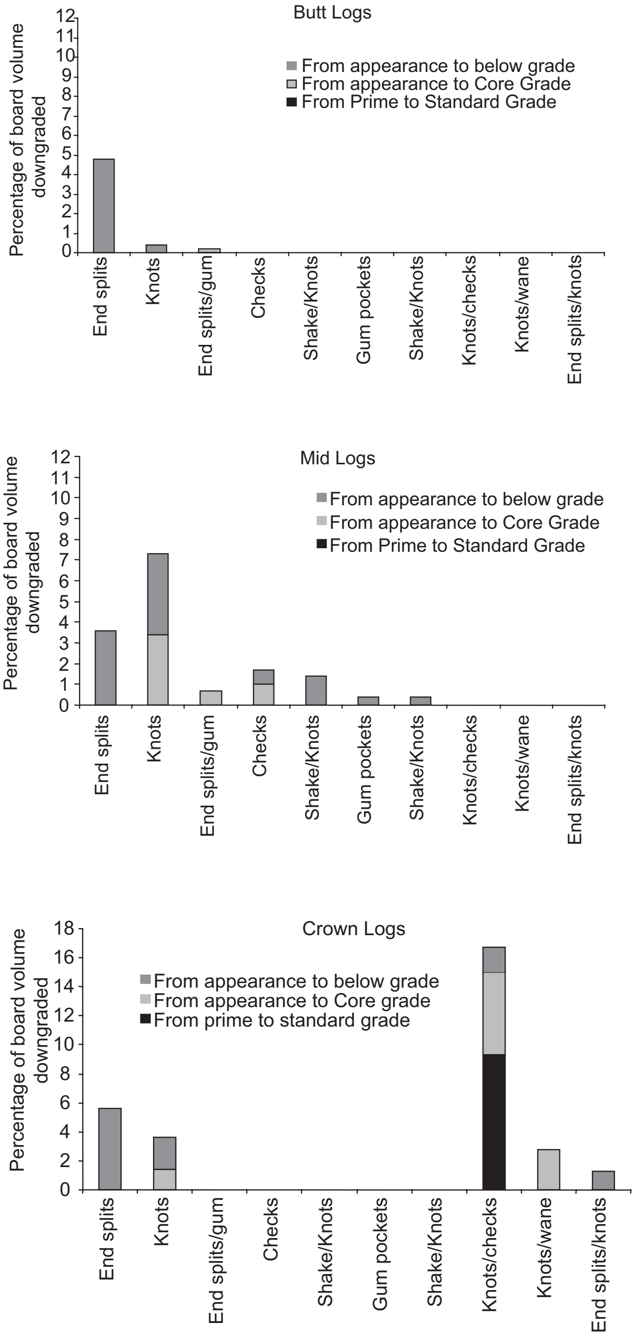

Figure 2. Reasons for downgrading 50 mm Tasmanian blue gum boards and percentages (based on board volume) downgraded for each log class

to Standard Grade, but knots caused 9.3% of the board volume cut from crown logs to be downgraded. For all timber thicknesses, the overall fraction downgraded from appearance grade to Core Grade or below was 7.7% for mid-logs and 11.0% for crown logs. This indicates that some boards from the mid and crown logs were cut from the knotty core section of the tree.

Wide-spaced trees produce large branches, which result in large knots that downgrade sawn timber products. Pruning at an early age, as occurred in this trial, is essential where the aim is to produce appearance-grade products, as it reduces the size of the knotty core and knot size in sawn timber, and restricts the development of loose knots which can result from encased dead branches. If pruning is timed to coincide with the period of most rapid diameter growth, branch stubs will be rapidly occluded, minimising the likelihood of infection by decay-causing pathogens.

Mechanical pruning[1] was in three lifts: at age 3 y to 2.5 m, then at ages 5 y and 8 y to about 6 m and 10 m respectively. The higher proportion of knots in the mid and crown logs would have resulted from pruning at either age 5 or 8 y. Pruning to 6 m or 10 m at an earlier age may result in fewer knots in the mid and crown logs, but the loss of overall leaf area and its effect on tree growth must also be considered. Pinkard and Beadle (1998) found that removing 50% of the lower green crown in *E. nitens* ((Deane and Maiden) Maiden) had no impact on height or diameter increment in the two years following treatment, but removal of 70% of the length of the lower crown resulted in significant decreases in both height and diameter increment.

In comparison, a milling study using 15-y-old unpruned *E. globulus* also found that knots were the major factor causing boards to be downgraded from select-grade products (Washusen *et al*. 2000b). In those unmanaged trees, decay and kino appeared to be associated with branches and were a serious problem, but those defects can be reduced with mechanical pruning. In our study knots were a common cause of downgrade in the mid and crown logs, but not to the same extent as reported in the unpruned trees. We found no decay associated with knots, and kino caused only a very small proportion of the boards to be downgraded from appearance grade to below grade (Figs 1 and 2), indicating rapid branch occlusion.

This study has shown that mechanical pruning will improve wood quality. Good silvicultural practice — early thinning and mechanical pruning as in this example — produces a healthy stand, reduces branch and knot size and results in rapid branch occlusion, which reduces the chance of fungal and insect attack. Efficient stand management improves overall wood quality.

Milling, drying and processing

In this trial minimal splitting of log ends was observed when the logs were cut to length. Applying a water-resistant log end sealer immediately after felling and docking reduced the amount of drying from the log ends and helped reduce end splitting. Bow and spring of flitches and board was not a problem during milling and drying. Cutting logs into short lengths and using a backsawing cutting pattern assisted in reducing the amount of bow and spring. Storing logs under water spray for up to six months before milling can also assist in relieving growth stresses in fast-grown eucalypts (Brennan *et al*. 1990).

The 17-y-old Tasmanian blue gum boards were dried under mild conditions in a solar kiln, using commercial drying schedules developed for marri. These schedules recommend increasingly severe drying conditions as the moisture content of the timber decreases. The drying rates for the 25 mm and 38 mm boards could have been increased, as minimal drying degrade occurred on these boards. Some cell collapse occurred in the 50 mm boards

[1] The removal of unwanted shoots or branches from a tree to improve its form and wood quality using mechanical equipment, for example small hand shears and saws, long-handled shears or light-weight chainsaws.

Table 5. Mean diameter and mean recovery of green sawn, appearance grade and laminated panel core grade wood from 17-y-old Tasmanian blue gum (based on volume of log and dry dressed boards), by log position. (LPCG = laminated panel core grade)

Log position	Sedub of logs (cm)	Fraction of log volume recovered as green sawn wood (%)	Fraction of volume of log recovered in appearance grades (%)			Fraction of volume of dry dressed boards recovered in appearance grades (%)			Fraction of volume of log recovered in LPCG (%)	Fraction of volume of dry dressed boards recovered in LPCG (%)
			Prime grade	Standard grade	Total	Prime grade	Standard grade	Total		
Butt	45.6	46.8	30.7	0.3	31.0	86.3	0.7	87.0	1.6	4.5
Mid	42.4	50.6	31.2	1.1	32.3	82.5	3.0	85.5	2	5.1
Crown	39.3	49.9	25.4	1.3	26.7	74.4	4.6	79.0	3.6	10.8
Overall[1]	42.4	48.8	29.2	0.9	30.1	82.6	2.4	85.0	2.2	6.3

[1]Overall mean recoveries are based on total volume

when dried under these mild conditions, but this was recovered in a steam re-conditioning treatment. Further research is required to develop efficient drying schedules for the three board thicknesses studied.

The local wood machining company which dressed the 1 m^3 sample of timber into floor boards compared the sample to standard timbers they process. No collapse or surface checking was observed when the timber was dressed, while end splits were minimal and did not significantly affect recovery. Any knots were generally tight and did not cause problems when dressing the timber. Planing and sanding the boards did not result in any lifting grain. The timber colour was a consistent light yellowish-brown, similar to Victorian ash and Tasmanian oak (P. Harris, Harris Wood Machining, Busselton, *pers. comm.*).

Woodworking students at the South-West Regional College of TAFE provided a positive assessment of the quality of the timber, most finding it very easy to machine and work, and sanding and polishing to a smooth finish. A sample of flooring has been placed in service, and stability and performance will be monitored.

Recovery of appearance-grade and laminated-panel-core-grade products

The recovery of appearance-grade and laminated-panel-core-grade products, based on log volume and dry dressed board volume, is given in Table 5. Thirty percent of the log was recovered into appearance-grade products, with a further 2.2% suitable for filler laminates in panels or panel products. Of the total volume of the dried and dressed boards, 85% of the volume was recovered in appearance-grade timber, and a further 6.3% could be used for filler laminates (Table 5). Moore *et al.* (1996) also reported high recoveries as appearance-grade products for 13-y-old Tasmanian blue gum.

The major reasons for downgrading boards from Prime Grade to Standard Grade, and from appearance grade to laminated panel core grade, were knots and the combination of knots and surface checks (Fig. 3). The major reasons for downgrading to a category below these grades were end splits and knots. End splits were generally less than 100 mm long and did not significantly affect recovery. In this trial, boards were end-sealed, which restricted end splitting during drying.

The figures for recovery of appearance-grade products from butt and mid logs were similar, and higher than those for crown logs. Crown logs produced a greater volume of laminated panel core grade than did butt and mid logs, as some of the boards from crown logs did not meet the specifications of an appearance product but were structurally sound and suitable for laminated panel cores.

The results in this study are considerably better than those reported by Washusen *et al*. (2000a,b), who found low recoveries of select grade or better from logs from an unpruned 15-y-old Tasmanian blue gum stand from a medium-rainfall area in the southern Murray-Darling Basin. The low recoveries in the latter studies were largely due to knots, decay, kino and drying degrade, which is partly caused by the presence of tension wood cells. The present study had substantially less of these inherent characteristics, resulting in a recovery of 30% of log volume into appearance-grade products and a better overall wood quality.

Air-dry density

Air-dry density was assessed when the timber dried below 12% MC. The mean air-dry density was 680 kg m^{-3}, with standard deviation

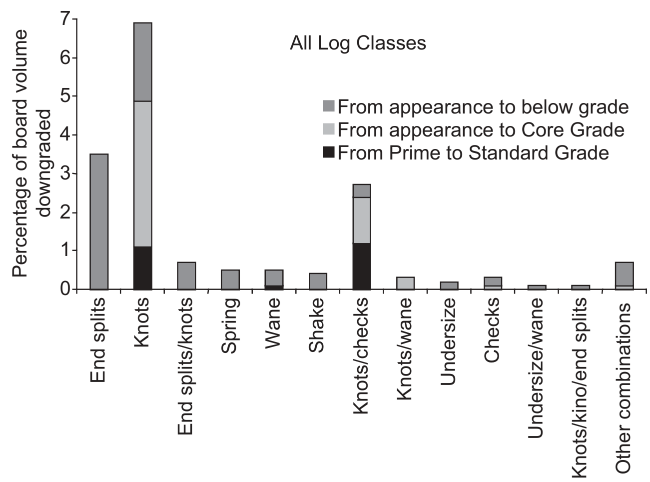

Figure 3. Reasons for downgrading 25 mm, 38 mm and 50 mm Tasmanian blue gum boards and percentages (based on board volume) downgraded for all log classes

±65 kg m^{-3} and range 525–780 kg m^{-3}. Kingston and Risdon (1961) quoted a mean air-dry density of 790 kg m^{-3} (before re-conditioning) and 727 kg m^{-3} (after re-conditioning) for 17–23-y-old Tasmanian blue gum. In comparison, Bootle (1983) quoted a mean air-dry density of mature Tasmanian blue gum of 900 kg m^{-3}. As expected the 17-y-old material had a lower density than wood from mature trees, because wood density increases with tree age; it can also be influenced by the combination of environmental and genetic factors and in some cases growth rate.

Brennan *et al*. (1992) assessed density of Tasmanian blue gum from the Manjimup area. The mean basic density of 8-y-old ex-pasture grown trees was 525 kg m^{-3}, and of 10-y-old ex-bush grown trees, 470 kg m^{-3}. Bishop and Siemon (1995) assessed the air-dry density of 13-y-old Tasmanian blue gum from the same trial as the 17-y-old trees assessed in this trial, and reported a mean value of 640 kg m^{-3}. Northway and Blakemore (1996) estimated the basic density of 24-y-old Tasmanian blue gum growing in south-eastern Gippsland in Victoria as 590 kg m^{-3}.

Future developments

There is now a project in Western Australia to grow eucalypts for sawlogs. In 2001 and 2002 about 650 ha were planted on cleared farmlands in water recovery catchments[2] to produce high-grade timber and to improve water quality (Moore and Buckton 2002). The long-term aim is to develop a new industry — using cleared private land in the 450–650 mm annual rainfall zone — delivering multiple benefits for landcare and regional development. The planting will also assist the protection and recovery of biodiversity and water resources threatened by salinity. The species planted are Tasmanian blue gum and Sydney blue gum on the better soils and in the wetter end of the rainfall range, and spotted gum (*E. maculata* Hook.) and sugar gum (*E. cladocalyx* F.Muell.) on the poorer soils at the drier end of the range.

Further studies are required of the milling and drying of the remaining trees at the Vasse trial and of trees from other trials. Results of the present and future studies will provide basic information for growers and timber processors involved with the new eucalypt sawlog industry, so they can have more confidence in using Tasmanian blue gum timber from trees grown at wide spacing.

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[2] Catchments recognised by the WA Government as being of high priority for protection and rehabilitation by revegetation with trees and other woody perennials. This will improve the quality of water from the catchments and protect biodiversity.

Assessing forest canopy density in a highly variable landscape using Landsat data and FCD Mapper software

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Summary

Forest canopy density (FCD), estimated with the FCD Mapper, was correlated with basal area and predominant height (PDH) for 48 field plots, measured in highly variable native eucalypt forest at Toolara, south-eastern Queensland, Australia. The Mapper was produced for the International Tropical Timber Organisation and is available on a CD-ROM. It estimates FCD as an undefined index of canopy density using reflectance characteristics of Landsat Enhanced Thematic Mapper images. The Mapper is a 'semi expert' computer program which uses interactive screens to allow the operator to make decisions concerning the classification of land into bare soil, grass or forest. The results of a FCD classification are therefore dependent on the operator's decisions and were found to be highly sensitive to small changes in settings. A positive, weak (r^2 = 0.36) nonlinear relationship of FCD with basal area was observed, while a strong (r^2 = 0.68) similar relationship was observed between FCD and PDH. The strong relationship of FCD with PDH suggests that this remote sensing technique has promise for forest inventory, but that a quick and robust method of measuring FCD in the field is still required for ground truthing.

Keywords: land classification; forests; forest inventories; assessment; remote sensing; landsat; multispectral imagery; canopy; stand density; Queensland

Introduction

There is a continuing need for information about the spatial distribution and density of forests for purposes such as quantifying trends in land clearing in Australia (Kuhnell *et al.* 1998), estimating national carbon budgets in Sweden (Eklundh *et al.* 2003) and plantation management (Baynes 1995). In plantations, field measurements of parameters such as stand height and basal area are time consuming and labour intensive. Native forests are inherently more variable in age, species mix and structure, and although aerial photographs have been widely used for native forest inventory, their use over extensive landscapes such as the Northwest Territories of Canada is logistically difficult and economically impractical (Gerylo *et al.* 2002). Consequently, the need to map the spatial heterogeneity of forests over a range of scales and for a variety of management purposes has led to the widespread application of satellite remote sensing.

In the literature, however, there are few remote sensing tools which can be applied to detect change in forest structure (Franklin *et al.* 2002). In Canada, older vegetation maps, derived from images with pixel sizes ranging from 8 km to 1 km, did not provide sufficiently detailed information because landcover varies over short distances (Cihlar *et al.* 2003). More recent investigations have therefore correlated digital data provided by the Landsat Enhanced Thematic Mapper (ETM) (with a pixel size of 30 m) with forest parameters such as leaf area index (LAI) (Baynes and Dunn 1997; Fernandes *et al.* 2003; Seed and King 2003). LAI is defined as half the all-sided green leaf area per unit ground surface area projected on the horizontal datum, and is a key parameter in canopy process models (McNaughton and Jarvis 1983). The process of correlating satellite digital data with LAI or other forest parameters requires access to Geographic Information System (GIS) software, an understanding of the theory of remote sensing, and expertise in bio-physical modelling. Without specialised training, few foresters would have the expertise to estimate LAI using some recently-published algorithms involving shadow fraction and soil-adjusted vegetation indices (Seed and King 2003; Hall *et al.* 2003). Therefore, the FCD (forest canopy density) Mapper has been designed (JOFCA 2003) to provide foresters with a GIS that can be used by semi-experts to process satellite images into maps of forest density.

FCD Mapper

The FCD Mapper (Mapper) is a computer software package compatible with Microsoft Windows-based personal computers. The Mapper uses the reflectance characteristics of Landsat ETM bands 1–7 with vegetation and bare soil to produce a forest canopy density map. Processing of the ETM images is done with a 'semi-expert' system wherein the operator makes key decisions concerning the classification of images into bare soil, grass, forest, etc. The end result is a new image, an FCD map, which shows the forest canopy density for each pixel as a percentage of canopy density, from 0% to 100% (JOFCA 2003). As the FCD is not precisely defined in the user guide and is not directly correlated with any parameter of canopy density, it should be considered as an undefined index of canopy or forest density.

The Mapper was produced by the Japan Overseas Forestry Consultants Association (JOFCA) for the International Tropical Timber Organisation (ITTO). The latest version, version 2, was revised as part of ITTO project PD 13/97 Rev. 1 (F) in 2003. It is available from ITTO as a CD-ROM.

Objective

The user manual (JOFCA 2003) describes version 2 of the Mapper as having achieved a 90% success rate in classifying the canopy density of tropical (evergreen) and monsoon (deciduous) forest. However, this version had not been tested in wet to dry eucalypt forest in a situation where seasonal swamps and eucalypt woodland are easily confused with grassland or bare ground. The objective of this study was therefore to assess the correlation of FCD with stand height and basal area in eucalypt forests of variable stocking, age, stand structure and species.

Background to the operation of the FCD Mapper

The theory and operation of the Mapper are described fully in the FCD Mapper User's Guide Ver. 1.1 (JOFCA 1999) and the FCD Mapper User Guide Ver. 2 (JOFCA 2003). It was originally developed as a tool to assess the regrowth of a forest canopy in logged tropical forest. In these forests, a 'type 1' situation is recognised (Rikimaru *et al.* 1999) as land with a sparse canopy, little understorey vegetation and bare soil visible from space. A 'type 2' situation exists where canopy density may still be low but understorey vegetation forms a complete ground cover. The Mapper aims to discriminate between type1 and type 2 vegetative cover and then assign an index of canopy density to land with a type 2 cover.

The Mapper uses the reflectance characteristics of Landsat ETM bands 1–7 as its data source (Table 1).

Briefly, the FCD of a study area is computed from Landsat ETM data, using four main indices:

1. a Vegetation Index (VI), selected from the NDVI (Normalised Difference Vegetation Index), the AVI (Advanced Vegetation Index), or the ANVI (Advanced Normalised Vegetation Index),
2. a Bare Soil Index (BI),
3. a Shadow Index (SI), and
4. a Thermal Index (TI).

These four indices are calculated as new images from the raw ETM bands 1–6 with the thermal band designated as band 7, i.e. B1–B7. From these indices, the program then calculates a vegetation density (VD), which includes grassland and forest but excludes bare soil. Grassland is then separated from forest using a scaled shadow index (SSI). Finally, a forest canopy density is calculated for each pixel of forested land. The relevant algorithms are:

- $NDVI = (B4 - B3) / (B4 + B3)$
- $AVI = (B4 \times (256 - B3) \times (B4 - B3) + 1)^{1/3}$, $(B4 - B3) > 0$
- ANVI, synthesised from NDVI and AVI by principal component analysis
- $BI = ((B5 + B3) - (B1 + B4)) / ((B5 + B3) + (B1 + B4)) \times 100 + 100$
- TI = calibrated value of B7
- $SI = ((256 - B1) \times (256 - B2) \times (256 - B3))^{1/3}$
- VD, calculated from the first principal component of VI and BI
- SSI = calibrated shadow index for forested land
- $FCD = (VD \times SSI + 1)^{1/2}$.

Table 1. Wavelength and characteristics of the seven Landsat ETM bands

Band	Bandwidth (µm)	Characteristic
1	0.450–0.515	Visible blue
2	0.525–0.605	Visible green
3	0.630–0.690	Visible red
4	0.76–0.900	Near infrared
5	1.550–1.750	Middle infrared
6	10.40–12.50	Thermal
7	2.09–2.35	Middle infrared

The program calculates these indices and integrates them into an FCD (as an index from 0 to 100) for each pixel of the final FCD image. The underlying principle for each of the four main indices is that the VI has a negative relationship with the quantity of vegetation, i.e. it decreases from bare soil to grassland to forest. The BI increases as the bare soil increases with increasing site aridity and consequent exposure of the soil. The high reciprocity of bare soil status and vegetation status is combined using the VI and the BI to assess land as a continuum ranging from dense forest to exposed soil. The SI increases as forest density increases, and this index is used to separate grassland from forest. The TI is less inside the canopy of a forest due to blocking and absorption of the sun's rays and because of the cooling effect of evaporation from leaves. The TI is therefore used to further differentiate bare soil from grassland and forest.

As each index is computed, the operator is required to visually classify the study area into mutually exclusive categories such as bare soil or vegetation. For each classification, the computer screen shows a histogram of the digital reflectance of the image and the operator moves the cursor bar to set threshold levels of the index (Fig. 1). This operation presupposes that the operator has some knowledge of the vegetative cover of the area and that classification errors will be picked up in subsequent field checking. FCD statistics for particular areas of the image can be calculated using a mask file to exclude pixels outside the area of interest and the FCD map can be exported as a bitmap.

Study site and data

Location

The study site was situated between Toolara Forest (north) and the town of Noosa Heads (south) in subtropical south-eastern Queensland. The long-term average rainfall at the Toolara Forest Station (26°05'S 152°50'E) is 1275 mm and, as is typical for coastal subtropical regions, more than two-thirds of this falls in the period October–March. Mean daily maximum and minimum temperatures are 29.6 and 20.2°C, respectively, in January, and 21.6 and 6.3°C, respectively, in July.

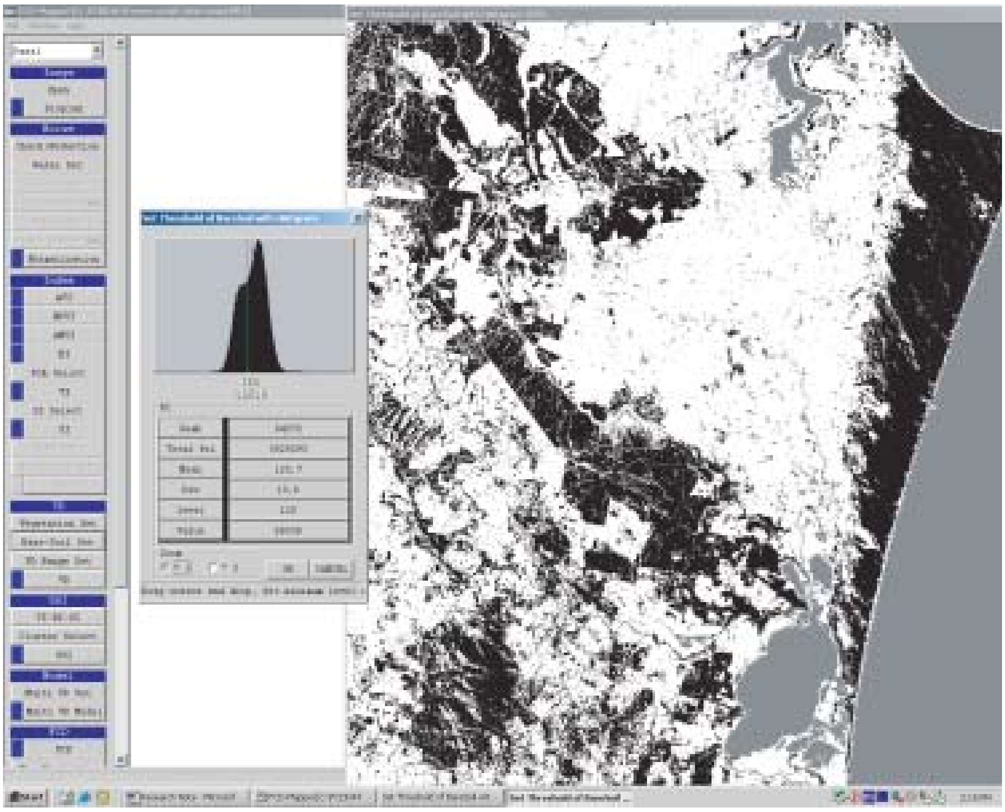

Figure 1. Screen window of the BI dialogue box of the FCD Mapper, showing the cursor bar of the bare soil index histogram set at the level which differentiates bare soil from ground with a vegetative cover. In this case, land which has a complete vegetative cover, i.e. no bare soil is visible to the Landsat sensor, is coloured black. Land which is partly or completely bare soil is coloured white.

Soils

The terrain is relatively flat with an altitude above sea level of less than 150 m, except for the Cooran Tableland which has a maximum elevation of 483 m over an area of about 5000 ha. Soils on the hilly and inland areas are derived from a variety of metamorphic, sedimentary and volcanic rocks (Young and Dillewaard 1999), whereas the eastern side of the study area consists of deep coastal sands and shallow podzols subject to periodic inundation (Stace *et al.* 1968).

Vegetation

For the purposes of remote sensing, vegetation over the study area consists of plantations of pine trees, agricultural grassland and a wide range of native forest.

Native vegetation is dominated by mixed stands of *Eucalyptus* and *Corymbia* species, with some pure stands of individual species. The species mix is mainly determined by soil fertility and water availability. The coastal sands particularly are phosphorus deficient, and tree cover, at its poorest level, is reduced to scattered mature trees, principally scribbly gum (*E. signata* F.Muell.) with a height of <15 m. This native forest is interspersed with low heath and seasonal swamps. It is known locally as 'wallum' (Debenham 1971). On slightly more fertile or wetter areas, bloodwood (*C. intermedia* (R.T.Baker) K.D.Hill and L.A.S.Johnson) and other eucalypt species form a forest cover with a canopy height of up to about 30 m and as low as 4 m where exposed to coastal winds. Inland, and particularly on dry ridges, stands of spotted gum (*C. citriodora* ssp. *variegata* (F.Muell.) A.R.Bean and M.W.McDonald) and Gympie messmate (*E. cloeziana* F.Muell.) form tall open forest which grows to heights of about 40 m. Understorey in these stands is often very much reduced. On wet, well-drained and more fertile coastal sands, blackbutt (*E. pilularis* Smith) forms pure stands with a canopy height of >40 m. Finally, 'wet eucalypt' forest, of which rose gum (*E. grandis* W.Hill ex Maiden) is a principal species, is found in association with rainforest in wet gullies and sheltered sites. The rainforest comprises a number of overstorey and understorey species including trees, vines, palms and ferns.

In summary, the native vegetation is highly variable and many species exist across the entire geographic range. Species intermixing rather than pure stands is the rule, but the broad vegetation types described above can be discriminated with suitable aerial photographs.

Remotely-sensed data

A Landsat 7 ETM (52 x 69 km) image of the study site, taken on 16 September 2000, was obtained for bands 1–7. The image had been radiometrically and geometrically corrected to remove detector-to-detector and band-to-band brightness variations and image distortions. The image had also been resampled to a 25-m grid and aligned to the Gympie 1:100 000 mapsheet using ground control points. As the original ETM thermal image was supplied with a pixel size of 50 m, this image was converted to pixels of 25 m using the EXPAND utility of the IDRISI GIS software. All images were then exported to the Mapper as TIFF files.

From previous experience in this region, September is ideal for the collection of remotely-sensed data used to discriminate between vegetation types. This is because annual grasses have died off through frost or dryness, and contrast clearly with perennial vegetation. The image was cloud free; one area of bushfire smoke which was present was ignored in the subsequent analysis. No rain had fallen in the previous 14 days, and the last rainfall recorded at the Toolara Forest Station was only 1.2 mm.

Method

FCD Mapper

The Landsat image was loaded into the Mapper and processed as per instructions in the user guide. To assist classification of the study area, eight reference positions were chosen, ranging from bare soil to forest with a closed canopy, i.e. dry white sand, a recently clear-felled pine plantation, dry red soil, an airport tarmac, a swamp covered with dense green vegetation, poor-quality bloodwood forest, Gympie messmate forest and wet eucalypt forest.

Processing was taken to the stage of calculating the initial FCD map. The program permits further processing to adjust the FCD map to forest canopy information derived from ground data points using regression analysis. This was not done, as the aim of the investigation was to assess the performance of the Mapper in estimating stand basal area or predominant height (PDH, the average height of the tallest 50 trees ha^{-1}) over a range of forest types.

To assist interpretation of the results of the FCD map, spectral signatures were calculated for ETM bands 1–5 for the swamp, bloodwood, Gympie messmate, blackbutt and wet eucalypt forest. From a field inspection, five positions were chosen across the range of each landcover and the reflectance of a matrix of 2 x 2 pixels was recorded for each position. Reflectance values were obtained from each image using the interactive query function in IDRISI and a mean reflectance of the 20 pixels calculated. Also, the algorithms used in the Mapper were used to calculate BI, TI and SI for each landcover.

Plot selection

To check the accuracy of the FCD classification, the PDH and basal area (i.e. $m^2\,ha^{-1}$ of tree cross sectional area at 1.3 m above ground level) were measured on 48 field plots of 0.1 ha. Twelve plots each were measured in (1) wet eucalypt and rainforest, (2) blackbutt forest, (3) Gympie messmate and spotted gum forest, and (4) poor-quality bloodwood forest. Plots were not measured in the wallum as the tree cover is highly variable, often with stockings of less than 50 trees ha^{-1}. Plot positions were located on the FCD image and the coordinates transferred to a Global Positioning System for location in the field. The plots were located in uneven-aged mature forest to minimise growth differences between the time of image capture (2000) and plot measurement (2003).

Table 2. Mean basal area, predominant height (PDH) and forest canopy density (FCD) for 12 plots each in wet eucalypt, blackbutt, Gympie messmate and bloodwood forest at Toolara, south-eastern Queensland

Forest type	Basal area ($m^2\,ha^{-1}$)	PDH (m)	FCD (%)
Wet eucalypt	27.8	39.6	61
Blackbutt	22.5	40.3	56
Gympie messmate	22.6	37.4	45
Bloodwood	15.9	13.9	36

Results

Field plots

Mean basal area was 27.8, 22.5, 22.6 and 15.9 $m^2\,ha^{-1}$ for the wet eucalypt, blackbutt, Gympie messmate and bloodwood forest plots, respectively (Table 2). Mean PDH was 39.6, 40.3, 37.4 and 13.9 m for the same forest types. Mean FCD declined similarly from 61 to 56, 45 and 36 for each landcover, respectively.

A weak, non-linear relationship ($r^2 = 0.36$), best described by a power function, was observed between basal area and FCD (Fig. 2). A strong non-linear relationship ($r^2 = 0.68$), also best described by a power function, was observed between PDH and FCD (Fig. 3).

FCD image

The FCD image classified 35.7% of the 223 852 ha study area as grassland, bare soil and surface water. This included agricultural fields and wallum in which vegetation cover was incomplete. Surface water had been masked out during processing. The remaining 64.3% of the study area was classified as having an FCD ranging from 1% to 80%. No forest was classified as having an FCD above 80%. As the wet eucalypt reference area has a closed canopy and a high level of shadow, it would be expected that the FCD of this forest type would be close to 100%. The estimates of FCD are therefore lower than expected, at least for

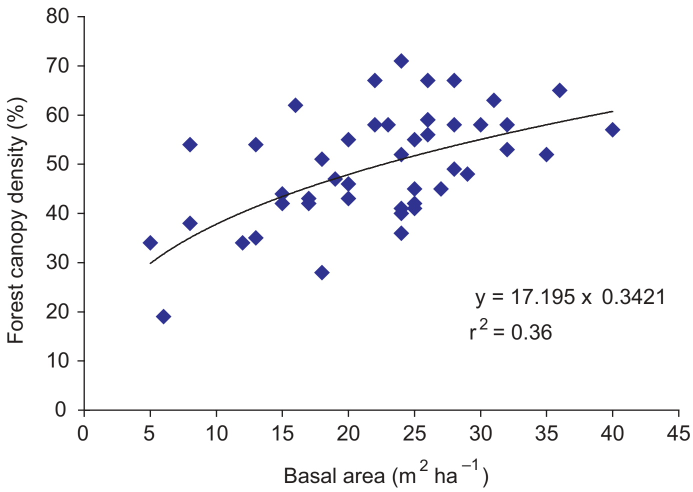

Figure 2. Relationship of basal area with forest canopy density for 12 wet eucalypt, 12 blackbutt, 12 Gympie messmate and 12 bloodwood plots at Toolara, south-eastern Queensland

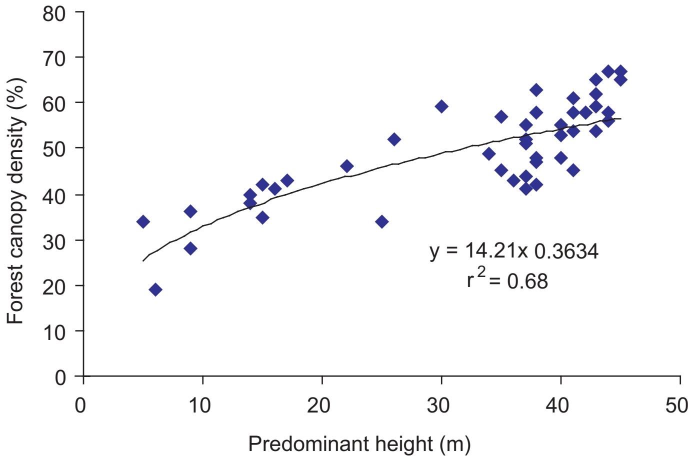

Figure 3. Relationship of predominant height with forest canopy density for 12 wet eucalypt, 12 blackbutt, 12 Gympie messmate and 12 bloodwood plots at Toolara, south-eastern Queensland

the wet eucalypt forest. Provision is made in the program to correlate FCD percentage values with ground control points to re-calibrate the FCD values. This is difficult, however, as the corrected data are input as FCD percentages and no method is offered for measuring FCD in the field.

In addition, the swamp reference point (which is covered with dense green vegetation) was classified as having an FCD of 0% – 30%. A field check and aerial photographs showed that this was an overestimate, as there were only isolated trees growing in the swamp. The program was rerun and the classifications altered to classify the swamp as grassland, using a process similar to that described for Figure 1. The SSI setting was altered to classify more of the image as grassland and less as forest. However, reclassifying swamp to grassland altered the settings of the FCD map (Fig. 4a and 4b) over the entire FCD range. For instance, the first run of the program classified 45% of the study area as FCD = 0, while the second run classified 51.2% as FCD = 0, as expected. However, this also had the effect of reducing the number of pixels with an FCD range of 60–70% from 11 209 to 7799. The Mapper is therefore highly sensitive to the settings used by the operator.

The spectral signatures of the forest types and the swamp (Fig. 5, Table 3) are similar. The swamp has the least vegetative cover and as expected, it shows the highest reflectance in bands 1, 2, 3 and 5 and the lowest reflectance in band 4. This has resulted in a BI slightly higher than the other forest types and a SI which is slightly lower. The TI of the swamp (137) is similar to the TI of dry white sand (140).

Table 3. The indices BI, TI and SI calculated for dry white sand, a swamp, bloodwood forest, Gympie messmate forest, blackbutt forest and wet eucalypt forest at Toolara, south-eastern Queensland

Surface	Bare Soil Index	Thermal Index	Shadow Index
Dry white sand	100	140	0
Swamp	94	137	188
Bloodwood	88	80	200
Gympie messmate	83	81	214
Blackbutt	78	96	211
Wet eucalypt	64	30	227

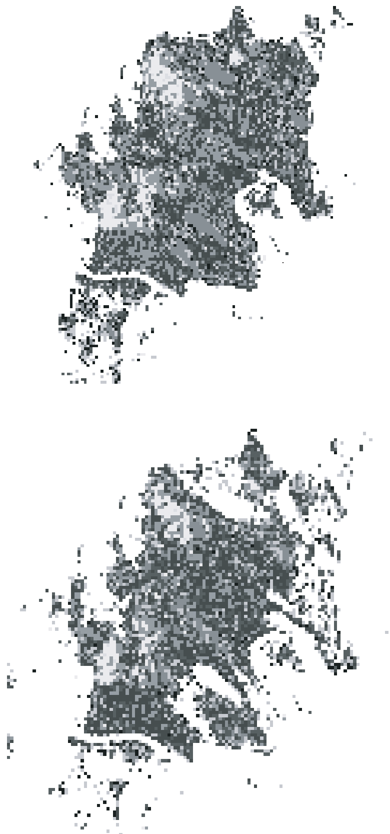

Figure 4(a) and (b). The 3 x 3 km images, show the forest canopy density (FCD) percentage on the headland of Noosa Heads, south-eastern Queensland, surrounded by sea. The images are depicted in greyscale with areas of sea, roads and bare dirt (zero forest cover) shown in white. Areas of wet eucalypt and rainforest are shown in light grey and dry eucalypt forest is shown in dark grey to black. A highway (white line, bottom left) divides the predominantly forested headland from a swamp to the south, shown with pixels classified as forest (Fig. 4 a) and grassland (Fig. 4b). The reclassification has altered the FCD of the entire FCD range.

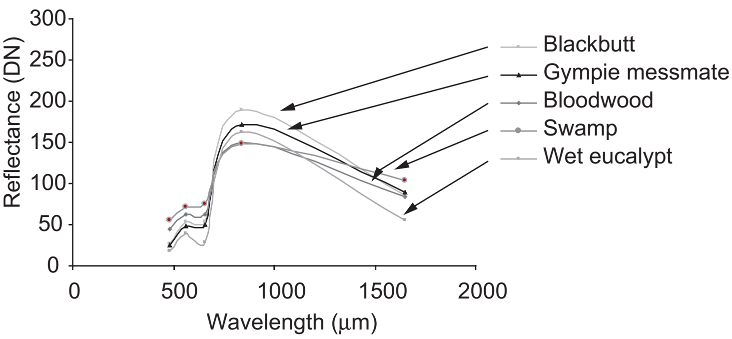

Figure 5. Spectral signatures of four different forest types, blackbutt, Gympie messmate, bloodwood and wet eucalypt, and a swamp for ETM bands 1–5, at Toolara, south-eastern Queensland

Discussion and conclusion

Traditionally, the term ‘stand density’ has had several meanings for foresters, as it involves the concept of stand crowding or competition between members of the stand, which is in turn determined for a particular age by stand stocking and stand basal area (Baskerville 1962). Various indices of stand density, usually incorporating stocking, tree height, diameter and canopy measurements are well described in the literature (Smith 1962; Carron 1968; Hocker 1979). However, indirect methods of canopy density estimation using ‘fish eye’ photographs or instruments such as ceptometers or spherical densiometers are liable to bias and are time consuming to use (Roy 1999). Hence recent investigations have used LAI, estimated with satellite imagery, as a principal index of forest or canopy density. Intuitively, the algorithms used in the FCD Mapper provide an index of LAI, even though the user guide describes FCD as being ‘the degree of forest density, expressed as a percentage’ (JOFCA 1999). Therefore, the challenge is how best to measure and extract image variance that maximises information on LAI of the forest overstorey (Seed and King 2003). The Mapper was successful in explaining a high percentage of the variation between PDH and FCD, but less so with basal area.

The weak relationship between FCD and basal area is not unexpected because the plots were chosen over a wide range of stocking, species mix and tree size. Stocking, particularly, was highly variable in all forest types. However, the high correlation of FCD with PDH indicates that the Mapper discriminates between forest types over a wide range of forest types. Tree height is relatively unaffected by stocking (Lanner 1985; Oliver and Larson 1996). It is possible that in mature stands of variable stocking but complete crown cover, PDH is a more reliable indicator of crown density, when plot sizes are small (0.1 ha), than basal area.

The Mapper is sensitive to changes to the settings which control the classification of land as bare soil, grassland or forest. These classifications are controlled by the operator, and where vegetation types and boundaries are distinct there should be no problem achieving a correct separation of landcover types. However, where the contribution of the understorey becomes significant, such as in wallum heath and swamp, and the spectral signature of the understorey is similar to that of the overstorey, then confusion between vegetation classes may result. In this study the author had a detailed knowledge of the study site, but without this knowledge misclassification of the vegetation classes would be a likely result. Consequently, the settings used for projects undertaken with the Mappper should be recorded, particularly if the Mapper is to be used for time series analysis. The study area in this project was reasonably large and encompassed a wide variety of vegetation types. Reducing the size and variation of the study area with mask files may assist the operator to discriminate between the vegetation types.

In conclusion, it would be most useful to have a robust field method of correlating initial FCD percentages with a field measurement of forest or canopy density. This would enable foresters to correlate FCD, which at present is just an index of reflectance, to a parameter which can be measured in the field. This could considerably enhance the usefulness of the Mapper to field staff.

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Relationships between longitudinal growth strain and some wood properties in *Eucalyptus nitens*

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Summary

The relationships between longitudinal growth strain and wood properties of *Eucalyptus nitens* were investigated. Sixty-three 10-y-old trees were selected for this study. Longitudinal growth strain, green density, green moisture content, basic density, radial shrinkage, outerwood and corewood densities, volumetric shrinkage and dynamic modulus of elasticity (MOE) at 12% moisture content and length-weighted fibre length were determined. Amongst all the studied wood properties, only shrinkage-related properties were found to have some association with the mean growth strain in trees. The mean growth strain was moderately but significantly related to the volumetric shrinkage of the outerwood, but not to the shrinkage of the corewood. However, the volumetric shrinkage differential (difference between outerwood and corewood shrinkage) was strongly related to the growth strain (r = 0.70), suggesting that the growth stress gradient might be related to variations in shrinkage properties within the stem. The wood of trees with the lowest growth strains had statistically significantly lower volumetric shrinkage, lower outerwood MOE and less collapse than wood of trees with the highest growth strains. The results suggest that *E. nitens* trees with low strains could exhibit a lower degree of drying defects such as collapse and checking during processing.

Keywords: forest plantations; wood properties; growth stress; strain; wood density; modulus of elasticity; fibre quality; drying; shrinkage; wood defects; *Eucalyptus nitens*

Introduction

The presence of growth stresses in trees and their influence on tree growth and development was reported as long ago as the 1930s. Since then there has been extensive research on the presence and distribution of growth stresses in various species, the mechanism of growth stress generation, means of measuring growth strains in trees/logs and their influence on processing of timber. This work has been reviewed by authors such as Chafe (1979a), Kubler (1987) and Yang and Waugh (2001). In practice, growth strain is measured and then presumed to be linearly related to growth stress because the stresses are thought to reside in the elastic region of the stress–strain diagram; consequently the two terms are often used interchangeably. It is well recognized that large growth stresses in wood, especially in hardwood species, result in severe processing problems. Many eucalypt species are notorious for having very high growth stresses.

An important stimulus to research on growth stress has been the development of tools to measure growth strain in standing trees and felled logs. Several destructive and semi-destructive ways of measuring growth strain have been proposed. In most techniques, growth stress is released either by drilling holes in the stem wood or by cutting out a rectangular piece of wood and measuring the changes in the longitudinal and transverse directions gauged by reference to two fixed points, or by using wire strain gauges (Nicholson 1971; Saurat and Gueneau 1976; Okuyama *et al.* 1994; Aggarwal *et al.* 1998, 2002; Yoshida and Okuyama 2002). Several researchers have sought some meaningful relationship between growth stress/strain and physical, chemical, mechanical and anatomical characteristics of wood (Nicholson *et al.* 1972, 1975; Chafe 1979b, 1990; Muneri *et al.* 1999; Muneri and Leggate 2000) to get an indirect indicator of the level of growth stress in trees. Many studies associating growth stress or strain with other wood properties have been on leaning stems. On leaning or reoriented stems extremely large strains are generated and usually those are associated with reaction wood (tension wood in angiosperms and compression wood in gymnosperms). The anatomical characteristics of reaction wood are significantly different to those of normal wood, and changes in the cell wall structure and properties cause changes in growth stresses (Yoshida and Okuyama 2002). Since many physical properties are associated with fibre structure, significant relationships have been established between properties such as volumetric shrinkage, basic density or modulus of elasticity and the growth stress in leaning stems of various eucalypts (Nicholson *et al.* 1972, 1975; Chafe 1979b, 1981, 1990; Boyd 1980).

Fewer studies have suggested a relationship between some wood properties and growth stress in normal wood as well, for example a significant relationship between volumetric shrinkage and the magnitude of growth strain has been reported in normal wood (Nicholson *et al.* 1975; Aggarwal *et al.* 2002). Growth strain was reported to have a positive relationship with basic density in normal vertical stems of 36-y-old *E. regnans* (Chafe 1990) and 10-y-old *E. globulus* (Yang *et al.* 2002) but the relationship was absent in 8-y-old *E. nitens* (Chafe 1990), 10-y-old *E. cloeziana* (Muneri *et al.* 1999) and 4-y-old *E. pilularis* (Muneri and Leggate 2000). Some studies have explored relationship of modulus of elasticity (MOE), modulus of rupture (MOR) and maximum crushing strength with growth strains (Boyd 1980; Chafe 1981, 1985a, 1990; Aggarwal *et al.* 1998, 2002; Muneri *et al.* 1999; Muneri and Leggate 2000); but there was no conclusive evidence of any generalized relationship between growth strain and these properties. Overall, the association of wood properties with growth stress/strain in vertical-straight stems is not well understood.

Understanding the relationships between growth stress/strain and wood properties in vertical straight stems could have a significant bearing on the breeding and silvicultural management of eucalypts. One needs to be aware of possible influences on other wood properties while selecting trees with low strain level. This paper explores the relationships between average tree growth strain and various physical and mechanical properties measured at about breast height in *E. nitens* wood.

Material and methods

Sampling

Sixty-three trees from a 10-y-old *E. nitens* plantation were selected for the study. The plantation is located on the Port Hills near Gebbies Pass, some 30 km from the University of Canterbury. The plantation is on a north-easterly sloping site and generally exposed to strong winds. The trees were grown from seedlings of uncertain genetic origin. The uphill side of the trees was marked using spray paint. The selected trees were felled with a stump height of about 10 cm. Total tree height, and diameter at intervals of 1 m up the stem, were recorded. The mean tree height and diameter over bark at breast height of the sampled trees were 11.5 m (SD ±0.9 m) and 17.4 cm (SD ±1.4 cm) respectively. Most of these trees had an essentially clear bole up to a height of about 5 m. From each tree, a butt log section (from ground to 1.3 m height), a second or upper log section (from 1.6 m to 3.6 m) and a short billet (300 mm in length, at breast height) were extracted. The billets were stored in polythene covers immediately after extraction to avoid any moisture loss. All logs and billets were transported to the laboratory on the day the trees were felled.

Growth strain measurements

The two logs from each tree were used for growth strain and green dynamic MOE measurements. Longitudinal growth strains were measured at approximately mid-length on two opposite sides (uphill and downhill side) of each log, using the strain gauge method and KYOWA 120 ohm strain gauges with a gauge factor of 2.05. The average of four strain measurements was taken to be the mean growth strain for that tree. A portion of the bark was removed carefully, with a hand chisel, to avoid damaging the cambium. The cambial surface was scraped with the edge of a chisel to remove the differentiating xylem and to smooth the wood surface, which was wiped with cotton to remove excess moisture and cleaned with ethyl alcohol. The strain gauge was glued onto the clean surface using a cyanoacryalate-based glue, and after the glue had fully cured the centre-line of the gauge and points were marked, 17.5 mm above and below the centre point. The lead wires of the strain gauge were connected to the strain meter in the half-bridge configuration, the bridge circuit was balanced to 0 and the initial strain value recorded. Wood fibres were cut above and below the gauge by two series of intersecting holes, 8 mm in diameter, made with a battery-powered hand drill. The horizontal centre lines of the series passed through the two positions previously marked. The resulting slots were about 20 mm long and 20 mm deep. The distance between the opposed edges of two slots was 27 mm. This distance was less than 1.5 times the width of the slots, necessary to obtain the strain value of about 90% of the actual value as suggested by Saurat and Gueneau (1976). Immediately after cutting, the released strain was recorded.

Radial shrinkage measurements

A disc 50 mm thick was cut from each 300-mm billet taken at breast height. To determine radial shrinkage, one strip was cut from each of the discs across the radial direction from pith to cambium. Samples 15 mm x 15 mm in cross-section and of maximum possible length in the radial direction were prepared from these strips. The radial sample length was 58–88 mm, depending on the disc diameter. For tangential shrinkage, samples 25 mm x 25 mm in cross-section and 100 mm in length in the tangential direction were prepared. From each disc one radial and one tangential specimen was taken. Some of the radial and tangential samples cracked or broke during sample preparation due to pre-existing end cracks in the discs, so these samples were rejected. In total, 50 radial shrinkage samples and 46 tangential shrinkage samples were obtained. The length of each radial and tangential sample was recorded in the green condition using a Vernier calipers with an accuracy of 0.01 mm. Subsequently these samples were dried to 12% moisture content (mc) in a controlled environmental chamber at 65% relative humidity and 20°C. The dried samples were reconditioned in steam for 90 minutes. As the steaming increased the moisture content in the samples by 3–4%, they were then returned to the air-conditioned room to re-equilibrate to 12% mc. The length of dried samples was measured. Unfortunately the dry tangential shrinkage samples exhibited severe distortion and, as it was not practical to measure their length accurately, measurement of the tangential shrinkage was abandoned. However, the severity of distortion in the tangential samples provided another index of wood quality.

The remaining billets (250 mm long) were used to determine green and basic densities. The billets were debarked and weighed to an accuracy of 0.1 g, and green volume was measured by water displacement. The billets were then oven-dried at 105°C, to constant weight. From the oven-dry weight and green volume, the basic density and green moisture content were determined.

Samples for volumetric shrinkage and MOE determination

Volumetric shrinkage and MOE of outerwood (near the cambium) and corewood (close to pith) were determined in the samples from 51 of the 63 trees in which growth strain was measured: this procedure was adopted only after the first 12 trees had been processed. A section 500 mm long was cut at the small end of each butt log to give clear wood specimens for measurements of MOE and volumetric shrinkage. Duplicate specimens, 20 mm x 20 mm cross-section, were prepared from both the outerwood and corewood regions. These specimens were trimmed to a length of 300 mm, numbered accordingly, weighed to an accuracy of 0.01 g and volume-determined to an accuracy of 0.1 mL, dried, weighed and volume-determined, reconditioned and dried to 12% mc to recover collapse, and weighed and volume-determined again.

Volumetric shrinkage from green to 12% moisture content was determined for both outerwood and corewood samples, for before and after reconditioning with steam, using the equation

$$\text{Volumetric shrinkage} = 100(V_g - V_d) / V_g,$$

where V_g and V_d are volumes when green and air-dried respectively. The percentage difference in the volume of the sample before reconditioning (V_{BR}) and after reconditioning (V_{AR}) with respect to the volume in green condition was considered to be the amount of collapse in the samples, i.e.

$$\text{Collapse} = 100\,(V_{AR} - V_{BR}) / V_g\ .$$

MOE determination

Acoustic velocity in the air-dried and reconditioned samples was measured using the resonance based tool 'WoodSpec' described by Lindstrom *et al.* (2002). The dynamic MOE was estimated from the air-dry density of the sample and acoustic velocity using the following relationship:

$$MOE_{dyn} = \text{density} \times \text{acoustic velocity}^2 .$$

Fibre property measurements

Outerwood chips were taken on the same sides from the billet (extracted from tree breast height) as growth strain was measured in the logs. The chips were initially treated with 10% NaOH solutions for 4 hours and subsequently macerated with peracetic acid solution for 4 hours at 95°C. The fibres were analysed using the Metso FibreLab analyzer. Length-weighted fibre length, fibre width and cell wall thickness values were assessed from a minimum of 5000 fibres in each sample.

Data analysis

The data analysis investigated significant differences in the means of various wood properties between trees with high and low strain. The sample population was ranked and then divided into four distinct groups according to their strain values (≤600 με: low-strain group; 600 με – 900με: medium-low group, 900 με – 1200 με: medium-high group, ≥1200 με: high-strain group). Both the low- and high-strain groups had 14 trees, while the medium-low group had 22 trees and the medium-high group had 13 trees. Average wood properties for the lowest-strain and the highest-strain group were determined and the mean values of the properties of each were compared by Fisher's Least Significant Difference (LSD) method at $\alpha = 0.05$ and 0.01, using SAS statistical software (SAS 1998).

Results and discussion

Wood properties

The descriptive statistics showing average values with standard deviation and range for various wood properties are presented in Table 1. The average tree growth strain and basic density at breast height were 898 με (standard deviation (SD) ±336 με) and 495 kg m^{-3} (SD ±49 kg m^{-3}), respectively, in the sampled trees. The observed growth strain was about 20% greater, and the density value was about 10% greater than that observed in 8-y-old trees measured at breast height (Chafe 1990), and at 3.3 m above ground level in 25 trees of *E. nitens*, 8.5-y-old, from five provenances in Australia (McKimm 1985). For comparisoin, Raymond and Muneri (2001) observed mean whole-tree basic densities of 444–563 kg m^{-3} in 9-y-old *E. nitens* grown at five different sites in Tasmania and Victoria (Australia).

The corewood density (heartwood) at 12% mc (Table 1) was significantly less than the outerwood (sapwood) density, in agreement with results obtained by McKimm (1985) in 8.5-y-old *E. nitens*. As with the density profile, dynamic MOE of the outerwood was significantly greater (about 56%) than the corewood MOE. The radial shrinkage measured on radial strips from green to 12% mc after reconditioning in steam was less than that reported by Lausberg *et al.* (1995) in boards taken just below the breast height (1.8% vs 2.26%). When the samples were dried from green to 12% mc, the observed shrinkage included shrinkage associated with collapse. Steaming of the dried sample for about 90 minutes was presumed to result in nearly complete recovery of collapse. After reconditioning, the volumetric shrinkage in outerwood samples was greater than the volumetric shrinkage in corewood samples. The average volumetric shrinkage and collapse was derived as the mean of outerwood and corewood volumetric shrinkage (after steaming) and collapse values (from the volume differences before and after steaming). A wide range in collapse was observed, ranging from 0.45% to 20%. Generally, collapse was greater in corewood samples.

Overall, the wood properties measured for the sample trees were in broad agreement with the properties reported by other researchers for the wood of *E. nitens* of about the same age (McKimm 1985; McKimm *et al.* 1988; Chafe 1990; Raymond and Muneri 2001).

Relationship between growth strain and other wood properties

The prime objective of the extensive wood property assessments was to search for any relationship between the average growth strain level in the tree and other wood properties measured in the samples taken from breast height area. The large variation in growth strains in the population sampled provided an opportunity to seek a relationship between growth strain and other wood properties. One of the major differences between this study and other studies relating growth strain to wood properties is the sampling procedure. In most of the earlier studies, wood properties were measured on the samples extracted either from the strain measurement positions or from its immediate vicinity and measurements were done at several locations around the periphery. In the present study, wood properties were assessed in the samples taken from breast height or near breast height, and growth strain value was the average of the four strain values per tree (two logs per tree and two positions per log). Results of a correlation analysis of the pooled data indicate the strength of association of wood properties and the level of growth strain (Table 2).

Only volumetric shrinkage of outerwood exhibited a significant positive relationship ($r = 0.56$, $P < 0.001$) with mean tree growth strain. The positive relationship of volumetric shrinkage with growth strains has been reported by other researchers (Nicholson *et al.* 1972, 1975; Aggarwal *et al.* 2002). In their studies, volumetric shrinkage was determined in the samples extracted from the vicinity of the strain measurement positions. In a recent study, Clair *et al.* (2003) found a significant positive correlation between growth strain measured using a single-hole method and tangential shrinkage in end-matched samples from normal wood, i.e. not tension wood, in two leaning trees of chestnut (*Castanea sativa* Mill.). They also reported a strong within-tree relationship

Table 1. Average values of wood properties together with standard deviation and minimum and maximum values for all the samples

Wood property	Mean	Standard deviation	Minimum	Maximum	CV (%)
Growth strain (microns)	898	336.2	430	1645	37.4
Green moisture content (%)	129	21.4	81.4	236.7	16.6
Green density (kg m^{-3})	1124	25.5	1066.4	1181.1	2.3
Basic density (kg m^{-3})	495	49.2	326.9	638.9	9.9
CWdensity at 12% mc (kg m^{-3})	556	47.3	453.0	682.3	8.5
OW density at 12% mc (kg m^{-3})	655	72.5	518.9	865.6	11.1
CW MOE_{dyn} at 12% mc (GPa)	7.84	1.02	5.95	9.96	13.0
OW MOE_{dyn} at 12% mc (GPa)	12.21	2.26	6.40	17.74	18.5
Radial shrinkage (%)	1.8	0.29	1.36	2.61	15.8
CW volumetric shrinkage AR(%)	6.0	1.25	3.88	8.86	20.8
OW volumetric shrinkage AR (%)	7.9	1.56	4.50	11.28	19.9
Average volumetric shrinkage AR (%)	6.9	1.31	4.31	10.07	18.9
Collapse (%)	10.3	4.95	0.45	20.61	49.7
Average OW LWFL (mm)	0.82	0.05	0.71	0.96	6.1
Average OW fibre width (µm)	21.3	1.13	18.22	23.68	5.3
Average OW cell wall thickness(µm)	5.21	0.30	4.38	5.92	5.7

CW = corewood, OW = outerwood, AR = after reconditioning, LWFL = length-weighted fibre length

between longitudinal Young's modulus and growth strain in normal wood measured at several positions around the periphery in the green condition. In the present study, however, no significant relationship was observed between average tree growth strain and dynamic MOE of either outerwood or corewood. McKimm *et al.* (1988) also did not observe any significant correlation between the magnitude of growth stress and other strength properties.

Correlation between basic density and growth strain was not significant in the sampled trees. The absence of any relationship between growth strain and basic density in *E. nitens* was also reported by Chafe (1990), although a significant positive relationship between basic density and growth strain has been demonstrated for *E. grandis* (Malan and Gerischer 1987), *E. regnans* (Chafe 1990) and *E. globulus* (Yang *et al*. 2002). Lack of any consistent and reproducible direct relationships of growth strain/stress with basic density and MOE, as reported in the literature and from this study, suggests that these properties are not influenced unduly by the magnitude of growth strain in vertical, straight trees. Any significant relationships observed elsewhere appear to be species-dependent and specific to the particular studied samples and sampling methodology. Results of any one study can be generalised only with considerable caution.

However, we observed several other significant and moderately strong relationships amongst wood properties. Basic density showed a strong negative correlation with moisture content in green condition ($r = 0.95$), which was to be expected. A moderate but significant negative correlation between basic density and collapse suggests that wood with extremely low basic density would tend to show severe collapse. Collapse is often associated with thin-walled fibres; Chafe (1985b) observed negative correlation between collapse and basic density measured in increment core samples at different heights from eight trees of 43-y-old *E. regnans*.

Table 2. Pearson correlation coefficients for various wood properties

Variables		1	2	3	4	5	6	7	8	9	10	11
1	Average tree growth strain	1.00										
2	Green mc	–0.09	1.00									
3	Green density	0.23	–0.47**	1.00								
4	Basic density	0.13	–0.95**	0.67**	1.00							
5	CW MOE_{dyn} (12% mc)	0.01	–0.55**	0.09	0.47**	1.00						
6	OW MOE_{dyn} (12% mc)	0.26	–0.59**	0.33	0.57**	0.53**	1.00					
7	Radial shrinkage	0.29	–0.06	0.04	0.08	0.42*	0.17	1.00				
8	CW volumetric shrinkage	0.17	0.17	0.12	–0.11	–0.02	0.17	0.35	1.00			
9	OW volumetric shrinkage	0.56**	0.06	0.17	–0.00	0.04	0.31	0.45**	0.73**	1.00		
10	Average volumetric shrinkage	0.42*	0.12	0.16	–0.05	0.02	0.28	0.43*	0.91**	0.94**	1.00	
11	Collapse	0.36*	0.51**	–0.11	–0.46**	–0.34	–0.18	0.12	0.70**	0.70**	0.75**	1.00
12	Average OW LWFL	–0.06	0.00	–0.05	0.04	0.11	0.44*	–0.05	–0.22	–0.16	–0.20	–0.21

* significant at $P < 0.01$; ** significant at $P < 0.001$
CW = corewood, OW = outerwood, AR = after reconditioning, LWFL = length-weighted fibre length

Significant higher correlations between density and MOE are partially influenced by the autocorrelation, as dynamic MOE is determined by both density and acoustic velocity.

We also observed that the collapse shrinkage had very little influence on the acoustic velocity in the samples. Figures 1 and 2 show the acoustic velocity and dynamic MOE before and after reconditioning. The acoustic velocity after reconditioning was found to be higher than that before reconditioning by about 1.6%. However, the dynamic MOE decreased substantially (up to 34%) after reconditioning, depending on the amount of collapse recovery. The decrease in MOE was mainly due to decrease in wood density as the wood volume increased with the recovery of collapse during reconditioning. In Figure 3, the ratio of dynamic MOE before and after reconditioning was plotted against collapse recovery for each of the samples. Samples with high collapse showed large differences in dynamic MOE before and after reconditioning.

Comparing the groups of trees with high and low growth strain, average growth strain in the low-strain group was 508 με, while in the highest-strain group it was 1350 με. Table 3 shows the average values of significantly different wood properties for the lowest- and highest-strain groups of trees.

Volumetric shrinkage of outerwood from the low-strain group was significantly lower ($\alpha = 0.01$) than that of the high-strain group, which was likely as a significant correlation was obtained between the two variables for the complete data set. There was no significant difference between the lowest- and highest-strain groups in green density, green dynamic MOE, basic density, density at 12% mc, or corewood and outerwood density. The interesting results of this analysis were the significant differences in radial shrinkage and collapse in low- and high-strain trees at the $\alpha = 0.05$ level, while the correlation analysis showed a poor association of these properties with growth strain. The significant difference in collapse indicated that wood from trees showing low growth strain would have less probability of severe checking since the severity of internal checking generally increases with collapse. A visual comparison of the discs from the lowest- and the highest-strain groups showed the difference in severity of checking in the wood of low- and high-strain trees (Fig. 4). The magnitude of checking and distortion was generally less in the discs from the trees with mean growth strain less than 600 με than in the discs from the high-strain group. The results suggest that screening of trees based

Table 3. Average values of various wood properties in the lowest and highest growth strain groups. Values in parentheses are coefficient of variation (%).

Wood property	Lowest strain group	Highest strain group
OW MOE at 12% mc (GPa)*	10.74 (20.5)	12.86 (10.2)
Radial shrinkage AR (%)*	1.64 (15.3)	1.92 (21.5)
CW volumetric shrinkage AR (%)*	4.98 (13.0)	6.01 (18.0)
OW volumetric shrinkage AR (%)**	6.31 (19.1)	8.88 (13.7)
Av. volumetric shrinkage AR (%)**	5.65 (15.9)	7.45 (12.4)
Collapse (%)*	6.42 (54.0)	12.74 (34.3)

* $\alpha = 0.05$, ** $\alpha = 0.01$, OW = outerwood, CW = corewood, AR = after reconditioning

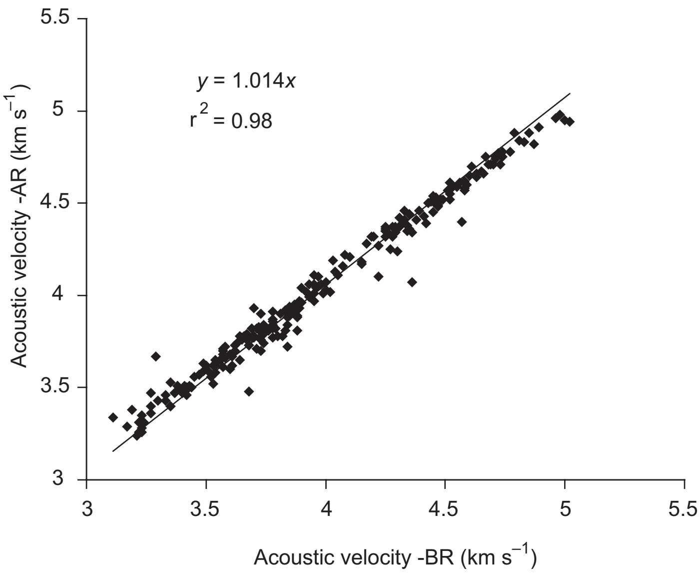

Figure 1. Acoustic velocity in samples before (BR) and after (AR) reconditioning

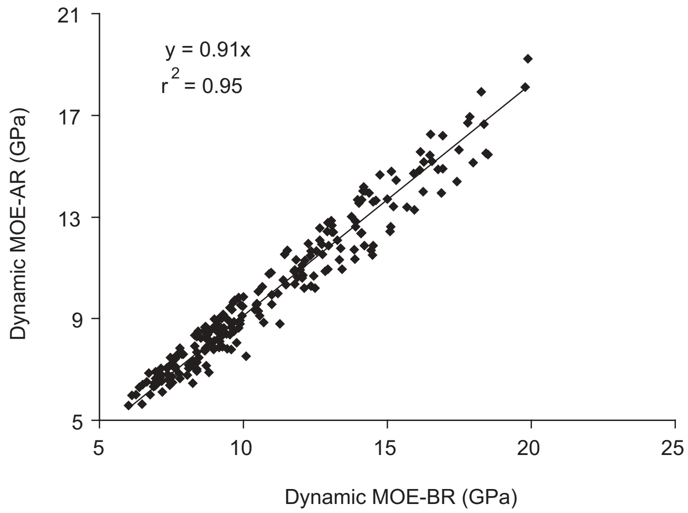

Figure 2. Dynamic MOE before and after reconditioning

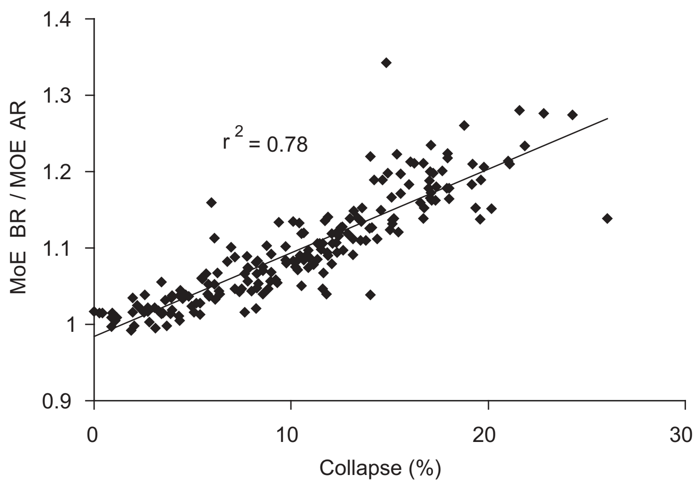

Figure 3. Relationship between the ratio of dynamic MOE before and after reconditioning and collapse in the sample

on the level of growth strain could result in the selection of trees with less drying degrade. However, as there were fewer trees in the low- and high-strain groups, these results are indicative only and need to be confirmed with a larger sample.

There was no significant difference in length-weighted fibre length, fibre width and cell wall thickness between the groups. These results contrast with other results on various eucalypt species. Malan and Gerischer (1987) found statistically significant differences in fibre length and double-wall thickness in low- and high-stressed trees of 28-y-old *E. regnans*. Cell wall thickness has often been related to the magnitude of growth stresses, and thick-walled fibres were found to be associated with the high growth stresses in normal and leaning stems (Nicholson *et al.* 1972; Boyd 1977). The results obtained in this study are in agreement with Wilkins and Kitahara (1991), who found no statistically significant relationship between the level of peripheral growth strain and fibre length, vessel diameter or ray width of wood from 12.5-y-old *E. grandis* trees. The absence of any relationship between fibre properties and growth strain in this study might be attributed to the age of sample trees, as Malan and Gerischer (1987) suggested that highly stressed trees in general exhibit a rapid increase in fibre length and cell wall thickness with increasing age. In most studies where fibre properties were found to be associated with growth stress level, the studied trees were mature (28–30-y old).

In the analysis discussed so far, outerwood and corewood properties have been treated separately and their individual relationships with growth strain have been explored. Since the sampled trees in this study were of similar size, the magnitude of the surface growth strain should indicate the growth stress gradient in the stem, i.e. high growth strains would result in a steep gradient in growth stress from periphery to pith within the stem. It was anticipated that the stress gradient within the stem could be related to some wood property gradient. Malan and Gerischer (1987) observed a steep gradient in wood density and some anatomical characteristics in highly stressed trees of *E. grandis*. In our study, the difference between the outerwood and corewood properties was considered to be an indicator of that wood property gradient within the stem. Wood density, dynamic MOE and volumetric shrinkage differentials were calculated as the absolute differences between the average outerwood values and the average corewood values of the corresponding property. Volumetric shrinkage differential exhibited a strong positive relationship with growth strain ($r = 0.70$, $P < 0.001$). Trees with high growth strain showed a large difference in volumetric shrinkage (Fig. 5).

A moderate but significant relationship of growth strain was observed with density differential ($r = 0.42$, $P = 0.002$) and with dynamic MOE differential ($r = 0.31$, $P = 0.04$). The relationships between wood property gradients and growth strain in the stem need to be further explored with large diameter trees, as the average diameter under bark of the selected trees was small (14–15 cm), and because some of our samples representing outerwood and corewood were taken from adjacent positions in the radial direction. With larger stems, samples with a clear distinction between outerwood and corewood could be obtained. Such a relationship warrants further investigation, as the shrinkage differential assessment can indicate both growth stress and drying related distortions.

Figure 4. Differences in checking in the discs from low strain and high strain trees: <600 microstrain (left); >1200 microstrain (right)

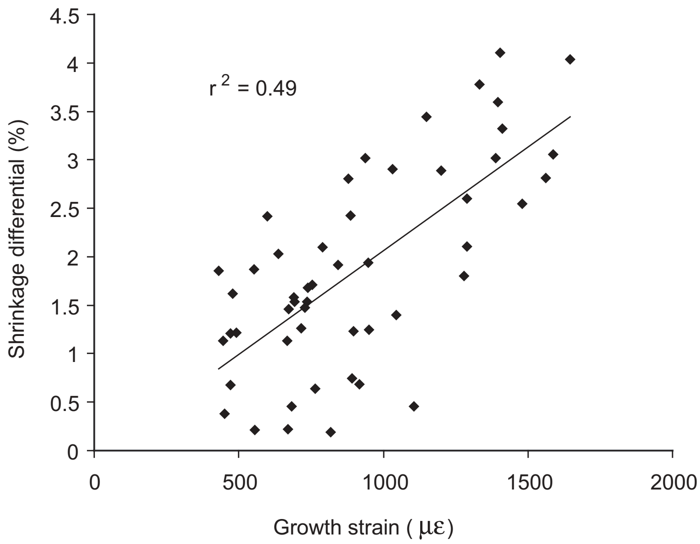

Figure 5. Association between volumetric shrinkage differential and mean tree growth strain

Conclusions

Amongst all the wood properties studied, only those related to shrinkage showed some association with growth strains. Volumetric shrinkage differential showed the best correlation with surface growth strain ($r = 0.70$) suggesting that the gradient in shrinkage behaviour is associated with the surface strain in the tree. The significant differences in collapse, radial shrinkage and volumetric shrinkage in the wood from the trees with the lowest and highest strain suggest that the wood cut from trees displaying least growth strain would be expected to have significantly less checking and collapse-related degrade. Consequently, the magnitude of growth strain could possibly provide a useful basis for initial screening of *E. nitens* trees to lessen collapse-related defects, as well as degrade during processing related to growth stress, without having any influence on wood stiffness (as a low correlation was found between growth strain and dynamic MOE).

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Acoustic segregation of Australian-grown *Pinus radiata* logs for structural board production

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Summary

The wood quality of sawlogs is highly variable and poorly reflected by log physical dimensions. Current log grading rules for structural timber, based purely on physical appearance, result in a significant loss of value to growers and processors. Growers and processors both require tools that are able to rapidly sort logs to yield timber of a uniform quality.

Ninety-two radiata pine (*Pinus radiata*) logs harvested from Green Hills State Forest, NSW, were measured at the Hyne and Son sawmill at Tumbarumba, NSW. Two non-destructive longitudinal stress wave acoustic devices, a FAKOPP single-pass transit-time tool and a WoodSpec resonance tool, were used to characterise the logs. The sampled logs were sorted into three sound speed classes: slow (<3.5 km s^{-1}), medium (3.5–3.7 km s^{-1}) and fast (>3.7 km s^{-1}).

The relationship between measurements of acoustic velocity in logs and the stiffness of the boards milled from the tested logs was established. The boards recovered from logs sorted into the fast sound class had a mean stiffness of 10.5 GPa. The boards recovered from the logs segregated in the medium and slow sound classes had mean stiffnesses of 9.3 GPa and 8.9 GPa, respectively. The acoustic segregation patterns were similar for each of the acoustic tools tested, with the coefficient of variation of repeated measurements with WoodSpec being 2.2% lower than with the FAKOPP, suggesting that the WoodSpec tool was more precise. This study indicates that acoustic measurement of wood stiffness in the field and in the mill may improve value recovery.

Keywords: log grade; wood properties; wood density; wood strength; juvenile wood; quality; grading; stress grading; outturn; instruments; acoustic properties; *Pinus radiata*

Introduction

Timber production from Australia's planted forests is expected to double over the next decade. Economics is a major factor in the development of existing and future plantation forests. Implementing effective measurement of the quality of wood in the resource is a key step in reducing cost and adding value to forest products.

The variation in wood quality within stands in plantations of radiata pine (*Pinus radiata*) is large. As a consequence, the wood quality of logs is also highly variable. Current log grading rules are based on log diameter, which is known to be a poor predictor of intrinsic wood properties (Walker and Nakada 1999). Currently, the processing industry has difficulty in producing products to specification. An ability to assess wood quality at the beginning of the timber stream (in the forest or log yard) offers potential economic gains. Managing wood quality variation by non-destructive measurement of wood properties, enabling log segregation, will allow improved matching of end-use requirements with wood supplies both from existing stands and from new or replacement crops (Matheson *et al*. 2002). Furthermore, data on wood quality provide a means by which silviculturalists can understand the effects of site, silviculture and genetics on the stand, thus guiding prudent silvicultural policies and genetic strategies (Bunn 1981).

Reducing the harvesting age of pine increases the proportion of low quality, juvenile wood in the wood supply. It is known that acoustic velocity is strongly related to fibre strength and length, and possibly microfibril angle (MFA) (Walker and Nakada 1999; Albert *et al*. 2002; Downes *et al*. 2002). Acoustic measurements may offer an opportunity to segregate logs that are stiffer and possibly more stable in the corewood: models have demonstrated an association between timber stability and stiffness (Astley *et al*. 1998). Acoustic velocity may also be a practical method for identifying wood prone to longitudinal shrinkage during drying (Jugo Ilic, CSIRO, *pers. comm*.).

Acoustic tools are logistically simple to operate, and measurements can be quickly taken and are relatively free of operator bias. Two acoustic tools currently available are of different types — a single-pass transit-time measurement system (FAKOPP[1]) and a multi-pass resonance system (WoodSpec[2]). Recently, engineers have indicated that they favour resonance systems for log sorting, as they measure a number of reverberations of the plane acoustic wave from which a dynamic modulus of elasticity (MoE) can be quantitatively determined, compared to the speed of a single expanding wave front that is correlated with MoE (Andrews 2000).

The primary objective of this study was to compare the stiffness of timber resulting from acoustically segregated logs. A secondary

[1]FAKOPP is available commercially through its manufacturer in Hungary
[2] WoodSpec was developed by Industrial Research Ltd, New Zealand.

objective was to gain experience in the use of the two acoustic tools and identify any differences in the measured data.

Materials and methods

Log measurement and sorting

Ninety-two commercial logs, 6.1 m long, were selected from a log supply at the Hyne & Son sawmill, Tumbarumba, in New South Wales, Australia. The logs originated from a single clearfelled stand of 35-y-old thinned radiata pine grown in Green Hills State Forest (Compartment 407) located south-west of Tumut, NSW. The trees were a mix of low- and high-pruned stems. To minimise the number of sawing patterns used, the selection was restricted to logs with a small-end diameter of 24–35 cm under bark. The logs were mechanically debarked before being placed on skids (unstacked) in the mill yard for the acoustic measurements. The diameters of both the small and large end of each log were measured and recorded.

The longitudinal acoustic velocity of each log was determined with the two instruments, the FAKOPP microsecond timer and the WoodSpec.

The FAKOPP has two probes, one a transmitting accelerometer and the other a receiving accelerometer. Measurements were made by inserting the transmitting probe in one end of the log and the receiving probe in the other end. Stress waves were then propagated by lightly tapping the transmitting probe. The transit time for the wave front to reach the receiving probe was recorded and used to calculate the acoustic velocity (FAKOPP velocity = log length/ transit time). For each log, a second measurement was taken by re-inserting the two probes in different areas of the log ends.

In contrast, the acoustic velocity determined by the WoodSpec is based on resonance. The instrument generates a reading from many hundreds of reverberations of an acoustic signal within a log, providing a highly accurate measurement of the plane wave acoustic velocity. The acoustic signal was generated by tapping one end of the log with a hammer and at the same end detecting the reverberations with the accelerometer. The WoodSpec determined the fundamental frequency of vibration for the log and calculated the acoustic velocity (WoodSpec velocity = 2 × log length × fundamental frequency). We made two measurements per log.

For sawing, the logs were sorted into three broad classes according to their acoustic velocities as determined by WoodSpec. The acoustic velocity cut-off points for each class were established simply by dividing the range of values obtained equally to give the following sound speed classes: Slow <3.5 km s^{-1}, Medium 3.6–3.7 km s^{-1}, and Fast >3.8 km s^{-1}. The logs were painted on the ends with a unique colour for each of the sound classes to enable identification during conversion.

Mill conversion and machine stress grading

All logs were sawn using one of Hyne and Sons' standard sawing patterns. The green sawn output was predominantly 100 mm × 38 mm and 200 mm× 38 mm boards; the latter were split to produce 100 mm × 38 mm pieces. Board of two other sizes (100 mm × 50 mm and 75 mm × 50 mm) were also produced but were not included in the study as they represented only a small fraction of the total sawn output. In the green chain, the boards were segregated into two classes, Heart-in (HI) and standard (STD), principally for drying purposes. The HI boards were those containing corewood, whilst the STD boards were mainly outerwood. All boards were kiln dried at high temperature using standard industry drying practice for radiata pine, dressed to a finished size (90 mm × 35 mm) and grouped into one of the three sound speed classes, with the HI and STD boards segregated within each sound class to ultimately make six classes in all.

Grading was carried out according to the Australian and New Zealand Standard AS/NZS 1748 (Standards Australia 1997) using a Metriguard CLT stress grader at the mill. Stiffness (MOE) was measured at regular intervals along the board by bending it in two directions using a 'double-bending' system and averaging the forces required to achieve a preset deflection. A stress grade was then assigned to each board on the basis of the lowest MOE along the length. The grades assigned were 'Machine stress grade pine' MGP 15, MGP 12, MGP 10, F4 or reject. The information on stress grade and the mean and minimum MOE values for each board were recorded electronically using the mill's data capture system linked to the stress grader. All data were saved to a separate file at the end of each class graded.

Basic density measurement

Basic density of logs like those used in the acoustic study was determined by sawing a disc 50 mm thick from either end of 92 logs from a neighbouring stand ('nearby logs') used in a separate unpublished carbon accounting study. The logs used for both that study and this report were harvested at the same time. The basic densities for the discs were determined gravimetrically in accordance with the Australian/New Zealand Standard, AS/NZS 1080.3:2000 (Standards Australia 2000).

Data analysis

Analysis of variance (ANOVA) was used to identify any significant differences amongst the three log acoustic velocity classes. If the analysis indicated significant statistical differences, an *a posteriori* test (Tukey HSD multiple comparisons) established where the differences existed. The Tukey HSD test has the simplicity of the least significant difference (LSD) test in having a constant yard-stick with which to test all pairs of treatment means.

Correlations between the acoustic measurements and wood stiffness were calculated to examine the strength of the relationship and thus indicate the potential for predicting timber outturn.

Results and discussion

Table 1 presents a summary of the mean values of the log and board measurements together with the grade recoveries. The logs segregated reasonably well across the three acoustic velocity classes. There was no statistically significant difference in mean diameter of logs (either at the small end or large end) across the three acoustic velocity classes. The total green log volume in each class was 16.2 m^3 (slow), 10.4 m^3 (medium) and 20.5 m^3 (fast). The volume of boards recovered was similar across the classes (19–25% of log volume).

Table 1. Summary of the mean values of log and board measurements

Sample and variable	Stiffness class			Units
	Low	Medium	High	
Logs				
No of logs	32	21	39	
Diameter, small end	29.1	29.1	30.1	cm
Diameter, large end	35.2	34.8	35.7	cm
Volume	16.2	10.4	20.5	m3
FAKOPP velocity	3.84	4.09	4.34	km s^{-1}
WoodSpec velocity	3.35	3.58	3.78	km s^{-1}
All boards				
No. of boards (90 x 35 mm only)	215	134	205	
Volume recovery (90 x 35 mm only)	25.5	24.6	19.2	%
Mean stiffness (E_{mean})	8.9	9.3	10.5	GPa
Min. stiffness (E_{min})	6.8	6.7	7.2	GPa
Grade recovery:				
MGP 15	4.7	6.0	12.2	%
MGP 12	40.5	39.6	41.0	%
MGP 10	46.5	41.0	35.6	%
F4	7.4	13.4	10.7	%
Reject	0.9	–	0.5	%
STD boards only				
No. of boards (90 x 35 mm only)	114	65	117	
Volume recovery (90 x 35 mm only)	13.5	12.0	11.0	%
Mean stiffness (E_{mean})	9.80	10.53	11.80	GPa
Min. stiffness (E_{min})	7.69	7.53	7.94	GPa
Grade recovery:				
MGP 15	8.8	10.8	16.2	%
MGP 12	58.8	53.8	53.0	%
MGP 10	28.9	27.7	24.8	%
F4	3.5	7.7	6.0	%
HI boards only				
No. of boards (90 x 35 mm only)	101	69	88	
Volume recovery (90 x 35 mm only)	12.0	12.7	8.2	%
Mean stiffness (E_{mean})	7.93	8.21	8.89	GPa
Min. stiffness (E_{min})	5.72	5.92	6.16	GPa
Grade recovery:				
MGP 15	–	1.4	6.8	%
MGP 12	19.8	26.1	25.0	%
MGP 10	66.3	53.6	50.0	%
F4	11.9	18.8	17.0	%
Reject	2.0	–	1.1	%

The mean acoustic velocity (±SD) for all 92 green logs measured with the FAKOPP and WoodSpec was 4.1 km s^{-1} (±0.3) and 3.6 km s^{-1} (±0.2), respectively. For the slow, medium and fast log classes the FAKOPP recorded an average sound velocity of 3.8, 4.1 and 4.3 km s^{-1} respectively, and corresponding WoodSpec values were 3.3, 3.5 and 3.8 km s^{-1}.

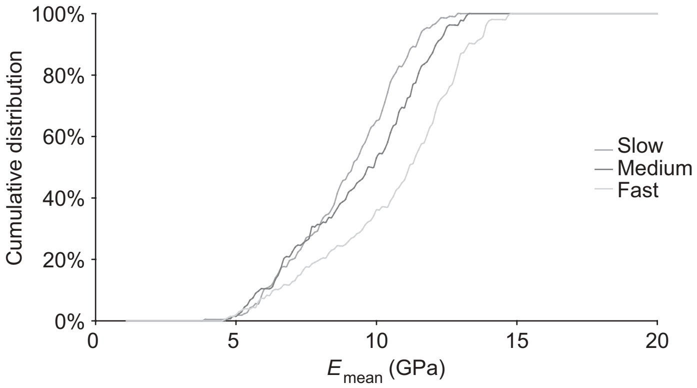

Figure 1. Cumulative distribution for the three acoustic velocity classes for boards

The results in Table 1 indicate that for both acoustic instruments there was a discernable relationship between the acoustic velocity of the green logs and the average modulus of elasticity (E_{mean}) of the sawn boards in bending as determined by the stress grader. The cumulative distribution of E_{mean} of boards (HI and STD combined) for each of the three acoustic velocity classes demonstrates the effect of the segregation (Fig. 1). At greater stiffness values (9–12 GPa) clear differentiation (20–40%) is achieved by the acoustic segregation of the logs.

This relationship was less convincing for the board minimum MOE (E_{min}) as indicated by the mechanical stress grading (MSG) results (Fig. 2). This weaker relationship is likely to be due to localised defects (such as knots) within individual boards. Grain distortion around a knot can extend at least five knot diameters and induce a zone of severe stress concentration. Usually, board samples incorporating knots and other defects have a bending strength that is substantially less than that of clearwood specimens. Furthermore, cross grain is known to greatly reduce bending strength (Bodig and Jayne1982). The E_{min} vs E_{mean} scatter plot for the timber (Fig. 3) clearly indicates this (E_{min} =0.71E_{mean}, r^2 = 0.66). The plot does confirm that E_{min} is proportional to $E_{mean,}$ with 95% of the data within ±25% of the regression line. Clearly there is significant scatter. Acoustic tools account for deviated

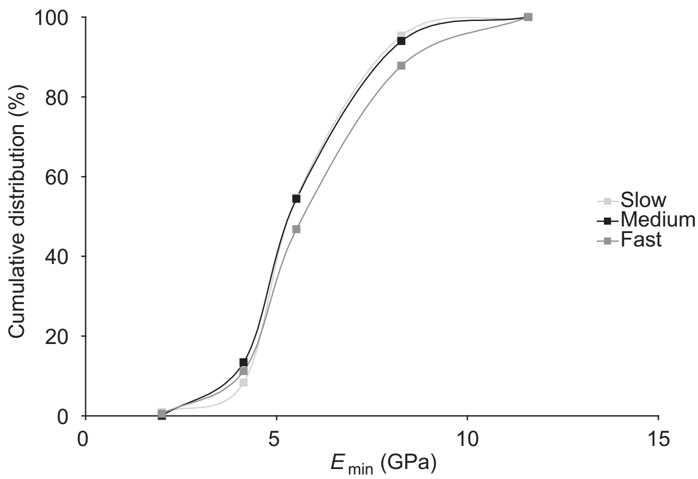

Figure 2. Cumulative distribution of the MSG grades for the three acoustic velocity classes

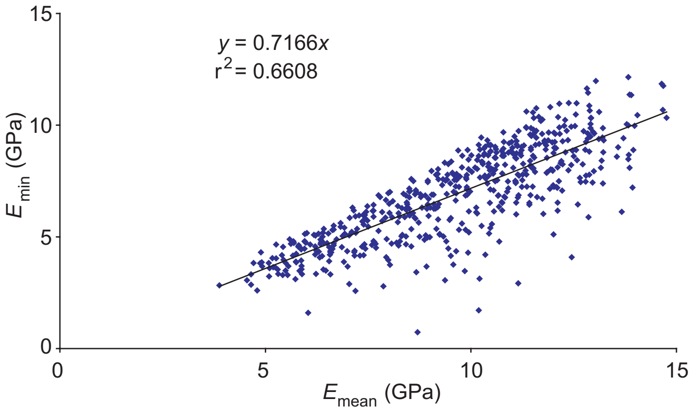

Figure 3. E_{min} vs E_{mean} scatter plot for the timber samples

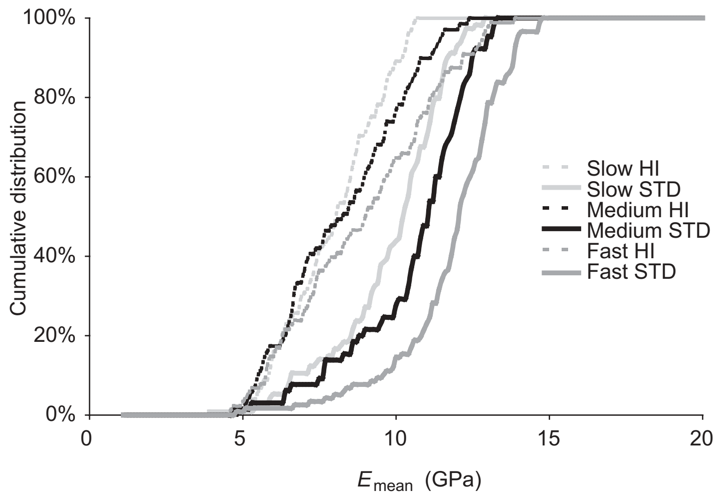

Figure 4. Cumulative distribution for the three acoustic velocity classes and HI or STD boards

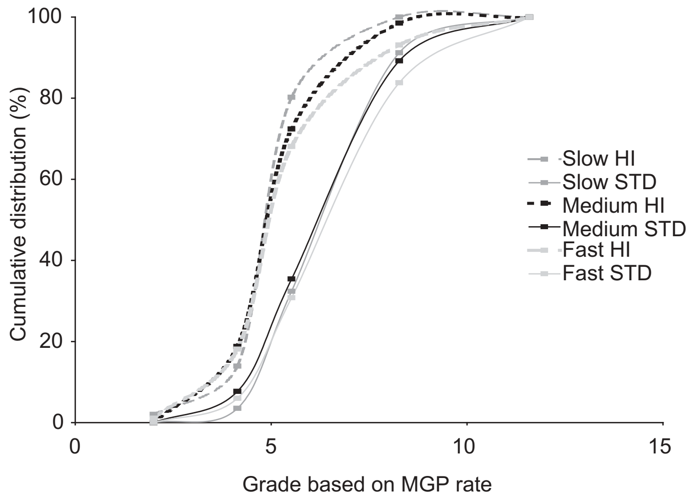

Figure 5. Cumulative distribution of the MSG Grades for the three acoustic velocity classes and HI or STD boards

grain arising from knots and defects only in their effect on the average for the board. Conversely, the presence and position of knots and defects greatly affects the MSG values because it is dominated by localised E_{min} values. This is indicated in Figure 2, which shows the cumulative distribution of the MSG grade outturn.

Despite the good segregation evident in Figure 1 based on the E_{mean} values, the final grade outturn showed poor segregation, with only about 10% differentiation of the high MGP grades achieved in the fast class. Unfortunately, grading for strength, whether by visual or mechanical (MSG) means, necessarily involves identifying the 'weakest' point (e.g. E_{min} or largest knot) along the board and assigning a grade for the whole board based on the assumed strength at that weak point. Moreover, for further structural safety, the derivation of design properties for strength for a graded population is based on strength values of the lower percentiles (usually the lower 5th percentile) and not on an average value. Nonetheless, within a graded population (e.g. MGP 10), the stiffness requirements must also be satisfied. This value is based on the graded population average (and not minimum) and herein lies the usefulness of acoustic segregation for satisfying grade requirements.

Recently it has been observed within the industry that radiata pine mills are able to demonstrate compliance for strength but are struggling to meet stiffness requirements, resulting in a change in perspective regarding design properties for possible new grades. Essentially, the industry is wishing to ensure that the average stiffness of a consignment of boards meets any agreed stiffness thresholds. Acoustic segregation of logs may achieve this outcome by assisting mills to comply with grading rules, whilst maintaining production targets. Furthermore, acoustic segregation of logs may be employed prior to incurring processing costs, thus maximising plant throughput.

The effect of the acoustic segregation and the radial stiffness profile is clearly demonstrated for the HI and STD boards E_{mean} cumulative distribution (Fig. 4). The three acoustically-segregated log classes show a nearly linear increase in the HI boards' cumulative distribution. This implies a broad range in wood stiffness in the core increasing steadily in a radial direction, and a plateauing of properties in the typical radial profile from about the corewood–outerwood boundary, and reflected in the abrupt increase in the STD boards' cumulative distribution at about 10–12 GPa. Note that the log segregation provides significant gain in both the core and outerwood, and achieves a gain of >40% in the outerwood. Overall, Figure 4 indicates that substantial gains can be achieved by adapting a sawing pattern to account for the average acoustic velocity for a specific log and the typical radial stiffness profile (by segregating boards cut from corewood from those cut from outerwood). A plot of the MSG outturn distinguishing the HI and STD boards re-emphasises this point, indicating that the effect of defects does not mask the radial profile effect, although it does diminish the segregation effectiveness (Fig. 5).

Wood basic density

The mean basic wood density of the samples from the 'nearby' logs was 463 kg m^{-3} (Table 2). This is on the high end of the basic density scale for *Pinus radiata* (Cown and McConchie 1983). These density data alone indicate that such logs would yield a high proportion of boards of MGP 10 or better. A separate unpublished study of a neighbouring stand ascertained that the branch index (BIX)[3] was 3–4 cm (C. Raymond, Forests NSW, *pers. comm.*). Based on the wood density data from the current

Table 2. The basic wood density of samples from 92 'nearby' logs from North Green Hills State Forest, New South Wales (F. Ximenes, Forests NSW, *pers. comm.*)

Statistic	Value (kg m^{-3})
Mean	463
Minimum	415
Maximum	521
Standard deviation	±23.6
Confidence interval (95%)	456–469

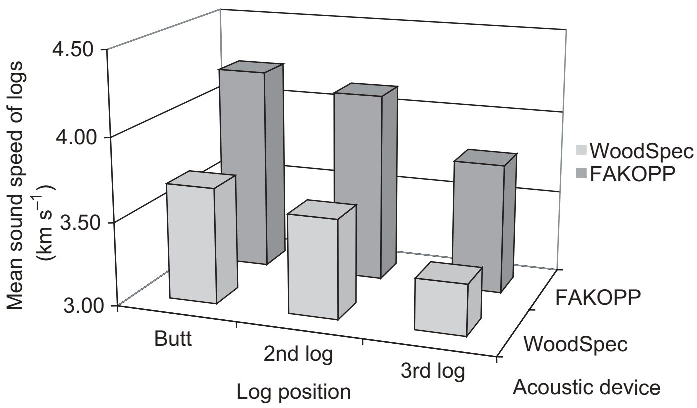

Figure 6. Effect of log position and acoustic tool on the average sound velocity of logs

study and a BIX of 4 cm, past research would suggest that the total sawn recovery of boards making MGP10 or better should have been above 70% (Cown *et al*. 1987). In our study, the actual grade yield data show that across the slow, medium and fast log classes, 92%, 87% and 89% respectively of the sawn board recovery made MGP 10 or better.

It could be argued that as basic density is high there is little point in segregating this resource. However, wood properties vary hugely amongst trees of the same stand, between stands and across regional forests (Bunn 1981; Donaldson 1992). Thus there is merit in seeking opportunities to identify and sort high- and low-quality logs within stands, enabling the extraction of stems suitable for structural timber from a resource of low to medium quality (C.Treloar, *pers. comm.*). Although density was not specifically assessed in this study, there is evidence that it does not necessarily predict stiffness (Lindstrom *et al.* 2002; Maclaren 2002). During recent years published information has indicated wood microfibril angle (MFA) is associated with wood stiffness, and acoustic measurements are thought to be related to variation in MFA (Tsehaye *et al.* 2000; Downes *et al*. 2002).

Impact of corewood

The average acoustic velocity was found to be slower for the top logs than for butt logs (Fig. 6). This trend may be explained by changes in the proportion of juvenile or corewood, since in the top logs the fraction of juvenile wood is greater and this has lower

[3] Branch index (BIX) is the mean diameter of the four branches representing the largest branch in each of four quadrants of a log.

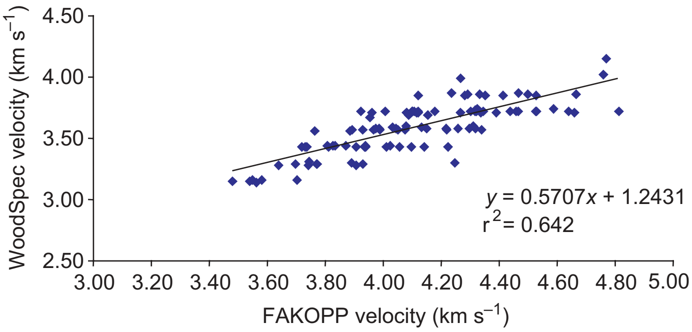

Figure 7. Relationship between the WoodSpec and FAKOPP acoustic velocity

stiffness (Zobel and Sprague 1998) and therefore lower acoustic velocity. Low-stiffness juvenile wood (HI) has a high propensity to warp and twist, so acoustic sorting of logs for stiffness may be useful as a screen for quality control. In processing logs, low volumes of juvenile wood are not noticeable in grade yield. However, in southern pines (e.g. lobolly pine and slash pine) when juvenile wood content approaches 10–20%, there is an important effect on both the yield and characteristics of the final product (Zobel and Sprague 1998). As the age at clear-felling is reduced, the segregation of juvenile wood in the wood supply may become economically desirable.

Hardware and methods

We found significant differences ($P < 0.001$) in the flight velocity of sound recorded by the two instruments when used on the same group of logs (Table 1). The FAKOPP instrument consistently determined a higher velocity along logs than the WoodSpec (Fig. 7). The FAKOPP measures the transit time of the initial disturbance, whereas the WoodSpec measures intervals between multiple reverberations of the reflected wave. It is generally known that the initial disturbance travels faster than subsequent reverberations, settling to the plane wave speed (Andrews 2000).

In this trial, the logs were selected within a narrow range of diameter, resulting in a log length:diameter ratio of about 20:1. One would intuitively expect close agreement between the results of the two methods. The fact that this is not the case implies that the initial disturbance travels over large fractions of the length of the 6.1 m logs without reflections from the walls of the logs, resulting in the plane wave condition. For a log diameter of 0.3 m, this is a surprising result.

In spite of the differences between results from the two instruments, the relationship between the two sets of estimates was highly significant ($r^2 = 0.64$) (Fig. 7). An analysis of how the logs were sorted by the two instruments is presented in Figure 8. Of the 92 logs, 66% were sorted into the same sound velocity class by both instruments. The remaining logs were 'borderline' cases, with the disparity in classification occurring between either the slow- and medium-speed classes, or the medium- and fast-speed classes. This was an encouraging result.

The duplicate estimates of the acoustic velocity by WoodSpec were consistently in good agreement, irrespective of how hard, or where, the log ends were tapped. The ability of the two instruments

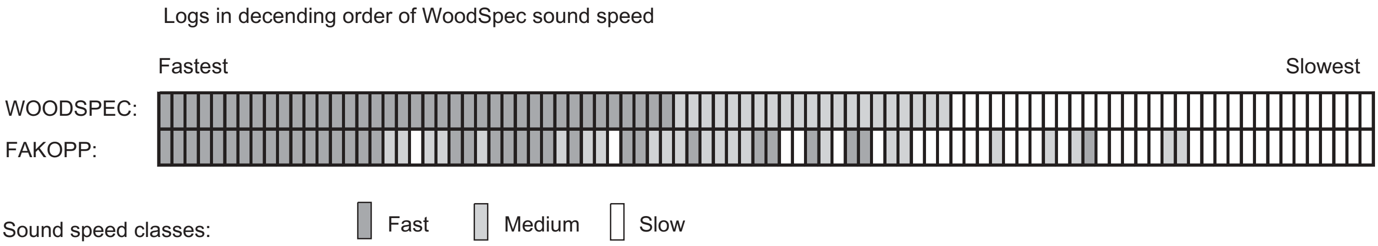

Figure 8. Comparison of how logs were sorted into the three sound speed classes using WoodSpec and FAKOPP. Logs are ranked from highest to lowest sound speed according to WoodSpec.

to give stable acoustic signatures for individual logs differed — the repeatability of the readings by the WoodSpec was far superior to that of readings by the FAKOPP. If we define repeatability as the difference between the two velocity readings for each log expressed as a percentage of the mean reading, then the overall repeatability of all the log measurements with the FAKOPP was about 2%, with a range of 0–8%. In contrast, the Woodspec repeatability was 0%: the same reading was obtained for a log each time.

Conclusions

This study indicates that there is scope to improve value recovery by acoustically segregating logs in the forest or mill yard. Application of this technology offers a cost-effective means of upgrading structural yields by identifying logs of a quality appropriate for structural purposes. It offers an opportunity for mills to hedge against the impact of reducing clearfell age, which increases the fraction of juvenile wood in the wood flow. Combining the average log acoustic velocity of a log parcel, segregated by the acoustic instruments, with grading reflecting the typical radial stiffness profile, significantly improved value recovery.

In future crops, acoustic tools may be used to make judicious tree improvement and silvicultural decisions to produce logs that yield greater fractions of stiffer wood. The use of non-destructive tools to measure intrinsic wood properties of either standing trees or logs has real merit, and potentially offers significant economic gain to growers. These instruments can inform forest growers about wood stiffness as it affects the wood quality of their estate, thus guiding the implementation of silviculture policy and genetic strategies. The challenge will be to find a system to effectively gather this information at the stand level and then ensure the information has relevance and an accepted value in the market place.

This study indicates that WoodSpec has advantages over FAKOPP for making log measurements. Resonance sweep technology employed by WoodSpec provides accurate information from reverberating waves and offers the advantage of needing access to only one end of the log to obtain measurements, which has logistical appeal.

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Greenhouse gas abatement: a review of potential social implications of land-use change in Australia

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Summary

There is growing support, both within Australia and internationally, for substantial changes to the way rural land — particularly farmland — is managed, in an effort to reduce net greenhouse gas emissions. Greenhouse gas abatement is part of the pressure that is redefining agricultural practices and the nature and extent of forestry in Australia in an attempt to meet international obligations (targets) defined in the Kyoto Protocol. While a considerable investment has been made to improve understanding of the processes of carbon emission and sequestration in the land sector, comparatively little effort has been devoted to understanding the social dimension of the massive changes that some expect landholders will have to make. In broad terms, the key social issues relate to the nature, scale and rate of change by individual landholders, geographical communities and industry sectors, but a full understanding of the key social issues is yet to be attained. For instance, many farming families and agricultural industries do not have the social and economic capacity to make widespread changes to current practices, even if alternative practices are highly desirable. Furthermore, there is great variation in the feasible options available to individual farming families, regional communities and rural sectors to reduce greenhouse gas emissions — forced change may see this disparity increase. This paper contributes to the debate in favour of carbon sequestration by providing information about appropriate and feasible change which is sensitive to the social context of rural Australia.

Keywords: greenhouse gases; carbon sequestration; land use; forestry; agriculture; change; social impact; social change; Australia

Introduction

This paper concentrates on the social dimension of rural land-use change that directly results from efforts to curb greenhouse gas emissions or to increase sequestration. It discusses the broad social implications of relevant changes in grazing and cropping systems, clearing of native vegetation, establishing plantations and potential trading in carbon credits (CRC 2000).

While recognising that the social dimension of land-use change has potentially far wider implications than noted above — such as change due to telecommunication technology altering business and travel in rural Australia, change in energy generation and usage, change in rural land-use due to urban development — this paper concentrates on those areas that are of immediate interest to the agricultural and forestry sectors.

The need for land-use change in rural Australia

It is widely believed that Australians must make considerable changes to the way we manage our farmland in order to:

- move towards sustainable agriculture to reduce rates of environmental degradation, amongst other reasons, and
- reduce land-based greenhouse emissions and increase carbon sinks.

For instance, much of the 100 million ha of Australia's wheat-sheep zone, comprising the largest land-use of the medium–low rainfall area, is now widely believed to have been over-cleared of its native vegetation and is showing signs of environmental stress — in particular, increased dryland salinity and loss of biodiversity. Research suggests that the cost of revegetating this agro-ecological zone to arrest land degradation exceeds $20 billion (George *et al*. 1999; Hatton and Salama 1999). At a national scale, the cost of environmental rehabilitation across all farmland is estimated to be $60 billion (George *et al*. 1999; Hatton and Salama 1999; VCG and Griffin Natural Resource Management 2000). This is more than 40 times the amount of funds made available through the Natural Heritage Trust — to date, the Australian Government's largest environmental rehabilitation program. Even the Commonwealth and State Governments' $1.4 billion seven-year *National Action Plan for Salinity and Water Quality* will cover only a small portion of the full costs of rehabilitating the nation's farmland.

In parallel is the international agreement-in-principle Kyoto Protocol (adopted in December 1997), which aims to commit most countries to reduce net greenhouse gas emissions to 5% below a country's 1990 level — although Australia is an exception with its emission target set at 108% of its 1990 level, in effect an increase, by the first commitment period (2008–2012). Some commentators argue that this exception makes Australia's compliance with the Kyoto Protocol a relatively straightforward task, as Article 3.7 has 'opened up a large loop-hole which only (Australia) is in a position to exploit' (Hamilton and Vellen 1999, p. 151), while others suggest that meeting the target of the Kyoto Protocol 'constitutes a significant reduction of net emissions below business-as-usual projections, and it will require significant policy initiatives to achieve this reduction' (Kirschbaum 2000, p. 83).

At a national level, the Australian Government developed the National Greenhouse Strategy (NGS), managed by the Australian Greenhouse Office (AGO), which has, as one major focus, the establishment of greenhouse sinks and sustainable land management. The AGO (2000, p. 18) stated that the NGS 'recognises that greenhouse sinks play an important role in reducing the level of greenhouse gases in the atmosphere and represents one practical means for Australia to reduce emissions and meet its international commitments.'

Understanding greenhouse gas emissions

In terms of the scope of this paper, rural land-use has implications for greenhouse gas emissions largely due to:

- clearing of existing woody vegetation for other land-use, with clearing of native vegetation contributing about 20% of Australia's 1990 level of emissions (AGO 1999);
- operations of existing agricultural industries, with agricultural emissions (mainly methane from beef cattle and sheep) contributing about another 20% to the national 1990 level of emissions (Howden and Reyenga 1999); and
- plans to expand the area of forestry on farmland, to act as a carbon 'sink' (AGO 1998).

Although arguably much of the detailed science is still to be fully understood (AGO 2003), undoubtedly the nature, scale and rate of land-use change required in rural Australia to develop more sustainable farming systems and establish large areas of plantations to considerably reduce net greenhouse gas emissions will have important social implications for individual landholders, regional communities and primary industry sectors.

Principal social issues for research and development

The key aspects of the social implications of widespread land-use change for communities and landholders within Australia are mirrored in the international setting (Rosa 2001), and are outlined below.

Key social issues

The key social issues relate to the nature, scale and rate of change for:

- individual landholders, groups of similar landholders and their surrounding communities (which of these have the capacity for change?);
- differing groups of landholders (e.g. farm families, corporate farms, indigenous communities) and agricultural sectors willing and able to make changes voluntarily, compared to those compelled by regulation to make changes; for instance, opportunities for profitable joint ventures between forestry companies and landholders exist only in some medium–high rainfall regions;
- differing agricultural sectors (e.g. cereal cropping compared to livestock, dairying compared to horticulture), regions dependent on agriculture and forestry, and the individual businesses associated with agriculture and forestry;
- markets, such as those for trading carbon credits, and the extent to which commercial incentives will emerge for desired land-use change (will small-scale growers be commercially competitive?);
- equitable or fair distribution of the benefits and costs of land-use changes between agricultural sectors, between regions, and between landholders within a region (also between countries, see Roberts 2001); and
- government agencies responsible for policy initiatives and responses to land-use changes (do primary industry agencies have the institutional capacity for change?).

Capacity for change by regional communities and landholders

Declining terms of trade for some farmers and regions

In terms of land area, cereal cropping (largely wheat) and sheep farming (largely wool) are the dominant private land-uses in Australia's low–medium rainfall (400–700 mm y^{-1}) areas. Areas of irrigated agriculture (e.g. cotton, rice) and horticulture (e.g. fruit) occur within this agro-ecological zone, but occupy far less, yet highly valuable, land. Wheat–sheep farming and associated industries have been experiencing declining terms of trade over the last four decades, and have recently been affected by extended periods of drought (arguably natural climate variability) — especially in inland Queensland and western NSW. Also, wool has dropped more than five-fold in value to the nation's economy in real terms since its peak period in the 1950s, with wool now contributing about 0.5% to the GDP (ABS 1998).

Within the wheat–sheep zone, 50–80% of household income is derived from agriculture, so it is not surprising that there was a steady rate of population decline in this zone during the 1990s, with the median age of farmers increasing. While just 4% of Australia's workforce is employed in the agricultural sector, its importance is much greater for regional centres and rural towns, where 30–50% of workforce is employed in agriculture and associated businesses (ABS 1998; Haberkorn *et al*. 2000).

During the last few decades, grain prices have generally been steady with occasional peaks in market prices. Wool prices, however, have generally been very depressed and are only just starting to make a slow recovery following the economic downturn of traditional customers (i.e. in Asia, Europe, former Soviet Union). Despite stronger world economic activity and increased numbers of consumers, retail demand for wool remains subdued. Some woolgrowers, however, are successfully exploiting what many in the industry see as the best long-term chance to remain viable — to produce low-volume, high-value wool for the luxury market. On such properties, changes in land-use to reduce emissions or increase sequestration (e.g. by adopting farm forestry) will need to generate \$180–200 ha^{-1} per year to match returns from wool production, or play a supporting role to sustain or improve wool production.

In the medium–high rainfall (>700 mm y^{-1}) areas of rural Australia, the major land-uses include livestock grazing (beef cattle and sheep), dairying, forestry and horticulture. The recent de-regulation of Australia's dairy industry is causing considerable structural change: about a third of dairy farmers are expected to exit the industry (with support of the Australian Government's

$1.7 billion *Dairy Structural Adjustment Package*) during the next few years as small or marginal dairy farms give way to larger and more efficient operations. It is uncertain if this structural change will reduce the size of the national dairy herd, or simply allow the remaining farms to expand with no net reduction in the size of the national herd. In general terms, dairy farms are located on fertile farmland with ample freshwater supplies (either from being in high-rainfall areas or with access to off-farm supplies), with land value usually exceeding $3000 ha^{-1}.

Forestry — both plantations (1.5 million ha) and native forests (13.3 million ha) — fulfils an important socio-economic role in rural and regional Australia in the >700 mm y^{-1} rainfall zone, with 35 small towns having more than 20% of the workforce employed in the forest industries (BRS 1998, 2001). When companies have run land-lease schemes offering farmers $160–240 ha^{-1} y^{-1} so they can establish plantations on farmland, these have been popular amongst landholders with grazing enterprises (Race and Curtis 1999). Yet, in recent years, the leasing of farmland in northern Tasmania and south-western Victoria by companies establishing plantations has caused mixed perceptions about the extent of benefits from forestry (Petheram *et al*. 2000; Schirmer *et al*. 2000). While in general forestry may serve as an important greenhouse 'sink', not all in rural Australia view the current approach to plantation forestry as providing broad social benefits — making the assumption that landholders will voluntarily establish large areas of plantations problematic (Gerrand *et al*. 2003). An added complication for a strategy for widespread land-use change involving commercial forestry is that global warming, in part due to human-induced greenhouse gas emissions, appears already to be contributing to more frequent climatic extremes — making forestry in marginal areas an increasingly risky business (Pearman 2004).

What change for wheat–sheep farmers?

General figures for profitability of farming within the wheat–sheep zone disguise the great disparity between individual farming businesses (Locke 2003). While most farms within this zone have been unviable in economic terms during the 1990s, a significant number — about 40% of cropping and 20% of sheep farms — still generated a reasonable household income (FarmBiz 500 uses a taxable income of $50 000 p.a. as the threshold). The profitable wheat-sheep farms are characterised as having:

- larger farm sizes (>500 ha);
- lower debt;
- continual investment in upgrading technology, equipment or genetics; and
- high quality produce.

A typical strategy for wheat–sheep farms without the above features is to increasingly gain off-farm income, thereby maintaining the household income. This option is available only on an appreciable scale near large regional/urban centres.

As discussed earlier, those with viable wheat–sheep enterprises are more likely to adopt farm forestry as an additional enterprise if it sustains or improves their current farming systems. That is, they are likely to integrate farm forestry with wheat–sheep production, rather than abandon the latter. Young farmers (<40 y) with large farms — in size and business — and those families with a positive intention of passing the farm onto the next generation, are most commonly associated with farm growth and making a serious investment in long-term farm improvements (Tanewski *et al*. 2000).

Even though wheat–sheep enterprises tend to have lower opportunity costs than dairying or horticulture, most wheat–sheep farmers do not have sufficient finance to invest in widespread land-use change, even if change is demonstrably commercially prudent. Also, suggesting that these farmers should have equity in the processing stage of a value-added industry (e.g. sawmilling based on farm forestry) denies their lack of liquidity for any type of investment. However, as seen in the medium–high rainfall zone, many farmers will be attracted by commercial forestry that provides annuity payments (i.e. regular and reliable income equal to, or higher than, that from their current enterprises), or provides them with the opportunity to sell-out and exit agriculture. Some of these farmers appear to be deferring their exit from agriculture until wool prices improve to allow the sale of the farm at a reasonable price to support their retirement (Barr and Cary 2000).

Outside finance needed for change

Given the low returns for much of Australia's dryland farming (particularly wool production) and its dependent regional industries (Lockie 2003), it appears farmers are unlikely to have sufficient financial reserves to undertake major changes to reduce greenhouse gas emissions or establish large-scale sinks, particularly within the first reporting period of the Kyoto Protocol 2008–2012. Such changes will require considerable injection of finance from outside these regional economies. Access to outside finance may be possible, as illustrated by the recent expansion of blue gum planting on farmland (in the 600–1000 mm y^{-1} rainfall zone) largely financed by urban-based investors and overseas companies. However, even if outside finance became available (e.g. via trading in carbon credits or taxation incentives), it will be important to identify which agricultural sectors, regions and landholders have the capacity for voluntary change, so those without that capacity are supported adequately.

Community concerns with widespread land-use change

Rapid and profound changes in land-use, particularly for rural and regional communities dependent on agriculture, have led to considerable anxiety. For example, while there are claims that widespread farm forestry can have positive outcomes for some aspects of the environment and communities, this opportunity needs to be carefully appraised and explored by the target communities before they adopt it. Even if farmers are favourably disposed to establishing trees on farms, developing the critical mass of plantations within a catchment to support a viable processing industry is far more complex — particularly when a perception emerges that forestry may displace existing agricultural enterprises (Gerrand *et al*. 2003; Williams *et al*. 2003). For example, during the 20+ y it takes a plantation to sufficiently mature for harvesting, science and public debate in relation to forestry can shift dramatically (Rolley 2001; Gerrand *et al*. 2003; Pearman 2004).

Widespread land-use change is unlikely to affect everyone similarly, nor even provide benefits to all (Vanclay and Lawrence 1995; Lockie 2003). New forms of land-use may simply be part of the response to long-term structural change, particularly in the wool industry, but assumptions about the extent of community acceptance of major land-use alternatives should be avoided. Also, despite the long-term decline in terms of trade in wheat–sheep farming, farmers and rural communities still retain considerable allegiance to these industries, reflecting the historical importance to their region's, and the nation's, development during the 20th century. Opportunities will need to be fully explored in partnership with communities so the nature, scale and rate of land-use change can be appreciated and tailored to the local context. As a general rule, the more forestry is integrated with (and supports) current agricultural practices — rather than displacing farming — the less likely it is that widespread community anxiety will arise (Tonts *et al*. 2001).

Land-use changes that increase business prosperity, allow for business diversification, encourage population growth, and add to the aesthetic appeal of a region are likely to be welcomed at a broad level by regional communities. However, as increased development does not affect everyone equally, communities can be divided over the type and extent of development that is preferred for their region. As such, an expanding primary industry that causes rapid and widespread land-use change is likely to be of concern for some segments of a community, with their concerns usually being that:

- existing agricultural industries will be replaced, leading to the demise of associated businesses;
- loss of economic activity will lead to population decline and loss of important social and community services (e.g. schools, hospitals and allied health facilities);
- uncompetitive markets and unfair trading partnerships may leave farmers with little scope to negotiate prices and trade arrangements;
- large-scale corporate businesses contribute less to the social structure and services (e.g. volunteer fire brigade, landcare) than small local businesses;
- new industries (e.g. industrial forestry) can undermine a region's aesthetic characteristics (e.g. restrict views);
- new industries will cause the decline of a region's already deficient transport infrastructure; and
- their neighbour's new activities will cause problems for themselves (e.g. pest plants and animals).

Several reports provide further detail on the socio-economic impacts of the expansion of forestry on Australian rural communities (Spencer *et al*. 1989; Dargavel 1990; Race and Curtis 1997; Race and Fulton 1999; Barr *et al*. 2000; Petheram *et al*. 2000; Tonts *et al*. 2001; Schirmer 2002; Schirmer and Tonts 2003; Williams *et al*. 2003).

Capacity for industries to change

Many of the small/medium-scale intermediate processors in rural towns and regional centres that are dependent on cereal cropping and grazing industries (e.g. initial processors such as cereal millers or wool scourers) have been struggling to remain viable over recent decades. These industries are unlikely to have sufficient financial reserves to allow for investment in new energy-efficient technology with low levels of carbon emissions.

Small-scale and geographically-remote processors are tending to be replaced by vertically integrated grower–processor–retailer partnerships, with the location of processing capital now more likely to be determined by low costs of processing (low land value, access to existing transport infrastructure and routes, economies of scale with other food and fibre industries), rather than necessarily being close to the primary feedstock.

Also, establishing efficient processing centres for food and fibre products at major towns or regional centres allows businesses to benefit from good power, telecommunication and transport infrastructure, reliable water supplies, and adequate social and community services for employees. The aggregation of small/medium-scale businesses in such locations allows them to benefit from economies of scale — as a 'cluster' economy. Examples of this approach appeared to work well for wine and olive oil businesses (Stayner 1999). It will be important for existing and new rural industries to acknowledge this trend, because many farms generate high-volume low-value products, with most of the benefits being associated with the processing stage that is often located outside the growing region.

Adoption of technology to reduce agricultural emissions

There appears to have been relatively little direct investment by the agricultural industries in research and development to create technology to reduce greenhouse gas emissions, compared to that sponsored by government. This is particularly noticeable within the livestock industries, which are responsible for most emissions from agriculture. This seems reasonable given that the likely changes are not yet mandatory and that the cost of change for some agricultural sectors may be considerable. This may not necessarily represent a deficiency in Australia's National Greenhouse Strategy, as continuing structural and technological change within the livestock industries may still deliver reductions in emission levels (e.g. steady decline in sheep numbers). The main areas for reducing emissions from agriculture that are relatively cost-efficient, low-risk and have a high chance of success include reducing livestock numbers and improving the efficacy of fertiliser application (also, a vaccine is being developed by CSIRO that aims to decrease methane emissions by livestock).

As discussed above, over recent decades many primary producers — in both the food and fibre industries — have had a weakening capacity to negotiate within markets. Current market structures make it difficult for them to pass on to processors and consumers their increasing input costs, and hence their terms of trade have declined. How competitive farmers will be in future markets remains uncertain.

Trading of carbon credits

Much is still to be developed in Australia before there is a well-structured and responsive market for trading carbon credits, compared to the European Union which has had a publicly-available carbon market indicator since early 2003. This indicator tracks recent trading (currently the indicator is about AU$10 t^{-1}

CO_2; *Carbon Trader* 6 August 2004, see www.pointcarbon.com). Despite the early optimism in the potential for carbon trading, the Australian Stock Exchange (Sydney) suspended its interest in such a market mid-2000. Also, even the most optimistic forecasters are careful to point out that markets for environmental services, such as carbon credits, should be viewed only as an adjunct to the more conventional markets for farm forestry (i.e. timber) and other benefits such as provision of shade and shelter for conventional grazing and cropping enterprises.

In terms of landholders establishing farm forests and wanting to sell the carbon sequestered by their trees, small-scale growers (<100 ha) may have to aggregate their resource with others to achieve a reasonable economy of scale. Some analysts believe that a minimum of 1000 ha of forest may be required before carbon trading will be warranted, as growers will have to deduct the costs of verification and sale. Cost-effective methods of carbon accounting and verification are still being developed.

In favour of small-scale growers being able to benefit from carbon trading, Australia now has an established regional network of tree-growers' marketing cooperatives, with a cooperative in most of the major forestry regions. Adding further strength to this network is the marketing cooperation between some cooperatives. However, not all farmers are familiar or comfortable with trading through a cooperative, and ultimately cooperatives face financial challenges similar to those of other businesses. Alternatively, a number of growers could commission a broker to coordinate and negotiate on their behalf, or simply sell their carbon credits to a neighbouring large-scale grower.

Nonetheless, economic logic suggests that the diverse nature of farm forestry and poor economies of scale will tend to work against small-growers (e.g. farmers) being able to derive much benefit from the trade in carbon credits. The costs of verification per hectare — especially with non-commodity species and unconventional silviculture in non-forestry regions — presumably will be higher than for industrial forestry.

While there is now an Australian Standard for Carbon Accounting (Standards Australia 2002), much research is still required to identify who is likely to pay for carbon emissions (people, regions, industries, government?) and who will receive financial returns for creation of carbon sinks (people, regions, industries, government?).

What role is there for government in a carbon market?

At this stage, farm forestry in non-forestry regions can sell some products on open commercial markets (e.g. timber), but relies heavily on government for establishing and developing the technology and critical mass for a viable industry. A blend of market forces (inherently dynamic) with government influence (a degree of stability) can be an uneasy mix, as illustrated by the wool industry that has only recently recovered from the massive stockpiles held for several years by the Australian Wool Corporation (underwritten with government funding) when there was a 'floor' price.

This situation could be difficult for farm forestry if it relies on several unrelated markets simultaneously for business viability. That is, timber markets may fluctuate over the 30–40 y period in which some trees are grown, thereby having a varying opportunity cost (i.e. commercial attractiveness) against the emerging 'service' markets (e.g. carbon, salinity and biodiversity credits). If the different markets become mutually exclusive in terms of establishment and silviculture, then presumably the most lucrative market will tend to have the greatest influence. Alternatively, aggregating a number of low-value markets (products and services) may provide an attractive forestry package for landholders.

It is difficult for government to support cost-sharing, taxation relief, research and development, and provide establishment grants, without adversely affecting the opportunity costs of alternate commercial industries within the region (e.g. by altering land prices), or the commercial comparative advantage of neighbouring regions (e.g. reducing the demand for cleared farmland to establish forestry in one region due to government-subsidised forestry in a neighbouring region). Again, in-depth assessment of the full (direct and indirect) implications of various government roles in a region's economy, and its neighbours', is required when appraising where and how to encourage widespread land-use change.

Of interest, Europe has reaffirmed its commitment to the concept of 'multi-functionality', where landholders are paid for a composite of agricultural produce, management of land and water resources, maintaining biodiversity, and contributing to a region's aesthetic qualities. Australia may also benefit from developing a holistic approach to rural land-use, rather than focusing on individual agricultural sectors.

Introduction of regulations to limit clearing of woodlands and native forests

Recent estimates indicate that clearing of native vegetation on private land, primarily for agriculture, is a major source of Australia's greenhouse gas emissions. The contribution is about 20% of Australia's 1990 level of emissions (AGO 1999, 2000). Legislated restrictions on clearing native vegetation will hinder one historical strategy used in Australia for improving farm viability — clearing 'unproductive' bush for expanding agricultural enterprises (e.g. cropping, grazing) or commercial forestry. However, unrestricted grazing may well cause the gradual decline in health of remnant vegetation by selective grazing of palatable plants, preventing regeneration of a wide range of plants, and introducing invasive weed species. Over time, this practice could lead to the loss — intentionally or unintentionally — of native vegetation and contribute to greenhouse gas emissions and reduce the capacity for sequestration.

Clearing restrictions — which exist in all States, although to varying degrees — are perceived by some farmers as a barrier to establishing and expanding high-value farm operations, such as growing rice, cotton and wine grapes. Land and Water Australia continues to fund research into various technical and socio-economic aspects of management of native vegetation on private land (Binning and Young 1999; Cary and Williams 2000; Hamilton *et al*. 2000).

Also worthy of consideration are the decision-making processes that determine plantation location, design, silviculture and harvesting used in commercial forestry and the effect of plantation operations on net greenhouse gas emissions (CRCGA 2000).

Potential social research to support land-use change

There are calls for a more comprehensive science base to underpin our understanding of the impacts of climate change (AGO 2003). In relation to increasing our knowledge of the social implications of land-use change, there needs to be:

- greater understanding of the social and economic heterogeneity amongst Australian farmers
- increased analysis of the various scenarios for land-use change, and the implications for individual landholders, geographical communities and industry sectors, and
- in-depth exploration with target audiences to identify the greenhouse-gas-reducing strategies that are most desirable and feasible.

Table 1 outlines some of the potential areas for social research that could be explored.

Conclusion

Although there is growing support, both within Australia and internationally, for substantial changes to the way people manage rural land, it is not clear how and where this change should occur to reduce net greenhouse gas emissions. Greenhouse gas abatement is increasingly seen as a reason for re-defining agriculture and forestry practices in Australia in an attempt to meet international targets agreed to under the Kyoto Protocol. While considerable investment has been made in complex science to explain the processes and implications of increasing greenhouse gas emissions, there appears to have been comparatively little effort to understand the social dimension of the changes expected of rural landholders.

In broad terms, if a considerable change in land-use is required to reduce greenhouse gas emissions, then the social implications of the nature, scale and rate of change expected of individual landholders, geographical communities and industry sectors (e g. the dairy industry) need to be fully explored. As discussed above, many farming families do not have the social and economic capacity to make widespread changes to their current farming practices, even if alternative practices are highly desirable. Furthermore, there is great variation in the extent to which individual farming families, regional communities and rural sectors have feasible options to reduce greenhouse gas emissions — so requiring careful consideration of how land-use change to avoid increasing existing disparities.

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Table 1. Potential social research to support land-use change

1. With various groups of rural landholders, explore and identify the important factors in their capacity and willingness to make changes to reduce greenhouse gas (GHG) emissions. Explore the most effective GHG-reducing strategies (in terms of cost-efficiency, feasibility, adoption); then explore these options with focus groups drawn from the various groups of landholders. Explore the decision-making processes and motivations of various groups of landholders which would lead to voluntary change.

2. Evaluate the social implications for individuals, communities and land-use sectors of various scenarios, including:
   - continue current land-use,
   - undertake voluntary change, and
   - undertake voluntary and regulated change.

   Explore the distribution of the benefits and costs of the various scenarios with different social groups.

3. Develop an ‘atlas of change’ that illustrates the extent to which GHG-reducing strategies are socially desirable and feasible across different agro-ecological zones and with different communities (e.g. wheat-wool dependent communities, rural Aboriginal communities). This will help to identify where some landholders are willing and able to undertake voluntary land-use changes.

4. Develop the social capacity of regional communities (e.g. critical analysis of information, strategic planning, community leadership and cohesion, co-learning practices), so they can explore land-use changes that would favour net reductions in GHG emissions.

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Short communication

Does logging favour bellbirds and promote tree decline?

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Summary

Bellbirds are increasing in south-eastern Australia, mainly in unlogged and unburnt forests. Some evidence, recently provided to support the hypothesis that logging favours bellbirds and promotes eucalypt decline, is unconvincing.

Keywords: forest decline; logging effects; birds; *Manorina melanophrys*; Psyllidae; *Eucalyptus*; Australia

Introduction

Eucalypt decline is widespread in forests and rural lands throughout temperate Australia (e.g. Jurskis 2004a). A wide range of causes has been proposed, including salt, climatic perturbations and a variety of pests, pathogens and parasites (e.g. Jurskis and Turner 2002; Jurskis 2004a). Psyllids and bellbirds are often associated with forest decline in south-eastern Australia (e.g. Stone 1999). Decline involving bellbirds has been portrayed as a disease of complex aetiology (e.g. Stone 1999; Old 2000), but this is essentially an elaboration of the 'germ theory' (Manion and Lachance 1992) that 'infection' by a single 'pathogen' kills the trees.

Stone (1999) suggested that selective logging, without effective overstorey regeneration, encouraged dense understorey development, and that dense understoreys are colonised by bellbirds, *Manorina melanophrys*, because they provide nesting sites. Bellbirds then trigger forest decline because they interfere with predators that would otherwise 'regulate' folivorous insects (Stone 1999). This is an elaborate example of the germ theory because repeated defoliation by insects is considered to be the cause of decline, whilst invasion by bellbirds is considered to be the cause of the insect outbreaks.

On the other hand, it has been suggested that psyllids and bellbirds are but two of a much wider range of 'predators' that respond to increased food resources provided by declining trees (Jurskis and Turner 2002; Jurskis 2004a,b). This accords with a general ecological principle that predators do not regulate their prey, but are limited by the abundance and quality of their prey (White 1993). The principle applies equally to herbivores that attack trees and to predators that attack herbivores (White 2004). It directly contradicts the germ theory. Nevertheless, there is continuing debate over whether populations are limited from below or regulated from above (e.g. White 2001) and whether pests initiate or respond to tree decline (e.g. Lowman and Heatwole 1992; Manion and Lachance 1992).

Kavanagh and Stanton (2003) monitored bird populations over 22 y following logging of alternate coupes near Eden. They claimed to have found evidence that supported Stone's (1999) hypothesis. This article examines their evidence in a wider context and argues that it is not convincing.

The study site

The study area was dominated by dry forest of silvertop ash, *Eucalyptus sieberi*, blue-leaved stringybark, *E. agglomerata*, and white stringybark, *E. globoidea* (Kavanagh and Stanton 2003). There were a few small areas of moist forest containing gully peppermint, *E. smithii*, and monkey gum, *E. cypellocarpa*, in the heads of gullies. Kavanagh and Stanton reported an increase in bellbird populations in parts of the study area 22 y after intensive logging, and suggested that this observation supported Stone's (1999) hypothesis. However, the dynamics of the bellbird population in comparison to the dynamics of the understorey did not fit Stone's (1999) model.

Four years after logging, there was a dense layer of shrubs under a regenerating eucalypt canopy (Kavanagh and Stanton 2003). Although this vegetation favoured other insectivorous birds that inhabit dense shrubbery, bellbirds were rare in both logged and unlogged coupes, and were still rare 13 y after logging (Kavanagh and Stanton 2003). The shrubby understorey in the logged coupes thinned out over time, and after 22 y the regenerating eucalypt canopy had almost reached its full height (Kavanagh and Stanton 2003). Bellbirds were then numerous only in the heads of moist gullies in two of the seven logged coupes that were examined (Kavanagh and Stanton 2003).

Bellbirds and tree decline

Kavanagh and Stanton (2003) stated that there were no signs of eucalypt decline in their study area, and implied that the increase in bellbirds could not be a result of increased food provided by outbreaks of pests in declining trees (e.g. White 1993). However, their study did not assess the health of the trees. Three years after their final survey, I observed dead and declining gully peppermint near their sample sites in the two logged coupes where they had reported high numbers of bellbirds. Decline had evidently commenced in the gully peppermint stands when Kavanagh and Stanton found increased numbers of bellbirds, because the process from initial thinning of the crown through to complete death normally takes several years (e.g. Jurskis and Turner 2002; Jurskis 2004b). In the early stages, declining trees often have dense crowns of epicormic foliage (e.g. Stone 1999), and symptoms are not evident to many observers (e.g. Manion 1991).

When I observed the tree decline, logging had been completed in the previously unlogged coupes. There were no bellbirds in either the 25-y-old regrowth or the newly-logged coupes. Bellbirds had evidently deserted the area during the second (alternate coupe) logging operation. Trees were still declining 3 y after bellbirds had left. This was not consistent with Stone's (1999) hypothesis that colonisation by bellbirds triggers forest decline. However, it was consistent with the observation of Clarke and Schedvin (1999) that trees in a declining unlogged forest continued to decline after bellbirds were deliberately removed.

Bellbirds typically occupy densely shrubbed gullies, usually near water (Anon. 1993). Logging is generally excluded from these areas because they are designated as streamside reserves, filter strips and buffers. In the early 1980s, bellbirds in the Eden region were associated with tall moist forests that were not subject to logging. For example, Recher *et al*. (1985) found bellbirds only in tall unlogged forests along creeks. They found no bellbirds in drier open forests, whether logged or unlogged. Smith (1985) found bellbirds at 70% of rainforest (unlogged) survey sites and 40% of unlogged gully peppermint sites, compared to 30% of sites that had been logged 9–13 y earlier, and 20% of unlogged woollybutt (*E. longifolia*) ridge sites. No bellbirds were found on ridges that had been logged 9–13 y earlier.

Since the 1980s more undisturbed forest (where both logging and prescribed burning are excluded) has been retained in drainage lines (Kavanagh and Stanton 2003). Concurrently, forest decline and bellbird colonies have been expanding (Jurskis and Turner 2002; Jaggers 2004; Jurskis 2004b). However, forest decline and bellbirds are mostly absent from even-aged regrowth stands established by intensive logging and wildfires over the past three decades (Jaggers 2004). The declining trees in the moist gully sites where Kavanagh and Stanton had found high numbers of bellbirds were mostly trees that had been retained in logging, together with coppice regrowth with root systems that were much older than the declining crowns.

The dry type of forest that dominates the area monitored by Kavanagh and Stanton is generally unsuitable for bellbirds. Their surveys could not test the impact of logging on bellbirds, because the number and distribution of bellbirds before the initial logging operation was not known and the logging treatments were not evenly distributed within the small part of the study area containing habitat suitable for bellbirds.

Although Kavanagh and Stanton (2003) found a statistical difference between numbers of bellbirds in logged and unlogged coupes after 22 y, this may have reflected the distribution of bellbirds in the study area before logging, and undoubtedly reflected the distribution of some moist forest types in the study area. The 'increase' in bellbirds in moist gully sites 22 y after the initial alternate-coupe logging may have been a recovery to prelogging levels. Bellbirds deserted the area after the second logging event in 2001. In a nearby study area, bellbirds declined in a coupe that was logged in 1988, before recovering to prelogging levels about six years later and continuing to increase thereafter. Meanwhile, bellbirds increased from a lower base in the adjoining unlogged coupe, and maintained consistently higher numbers than in the logged coupe (Forests NSW unpublished data).

In 1998, when Kavanagh and Stanton (2003) found high numbers of bellbirds in some moist gully sites, trees were declining and bellbird colonies were already established in most large unlogged creek reserves around their study area, as well as in nearby unlogged coupes containing some moist forest types (Jurskis and Turner 2002; Jaggers 2004). Forest decline together with increasing bellbird populations across an increasing range have been widely reported in eastern Australia, often at unlogged and unburnt sites (e.g. Clarke and Schedvin 1999; Old 2000; Higgins *et al.* 2001; Martin *et al.* 2001; Jurskis and Turner 2002; Jurskis *et al*. 2003; Billyard 2004; Jurskis 2004b; Smith 2004).

The role of fire

Exclusion of fire has been suggested as a cause in several cases of forest decline involving bellbirds. In other cases, where there has been no logging, and fire has been excluded for long periods, it has not been considered as a possible cause of environmental change. However, there is much evidence of environmental change, change in forest structure and eucalypt decline with fire exclusion (e.g. Jurskis *et al*. 2003).

Most of Kavanagh and Stanton's (2003) study area, including the small part occupied by moist gully heads and bellbirds, had not been burnt for at least 26 y when they found high numbers of bellbirds. The natural fire regime in this mostly dry forest entailed more frequent fires (Jurskis *et al*. 2003). Fire management is likely to influence both forest health and bellbird populations, but Kavanagh and Stanton (2003) did not consider it as a confounding factor when they interpreted their data on bellbirds. They also did not consider these data in the context of increasing bellbird populations in unlogged areas across eastern Australia.

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Development of a carbon accounting model (FullCAM Vers. 1.0) for the Australian continent

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Summary

Continental-scale carbon accounting capable of the spatial and temporal distinctions demanded by the Kyoto Protocol requires a modelled approach which integrates over space and time the effects of changing land use, land management and climate variability.

To assist in the development of Australia's National Carbon Accounting System (NCAS), the Australian Greenhouse Office has developed and calibrated an integrated suite of models relevant to Australian conditions for which data were available or could be generated for their application. These point-based models were then made operational within a GIS environment to enable application at a fine spatial (25 m) and temporal (monthly) resolution for the Australian continent.

This paper focuses on the FullCAM model, capable of carbon accounting in transitional (afforestation, reforestation and deforestation) and mixed (e.g. agroforestry) systems.

The FullCAM model can be run in a spatial mode which integrates information drawn from remotely-sensed land-cover change, modelled productivity surfaces, mapped resource inventories and other ancillary data to perform the various accounting procedures for Australia's NCAS.

This framework has been developed in parallel with a range of data collation, model calibration and verification activities across the continent. The framework provided by FullCAM has allowed highly specific and therefore targeted and cost-effective model calibration and verification activities. FullCAM, as the analytic model for Australia's NCAS, will continue to be refined within the established framework.

Keywords: carbon; carbon cycle; carbon sequestration; models; accounting; inventories; Australia

Introduction

A National Carbon Accounting System (NCAS) has been established by the Australian Government to provide a complete carbon accounting and projection capability for land-based (agricultural and forestry) activities.

Early in the development of the NCAS it was recognised that carbon accounting at both continental and project scales would have to rely on the collation and synthesis of resource information and the calibration and verification of a series of models. The vast and heterogenous land areas in Australia under extensive forest and agricultural management demand an approach founded on modelling. An approach based purely on measurements (inventory and monitoring) is not practical given these conditions and the spatial (maximum 1 ha land unit) and temporal (annual) carbon accounting requirements of both the United Nations Framework Convention on Climate Change, and the Kyoto Protocol to the Convention (Climate Change Secretariat 1997). Following the development of an Excel-based forest carbon accounting model (CAMFor), a linked model for forest and agricultural systems (known as FullCAM) has also been developed. It integrates the CAMFor and CAMAg-based routines into a single (C^{++} code) model capable of carbon accounting in transitional (afforestation, reforestation and deforestation) and mixed (e.g. agroforestry) systems. The fine spatial and temporal resolution modelling capability provided by FullCAM is fundamental to Australia's ability to respond to these accounting requirements at both national and project scales.

This paper is the first of a series of three in this issue of *Australian Forestry*. It provides a description of the first operational version (1.0) of the FullCAM carbon accounting model. The other papers in the series:

(i) provide a detailed overview of the site biomass-productivity-based method developed for continental biomass stock and stock change, and
(ii) apply the model to account for carbon in the post-1990 national plantation estate, using stem-volume-based inventory approaches.

An overall system framework (Richards 2001) was developed to guide the development of data gathering and analytic projects and programs which could then be integrated using spatial modelling approaches. Various models were selected, calibrated and verified through these projects and programs. A range of related projects was undertaken to identify, collate and synthesise the additional data needed to operate the models continent-wide at a fine resolution.

The models were integrated to provide an activity-driven carbon accounting model (FullCAM) capable of dealing with multiple carbon pools for the NCAS. FullCAM is an integrated compendium model and accounting tool. It has components that deal with the biological and management processes that affect carbon pools and the transfers for forest, agricultural, transitional (afforestation, reforestation) and mixed (e.g. agroforestry) systems. Multiple agricultural and forest species can be accounted for through time via a range of parameterised default species tables. Likewise, data describing the range of land-use practices and soils parameters are provided via default tables within the model. These default tables were constructed specifically for the NCAS development of FullCAM through a nationwide review program.

The models that comprise FullCAM are: the physiological growth model for forests, 3PG (Landsberg and Waring 1997; Coops *et al*. 1998, 2001; Landsberg *et al*. 2001); the carbon accounting model for forests (CAMFor) developed by the Australian Greenhouse Office (AGO), (Richards and Evans 2000a); the carbon accounting model for cropping and grazing systems (CAMAg) (Richards and Evans 2000b); the microbial decomposition model GENDEC (Moorhead and Reynolds 1991; Moorhead *et al.* 1999); and the Rothamsted Soil Carbon Model (Roth C) (Jenkinson *et al.* 1987, 1991).

These models have been independently developed for the purposes of:

- the prediction of growth in trees (3PG);
- the determination of rates of decomposition of litter (GENDEC); and
- soil carbon change in agriculture and forest activities (Roth C).

CAMFor and CAMAg are carbon accounting tools that are able to apply management effects resulting from fire, harvest, cropping and grazing to externally-generated growth and decomposition rates.

In preparing each model for integration into FullCAM, each (except for CAMAg, the only model which cannot be independently implemented as it is linked to the Roth C model) was translated to a common Microsoft Excel workbook format. The Excel workbooks used only sheet-based formula. No ‘macros’ or other code were applied. This provided a consistent and transparent model platform from which to review and integrate the various models. Having a consistent structure and format for the models allowed for the independent calibration of various models (Paul *et al.* 2003a,b) while providing for ease of later integration. The transparency of the development process also facilitates detailed review.

The integration of the models serves two primary goals. The first is to provide for complete carbon accounting for a particular area of land. This includes all carbon pools and transfers between pools to ensure that there is no double counting or omissions in accounting. Potentially, this could occur if any of the primary carbon pools (in soil, biomass or litter) were considered independently. The second is to provide the capacity to run the model continentally as a fine resolution, grid-based spatial, multi-temporal application. A single model is efficient for addressing the requisite large input data sets in a spatial context.

Model evaluation and selection

The need to develop an integrated model was highlighted during the International Review of the NCAS Implementation Plan for estimating carbon levels for the 1990 baseline (AGO 2000a,b). A key review recommendation was to take a holistic approach, with modelling and measurement considering all carbon pools and transfers between them.

Other recommendations from the review which had direct implications for the development of the NCAS, and therefore FullCAM, were:

- the adoption, within the NCAS suite of tools, of a generic and widely applicable physiological tree growth model;
- the adoption of a microbial litter decomposition model, with a direct suggestion to consider the GENDEC model of Moorhead *et al*. (1999); and
- support for the calibration of the Roth C soil carbon model for Australian conditions.

The initial selection and further development of the models for integration into FullCAM arose from early analysis carried out in developing the system framework for the NCAS. Various strategies for data accumulation and assimilation into models capable of continental and project-scale carbon accounting (largely directed at satisfying the requirements of the Kyoto Protocol) were developed. Detailed specifications were prepared to guide the fundamental data collection, research program and model calibration.

CAMFor (carbon accounting model for forests) (Richards and Evans 2000a) was developed within the NCAS to provide capacity for both project and continental-scale accounting. CAMFor is an Excel-based model which has its conceptual foundations in the CO_2 Fix model of Mohren and Goldewijk (1990).

CAMAg (carbon accounting model for agriculture) (Richards and Evans 2000b) performs similar functions to CAMFor, but unlike CAMFor it was developed with direct integration of the Roth C model.

Except for CAMAg, which was programmed directly in C-code computer language, models were translated from source code into a Microsoft Excel platform. The integrity of each of the original models was maintained during this initial translation. The translation process also allowed for the development of consistent naming conventions, methods and approaches which were transparent and readily reviewed. The replication of the models in their new format could be tested through comparison of results between original and derived models using identical model parameters.

Each component model within the FullCAM model is capable of being used independently, and linkages between component models are available in a variety of configurations (32 in all). This flexibility has encouraged wide use and application of FullCAM, providing further opportunity for independent model testing and development.

Model development

When there was confidence that the models were yielding the same results as the source code versions, the Excel models were fully documented and returned to the original authors or host organisations for checking and commentary. Modifications were subsequently made to improve code efficiency (improving computational speed and resource use), in recognition of the diverse biophysical conditions in Australia, and to provide spatially explicit, multi-temporal and multiple species implementation of the model. The integration to a single application of the various sub-models was initially undertaken in Excel. This provided a transparent test version of the proposed application.

The component models are being independently calibrated (Paul *et al.* 2003a,b; Skjemstad and Spouncer 2003) for the NCAS through a variety of programs, which are largely focussed on the development of the 1990 baseline (an estimate of the emissions of greenhouse gases in 1990) for the Land Use Change and Forestry activities under the Kyoto Protocol. This activity involves considerable investment in the calibration of each of the models for the range of conditions and management practices present throughout Australia. Over a 2–3 y period, the total investment in data collection and synthesis, and further development of understanding of biological processes required for model calibration was in the order of A$9M.

Model calibration includes collating a series of previous (quality audited) site measurements, and conducting additional field work and laboratory analyses. Independent data sets are maintained for model calibration and verification. The application of calibrated models in the spatial version of FullCAM will rely on interpolation across a range of spatially-continuous layers of input data. These include data such as those on climate and soil type.

Model description

A brief description of each model, modifications made to the original models and supporting fundamental information follow.

3PG (physiological growth model)

The version of 3PG adopted is that described as Version 3-PGpjs 1.0 (Sands 2000) (http://www.ffp.csiro.au/fap/3pg/).

In its original form, this is an Excel version of the model supported by Visual Basic macros. This was translated into a consistent sheet-based and formula-driven (no macros or other code) model. Subsequent changes were made to this model to enable spatially explicit application while still reflecting the development of the previous version by Coops and Waring (2000) and Landsberg and Kesteven (2002).

3PG is a monthly time-step model based on the calculation of net primary productivity (NPP) via estimation of the photosynthetically-active radiation absorbed by plant canopies (APAR). APAR is estimated using leaf area index (LAI) and incoming shortwave radiation. A conversion factor is used to convert APAR to NPP. Modifiers related to temperature, water availability, nutrition and atmospheric vapour pressure deficit are used to reflect non-optimum growth conditions. The principal task to implement this model spatially was to compile the fundamental spatial input data. This entailed:

- development of a slope- and aspect-corrected solar radiation (direct and diffuse) surface at a resolution of a 250 m grid, using the Digital Elevation Model (DEM) of AUSLIG – Geodata 9 second DEM (version 2);
- provision of access by CSIRO Land and Water to their Fertility and Soil Moisture Continental Surfaces (McKenzie *et al.* 2000);
- derivation of soil surfaces from the Atlas of Australian Soils (Northcote *et al*. 1960–1968);
- using the ANUCLIM software package (McMahon *et al*. 1995) to derive rainfall, temperature and evaporation surfaces;
- development of a frost (number of frost days per month) surface by the NCAS; and
- derivation of a Normalised Difference Vegetation Index (NDVI) 10-year average (1981–1990).

CAMFor (carbon accounting model for forests)

CAMFor has its origins in the CO_2 Fix model of Mohren and Goldewijk (1990). The published Fortran code for this model was converted to an Excel spreadsheet (sheet based, formula driven) format as reported in Richards and Evans (2000a). A series of modifications was made to the original model including:

- the introduction of an inert soil carbon pool, in recognition of the nature of the carbon in Australian mineral soils (the high charcoal content and the potential long-term protection of fine organic matter through encapsulation and absorption by clays);
- the addition to the model of a fire simulation capacity to deal with stand-replacing and/or regenerating fires, being either low-intensity fires on the forest floor largely removing litter, or crown fires affecting the whole tree;
- the structures and lifecycles within the wood product pool were modified to reflect Australian data (Jaakko Pöyry 1999, 2000);
- greater resolution was added to the recognised components of standing trees, separating coarse and fine roots, branch and leaf material;
- the potential to override the soil carbon model component by directly entering either field data or externally modelled inputs; and
- an added capacity to use, as a primary data input, above-ground mass increment as an alternative to stem volume increment.

Within FullCAM, the CAMFor sub-component (see http://www.greenhouse.gov.au/ncas/publications/index.html) can take its growth information from any one of four sources:

- net primary productivity (NPP) derived from 3PG with feedback from management actions (thinnings, etc.) specified in CAMFor;
- information entered from external models;
- measures of either above-ground mass increment or stem volume increment; or
- a 3PG-derived forest productivity index applied to a simple growth formula.

Material entering the debris pool (above-ground coarse and fine litter) and the decay pool (dead root material) is accounted in either a decomposable or a resistant fraction, with the potential to apply separate decomposition rates to each.

A series of empirical defaults for plantation forests were developed for CAMFor using the growth rates and management descriptions drawn from the work of Turner and James (1997). Turner and James (2002) converted estimates of wood flow for typical silvicultural regimes, growth rates and harvest rates — prepared through survey of forest growers for the National Forest Inventory (NFI) — to standing volumes and volume increments. Wood densities are available from the work of Ilic *et al.* (2000), biomass carbon contents from Gifford (2000a,b) and decomposition rates from Mackensen and Bauhus (1999).

The information flowing from 3PG to CAMFor is the total NPP, as reflected in whole-tree productivity/growth. Rules for the allocation to various tree components and for the turnover rates that will affect the standing mass increment at any one time (change in mass as opposed to total productivity) are specified within a CAMFor table.

Neither CAMFor nor 3PG (in this form) deal with a number of stems, but work on proportional change to mass per unit area. Thinning activities, such as harvest or fire which are specified in CAMFor, are treated as a proportional decrease of biomass and are reflected as an equivalent proportional decrease in canopy cover within 3PG.

CAMAg (carbon accounting model for agriculture)

Within FullCAM, CAMAg (see http://www.greenhouse.gov.au/ncas/publications/index.html) serves the same role for cropping and grazing systems as CAMFor does for forests. The CAMAg model reflects the effects of management on carbon accumulation, and allocates masses to various product pools within plants and to decomposable and resistant organic residues. Yields may be entered in the model in a variety of ways including above-ground, total or product mass, along with turnover rates above and below ground.

With both CAMFor and CAMAg embedded within FullCAM, it is possible to represent transitional afforestation, reforestation and deforestation (change at one site) or a mix of agricultural and forest systems (discrete activities at separate sites). Under afforestation and reforestation there is a gradual change from the characteristics of the original pasture or cropping system, with the mass of organic matter derived from those systems decomposing and decreasing with declining input. For deforestation the same applies, but with a large residual of decomposing woody material being the primary change remaining within CAMFor.

Within FullCAM, CAMFor and CAMAg can be proportionally represented (as under afforestation, reforestation and deforestation) according to the relative proportions of canopy cover for each of the woody (CAMFor) and non-woody (CAMAg) categories. This also provides capacity for modelling ongoing mixed systems such as agroforestry.

GENDEC (general decomposition model)

GENDEC is a microbial decomposition model, developed by Moorhead *et al.* (1999), which considers the environmental and biological drivers of microbial activity, namely temperature, moisture and substrate quality.

GENDEC addresses both carbon and nitrogen, using nitrogen-to-carbon ratios and available nitrogen as factors which may constrain the rate of microbial activity. When GENDEC is brought into operation within FullCAM, it can replace the empirical decomposition routines which deal with the resistant decomposable fraction of each above-ground litter component embedded within either or both the CAMFor and CAMAg components of the model.

The effect of invertebrate activities on the breakdown of debris is addressed within FullCAM, whereby the microbial decomposition of GENDEC is paralleled by a breakdown factor which can account for losses in above-ground litter due to processes such as macroinvertebrate activity prior to material reaching a soil interface where decomposition is most active. Root material is incorporated directly into the soil carbon pools, and therefore is subject to the decomposition activities of the Roth C component of the FullCAM model.

Roth C (soil carbon model)

The Rothamsted soil carbon (Roth C) model (http://www.rothamsted.bbsrc.ac.uk/aen/carbon/rothc.htm) accepts pre-determined masses of plant (above-ground litter) residues which are then split into decomposable and resistant plant material. Required model inputs include the fractionation of soil carbon into various soil carbon pools, generally defined by classes of resistance to decomposition. Turnover rates for each fraction are determined by rainfall, temperature, ground cover and evaporation. The Roth C source code was made available to the NCAS in two versions, 26.3 and 26.5, and both have been incorporated in FullCAM. Version 26.3 is the recent 'release' version, while 26.5 is a developmental version yet to be fully tested.

It is recommended that, if calibration data are available, the Roth C model should be used in conjunction with CAMFor. It is a more widely calibrated and verified multiple-pool soil carbon model than simplistic soil carbon procedures implemented within CAMFor. As calibration data are more readily available for agricultural systems, Roth C has already been directly integrated into CAMAg. CAMAg must be operated in conjunction with the Roth C model.

Model integration

FullCAM was initially integrated on a Microsoft Excel developmental version of the forest component of FullCAM and linked with the Excel versions of the models 3PG, CAMFor, GENDEC and Roth C. The resultant developmental model (named GRC3) was used to test and refine the linkages between the models (Paul *et al.* 2001; Paul *et al.* 2003a,b). It formed a 10-Mb Excel workbook which could be used for developmental purposes, but was not a realistic option for general or routine application.

No equivalent developmental Excel version of CAMAg and its integration with the Excel GENDEC and RothC in the agricultural suite of models was created because the linkages in this integrated model would mirror those in the forest sector model being tested in GRC3. As the developmental work on linkages was not required specifically for the agricultural suite of models, and with the Excel-based models being unsuited to general application, a decision was taken to program the agricultural component of FullCAM

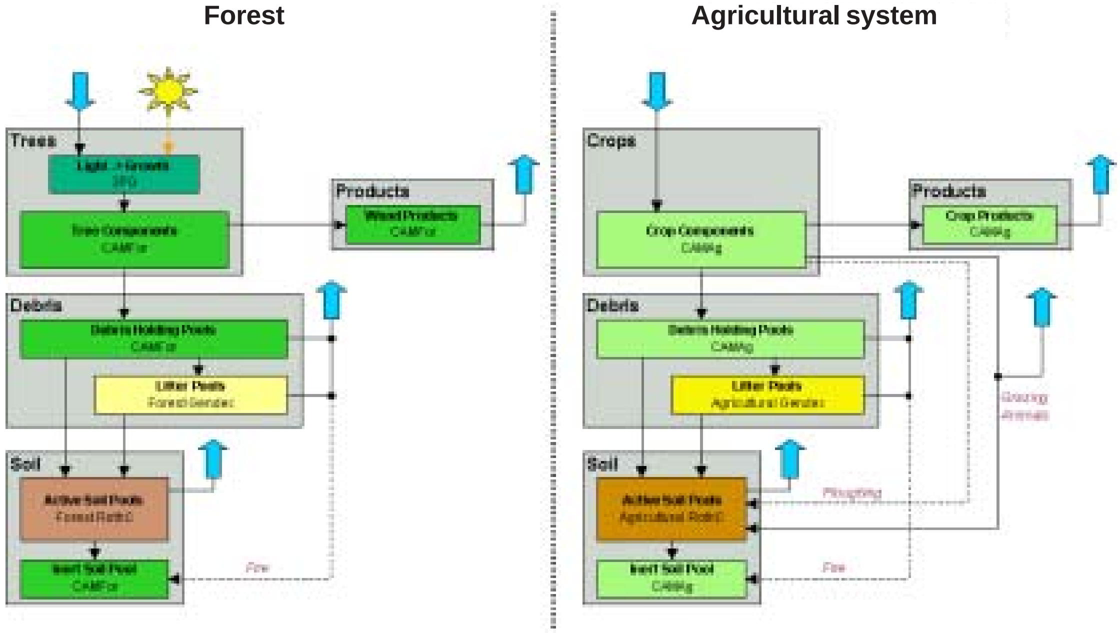

Figure 1. Overview of the FullCAM model

directly using the C++ computer language. This version is far more efficient and transportable (in size) than the Excel version, with run speeds capable of continental-scale application at fine spatial and temporal resolution.

The linkages between models are sequential, from growth estimation (3PG for forests only) to management (CAMFor and CAMAg), decomposition (GENDEC) and soils (Roth C).

The linkage from 3PG to CAMFor is achieved by inputting the total biomass increment from the 3PG output to the CAMFor biomass table. This material is allocated to various tree components (above- and below-ground) through the CAMFor mass distribution species default table.

CAMFor links to GENDEC through a transfer of live material to the above-ground litter pools, splitting the decomposable and resistant material described in CAMFor between the soluble, cellulose and lignin plant input pools of GENDEC. When operated in conjunction with GENDEC, the CAMFor breakdown rates for input material are applied to act as a 'flow' mechanism to introduce material to the GENDEC model. The above-ground litter pools of CAMFor thus act as holding pools for material which can then flow to the GENDEC pools. Below-ground material is treated independently of GENDEC and is either transferred directly to the resistant and decomposable plant material pools (RPM and DPM) of Roth C from CAMFor, or, if Roth C is not being implemented, given an empirical decay rate within the CAMFor 'Active' soils pools.

If CAMFor and Roth C are used (without GENDEC), the 'breakdown' rates in CAMFor are used to decompose above-ground litter (unless it ploughed in) into the Roth C humified organic matter (HUM), RPM and DPM below-ground pools (minus losses to the atmosphere). Root material is transferred to the Roth C DPM and RPM pools.

The interaction between CAMAg and GENDEC mirrors that of CAMFor and GENDEC. Again GENDEC operates only on the pool of above-ground litter.

The transfers of material when CAMAg and Roth C are run together (without GENDEC) are the same as for CAMFor to Roth C. Below-ground material (and above-ground material 'ploughed in') is dealt with in the DPM and RPM pools of Roth C.

Full descriptions of the sub-models that form the FullCAM model and of the process of standardising the programming (e.g. into a single program code version with consistent carbon pool structures and naming conventions) can be found in Richards (2001) at http://www.greenhouse.gov.au/ncas/publications/index.html.

Model calibration and testing

FullCAM is a mix of accounting tools and empirical and process modelling. Many of the options are at the discretion of the user and reflect management decisions, such as forest harvest and ploughing. A further set of required inputs, particularly in CAMFor and CAMAg, determine the empirical rates of transfer between pools or to the atmosphere. Unlike the 'process' elements of the model, these components need to be user-defined, based on rates determined from sources such as field trials, literature or third-party models. It is critical that appropriate empirical rates are used when applying the model.

The final components of the model are the process elements, generally contained within the 3PG, GENDEC and Roth C model components. The distinguishing feature of the process and empirical components is that the empirical rates are static in that they do not respond to changes in climate. Each of the process components of the model (3PG, GENDEC and Roth C) is dependent on inputs such as temperature and rainfall in various ways.

While the model is capable of being run at daily, weekly, monthly and annual time steps, the NCAS will generally operate the model at monthly time steps. The choice of time step for any operation will largely depend on the temporal variability of the system being modelled and the temporal resolution of the available data.

The early testing of FullCAM was carried out on GRC3, the developmental Excel version, providing maximum transparency and therefore an ability to track iterations of the spreadsheet formula. Another advantage was an ability to attach the @Risk add-on (Palisade 1997). Among other things, @Risk provides a capacity for sensitivity analyses within the Excel model, given specified correlations between the various input variables. Each specified output is assessed for its sensitivity to each input variable. Correlations between input variables can be specified and Monte Carlo analyses run to enable uncertainty analyses given specified variability. @Risk can also interact with the FullCAM code version and is being implemented within developers' versions of the model.

A range of activities are underway within the NCAS that provide required calibrations for the various components of the FullCAM model. Much of this activity was initiated upon selection of the various component models for external model calibration and verification programs. Each of these programs also provides for ongoing model testing and verification.

Conclusions

The adoption of a modelling approach to Australia's national carbon accounting has been a technically and administratively complex task, despite the prior existence of component sub-models calibrated for a range of situations. This approach links together remotely sensed, natural resource inventory, climate and management data with a set of process and accounting system models.

The modelling framework has been developed around a number of existing models, with new models and links created where needed. The development of FullCAM has provided the needed integration of these models for national application. The linkages between models and multi-temporal spatial data within a geographic information system (GIS) provides an enormous analytic capacity which cannot be achieved through the application of point-based models to regionally 'averaged' data. It removes many of the problems of scaling by application at a fine spatial and temporal resolution, and is well suited to the 'land-based' accounting required under the Kyoto Protocol.

FullCAM provides the overall framework that integrates the component models, and therefore the various programs providing input to the NCAS. Rigorous model testing and verification initiatives are ongoing within the individual supporting programs. The principal focus of the testing of FullCAM has been, and continues to be, on the linkages between the models. Testing undertaken on the GRC3 Excel beta-version of FullCAM provided confidence in the structure of the model being able to robustly manage flows between model components, while providing enormous flexibility in the nature of input data and in selection of models in any implementation. The linking of the FullCAM model to the @Risk uncertainty and sensitivity capacity provides for good-practice application and analytic rigour in both model testing and implementation. It also provides a transparent and understandable analysis of the uncertainty in any input variable for the model.

FullCAM provides modular capacity whereby models can be taken in or out of operation, but this capacity is constrained by the necessity to maintain the appropriateness of pool transfers. It is recommended that any calibration or verification be done on a chosen configuration (of 32 options) of FullCAM to avoid any possibility that inconsistencies in pool transfers could occur through changing model structure after its calibration in original form.

A comprehensive approach to carbon modelling and accounting required consideration of carbon budgets across the forest and agriculture sectors, including both the biomass and soil carbon pools. This allowed for alignment of program activities for the calibration of each component of the FullCAM model. The independent data collection and model calibration can be easily transferred into the calibration and verification of the FullCAM model in both its plot and spatial versions. This was made possible (both technically and administratively) by the development of the NCAS being undertaken wholly within the Australian Greenhouse Office, the lead Australian Government agency on greenhouse matters.

The vast and diverse land mass of Australia, with its great complexity and variability of management and climate, often subjected to broadscale natural phenomena such as drought and fire, has demanded a relatively complex (yet highly efficient) model framework in order to satisfy the Kyoto Protocol accounting guidelines. These guidelines require that the developed nations develop accounting systems capable of fine spatial and temporal distinction in response to a variety of land management activities. Australia is well placed to meet these requirements through the development of the FullCAM model linked to a comprehensive natural resource management GIS system.

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A continental biomass stock and stock change estimation approach for Australia

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Summary

To implement Australia's National Carbon Accounting System it is necessary to estimate biomass stock, continentally, and change in stock, at a sub-hectare spatial resolution. The approach developed to meet this requirement is a hybrid between GIS-based process modelling and empiricism.

Multi-temporal mapping of productivity was carried out using a variant of the 3PG (physiological principles predicting growth) model. Relationships were found between mapped productivity indices and measurements of biomass at maturity (i.e. long-term-undisturbed stands). This information was then used to interpolate maps of biomass potential.

Simple growth formulae were used to plot biomass accumulation, with the 'rate of approach to mature biomass' set by the age at which maximum current annual increment occurs and the predicted site plant productivity over time. The age of the forest stand was determined from disturbance events detected by twelve national coverages of Landsat MSS, TM and ETM+ remotely-sensed data collected between 1972 and 2002. Responses to thinning of existing forests are calculated using an adjustment of stand age concurrent with the intensity of the thinning event.

Keywords: carbon; carbon sequestration; models; accounting; inventories; area; remote sensing; forest management; productivity; growth rate; increment; thinning; Australia

Introduction

Australia's National Carbon Accounting System (NCAS) will provide a comprehensive carbon accounting capability for Australia to report on related international obligations, to support domestic policy development, and to monitor carbon stock change at fine resolution in support of project-level carbon accounting. Australia's international carbon accounting commitments include the United Nations Framework Convention on Climate Change and its Kyoto Protocol, and the Montreal Process.

To achieve this capability, the Commonwealth Government committed $12.5 million over five years (1998/99–2002/03) for development of the NCAS. The NCAS considers all forms of greenhouse gases and activities in both the agricultural and forestry sectors.

The decision to implement a comprehensive and integrated NCAS was based on the development of a critical mass of resource information and significant core capabilities that have broad applications. The most significant of these is coverage of Australia by twelve Landsat MSS (1972–1988) and TM/ETM+ (1988–2002) data sets. The pixel resolution of the data is 50 m for MSS and 25 m for TM/ETM+ (Furby 2001). Another core product was interpolated monthly climate maps of Australia for rainfall; evaporation; minimum, maximum and average temperature; and number of frost days per month. Slope and aspect-corrected 250 m resolution solar radiation measurements, direct and diffuse, were also developed (Landsberg and Kesteven 2001). Together these products provided the time-variable process-based inputs to the modelling activities of the NCAS.

A major objective of the NCAS is the measurement of change in carbon stocks: uptake and loss of carbon by biomass, litter and soil. In both agricultural and forestry land systems this requires estimation of tree biomass, including changes due to growth and loss from land clearing and forest harvest.

The specific issue addressed in this paper is the development of a model to estimate biomass stock and growth. The methods used in the FullCAM model to estimate continental carbon stocks and change for the NCAS are described. Richards (2001b) provides a broader account of the development of NCAS.

This paper is the second of a series of three in this issue of *Australian Forestry*. The other two papers in the series:

(i) describe the development of the integrated carbon accounting model FullCAM, and
(ii) apply the model to account for carbon in the post-1990 national plantation estate, using inventory approaches based on stem volume.

Methods

Method selection

Several possible methods were available to implement a national program to estimate biomass for the NCAS. These included direct estimation via a range of remote sensing techniques such as radar and lidar, field sampling such as stratified random or plot sampling (inventory approaches), and process modelling.

The main determinants of the choice of method were that:

1. measurement should be dynamic through time, and include estimates as far back as the early 1970s;
2. all forests (some 160 million ha of managed and unmanaged forests) should be included;
3. measurements should have a spatial resolution of less than one hectare and take account of biomass stock, disturbance history and growth at a corresponding scale; and
4. the land-based accounting should conform with the Kyoto Protocol requirement that qualifying land units are reported upon (i.e. the accounting of carbon stock changes and emissions relevant to each relevant land unit through time).

These criteria require a dynamic approach at a fine temporal and spatial scale. Conventional measurement (inventory) of Australia's forests at such a fine scale is, however, not feasible. There are also insufficient data to construct historic inventories. This means that measured (inventory) approaches alone are not a practical means of implementing the requirements of the United Nations Framework Convention on Climate Change and the Kyoto Protocol in Australia's circumstance.

The historic requirement (i.e. estimates back to the early 1970s) for forest disturbance data (land clearing, harvest, reforestation) meant that contemporary remote sensing techniques such as radar and lidar, which were not generally available until the early 1990s, could not be used. However, the optical instrument Landsat was available over this period, and could be used to identify canopy disturbance at a fine resolution, therefore providing the ability to determine forest age.

Under the circumstances, the available approaches were limited to the use of process or empirical growth modelling, supported by the identification of forest disturbance using Landsat data. Unfortunately the paucity of mensurational data for many non-commercial forest types (and supporting models to estimate total biomass from measured stem volume or basal area) meant that empirical growth modelling was not a feasible approach. The applicability of process-based growth models was also limited as none of the models was widely calibrated for the range of forest systems under consideration.

Continental biomass inventory

The available options for the design and implementation of a continental biomass inventory, given the available information, were developed via an expert workshop (CSIRO 2001a,b). The recommendation was to develop a hybrid approach using remote sensing (Landsat), and empirical and process models (see Richards 2001a,b).

CSIRO Forestry and Forest Products was engaged to compile a data-base of biomass measurement from published and unpublished studies, providing each had adequately reported methods, as needed to establish confidence in the robustness of the data. The data are representative of Australia's major forest types, ranging from savannahs to rainforest. The spatial distribution also covered most of Australia. The data compilation is available from the authors on request.

A key element of this approach is the use of Landsat data to provide fine-resolution data on disturbance history over a 30-y period, which in turn can be used to estimate stand age. The forest type disturbed is extracted by merging the disturbance history mapping and the vegetation mapping of the National Vegetation Information System prepared by the National Land and Water Resources Audit.

Index of biomass productivity

The hybridisation of empirical and process modelling to determine an index of productivity was achieved by using the monthly climate surfaces developed for the NCAS (Kesteven *et al.* 2004) in conjunction with CSIRO's national soil moisture holding capacity and fertility mapping (McKenzie *et al.* 2000), the nine second (250 m) Digital Elevation Mapping Version 2.0 (AUSLIG 2001), and Normalised Difference Vegetation Index (NDVI) data of the Environmental Resources Information Network (ERIN), to produce a relative index of productivity, both spatially and temporally. The monthly climate surfaces (Kesteven *et al.* 2004) were derived using the ANUCLIM software (McMahon *et al.* 1995) and Bureau of Meterology weather station data. The model used to develop the productivity mapping was a modified version of the 3PG model (Landsberg and Waring 1997; Coops *et al.* 1998; Coops and Waring 2001; Landsberg *et al.* 2001). The development of the productivity index mapping (Fig. 1) is reported in Landsberg and Kesteven (2001).

Results

Correlating biomass and productivity

The empiricism was introduced in relationships derived between productivity maps and available above-ground biomass measurements. The spatially-referenced data for sites with no reported recent disturbance were then plotted against calculated long-term average productivity. This regression considered biomass accumulated (with no known disturbance history) against the long-term average productivity of the site. The relationship between mass and productivity was then used to derive a map of potential site biomass at maturity (i.e. for long-term undisturbed stands).

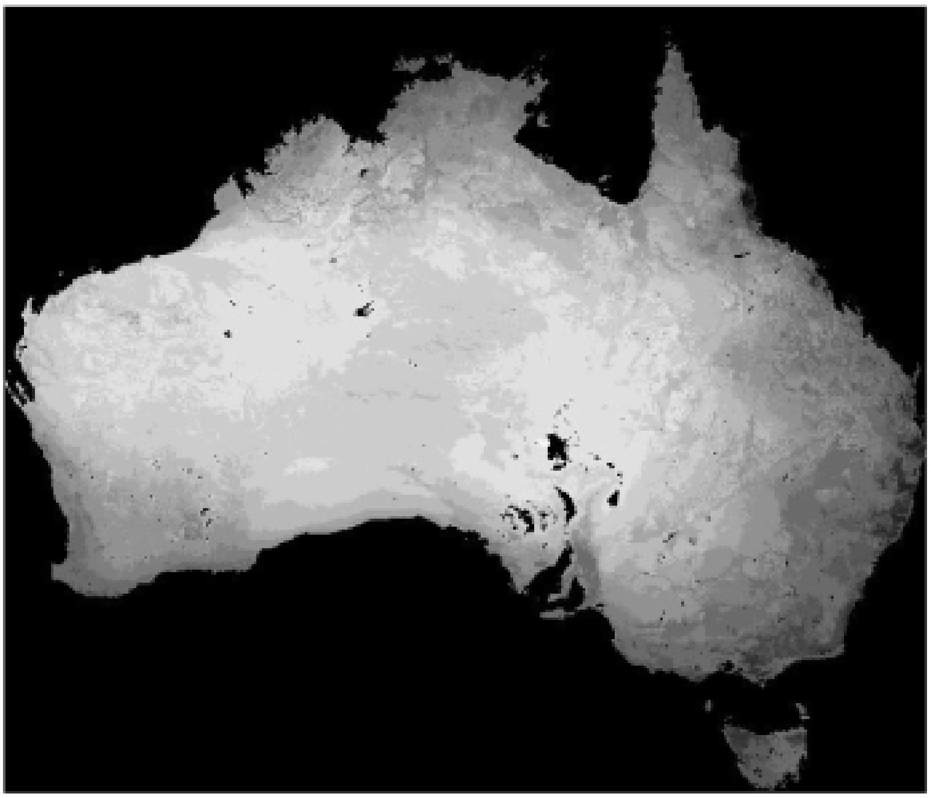
A linear regression found a significant correlation ($P < 0.01$, $r^2 = 0.68$) between long-term above-ground stand biomass (M) and long-term average productivity (P_{avg}). A square root transformation of both dependent and independent variables was required to meet assumptions of normality and homogeneity (Fig. 2):

$$M = (6.011 \times P^{1/2} - 5.291)^2 \qquad (1)$$

where P is the long-term average productivity index and M is the above-ground biomass in t dry matter ha^{-1}.

Other linear and non-linear regression models were tested to explore the relationship between mass and productivity, but none of these alternatives showed any marked improvement over (1) in error distribution or in root mean square error. The higher-order polynomial equations and logarithmic transformation also resulted in models that could not reasonably be extrapolated.

The regression approach has an advantage over a purely process-driven model which has been shown to generally over-predict site biomass since factors such as insect attack are not taken into account (Kurz *et al.* 1998). The potential (site) biomass estimate represents the biomass which growth will generally approach.



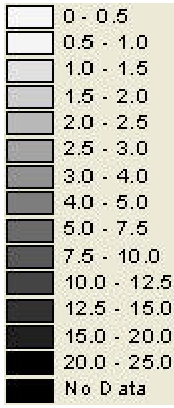


Figure 1. Estimated long-term average biomass productivity index for Australia

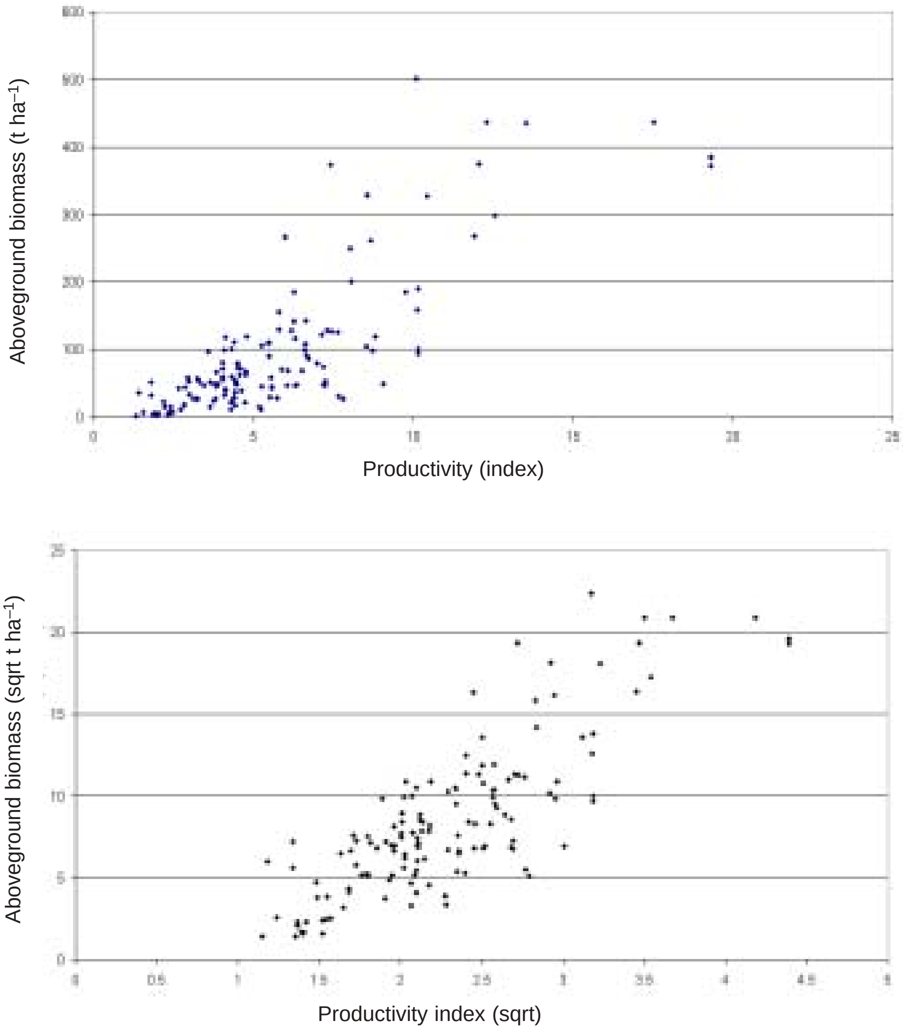


Figure 2. Plot of (a) raw biomass and productivity data and (b) square-root-transformed data

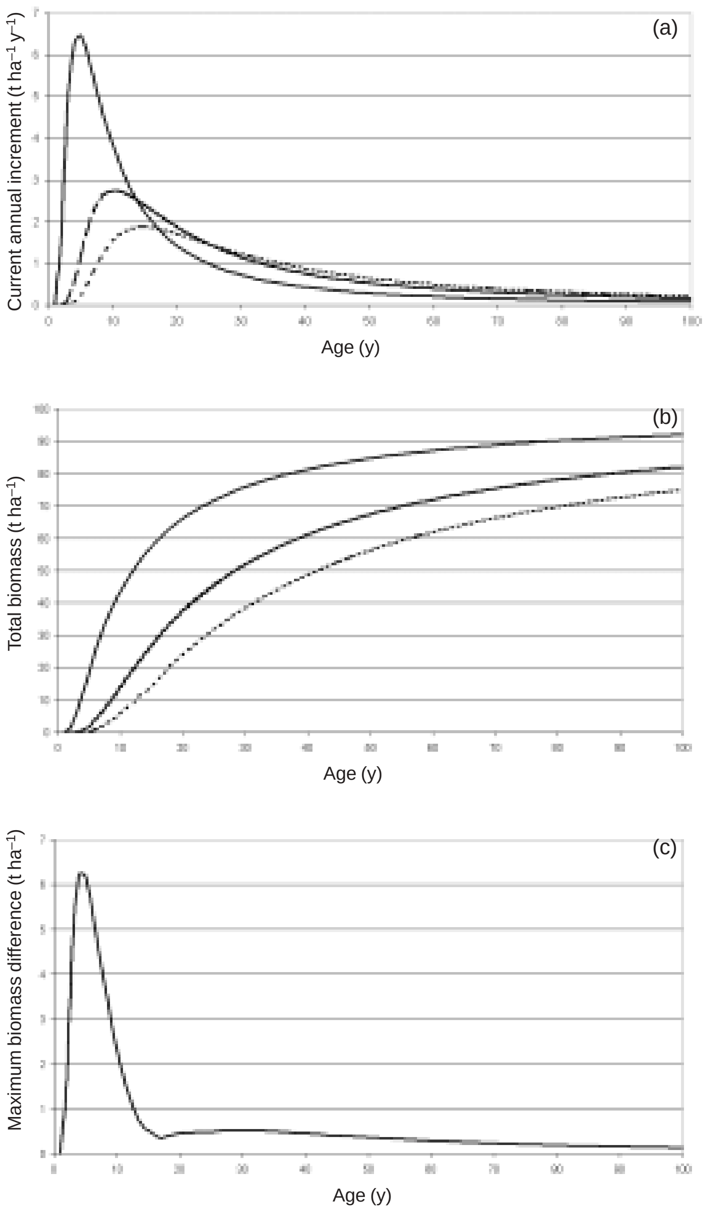


Figure 3. (a) Current annual increment (CAI), and (b) total biomass for varying k values and M = 100 t ha^{-1} (— max @ 5 y; - - - max @ 10 y; . . . max @ 15 y); and (c) difference in current annual growth (CAI) with age, for k set to maximise CAI at 5 and 15 y

Therefore, a mathematical model was developed to enable calculation of biomass and age and the rate at which the maximum biomass is approached.

Age-based stand growth can be expressed by equation (2),

$$M_A = M e^{-k/A}, \qquad (2)$$

where M_A is the predicted aboveground tree biomass (t ha^{-1}) at age A (y), M is the maximum long-term above-ground tree stand biomass; and k is an estimated constant that determines the rate of approach towards M.

Available data, such as those reported by West and Mattay (1993), suggest the age of maximum current annual increment (CAI) is approximately constant for many eucalypt species and independent of site productivity. The constant k is set to reflect this age of maximum CAI.

Given (1) and (2), the long-term average annual increment between A and $A+1$ years (I_A) for a stand can be estimated from the long-term average productivity (P):

$$I_A = (6.011 \times P^{1/2} - 5.291)^2 \times (e^{-k/A} - e^{-k/(A+1)}). \qquad (3)$$

However, as productivity in any given year (P_A) may vary around the average productivity (P) due to non-average weather or other factors, the average annual growth increment may be adjusted for the productivity in that year (P_A) as a ratio with the average productivity (P):

$$\bar{I}_A = I_A \times (P_A / P). \qquad (4)$$

Discussion

Fundamental to the implementation of the method is the existence of a robust relationship between biomass and site productivity. However, it was recognised that the use of a range of methods by independent researchers taking the site measures (many of whom applied models of allometry to independent variables such as basal area and tree height) would possibly result in a researcher-driven variability in the field measurements. This would inevitably weaken the relationship between biomass and productivity.

While there was little doubt that the relationship between site biomass and site productivity would exist, the robustness of the relationship in terms of the quality of fit and error distribution was considered to be good, given the variability likely to be embedded in the site estimates from the various research studies. Further site study should target the areas where productivity is high (Productivity Index greater than 15), to clarify the relationship at this extreme. It can be seen from Figure 1 that only a very small fraction of forests are of this high productivity class.

The derivation of a maximum potential (undisturbed) biomass is a straightforward application of (1) to the 250 m slope-and-aspect-corrected productivity index (Fig. 1). Monthly productivity maps at a 1 km resolution were also created for the period between 1970 and 2000. The monthly maps were summed to years and then averaged over the 30-y period to re-estimate the annual average biomass potential P in (1). This re-estimated long-term site potential (P_{avg}) is used in (4), instead of P, to maintain an average correction of 1 in the calculation of growth in particular years.

Age-related biomass and productivity

Varying the value of k for a given M in (2) so that the maximum CAI occurs from 5 to 15 y (Fig. 3a) shows how the CAIs become very similar after about age 20 y despite this wide range of k values (Fig. 3b). The maximum difference in annual growth appears to occur between ages 2 and 15 y (Fig. 3c). After about age 15 y, the maximum difference in annual growth is less than about 0.5 units y^{-1}, i.e. it is relatively insensitive to the value of k.

The application of this method to plantation systems would require the recalculation of M and k to reflect lowering the age of maximum CAI and increasing the potential maximum growth due to improved establishment techniques and genetic improvement of plant stock. This would entail reviewing and analysing annual growth data for various plantation types.

This modelled approach predicts the total above-ground biomass, but, by applying general or species-specific allometry, estimates of gross or even net volume would be possible. Field inventory for verifying or correcting these estimates would be much less demanding than the equivalent complete measurement of biomass or volume.

Conclusion

The use of a hybrid approach — both process-driven and empirical — has enabled development of a robust generalised method for determining forest biomass stocks and rates of forest growth for Australia. The generalised model performs well when compared to available data, although these are sparse for many forest types. The absence of any significant bias or pattern within the error distribution for forest type or parts of the biomass range indicates that the general model will provide satisfactory performance across the whole continent. The r^2 value of 0.68 for the linear regression between site productivity and above-ground biomass also suggests good performance, particularly given that the 'measured' data for above-ground biomass are derived from many sources and methods of data capture.

Within the NCAS FullCAM model the biomass productivity of a site (nationally at a 250 m grid resolution) is used to determine the site biomass potential. This potential is presumed to have been reached in undisturbed forest systems. In disturbed systems, as identified through the NCAS multi-temporal remote sensing program, the biomass potential sets the site's maximum stock that successive modelled growth increments will approach according to growth equation (2). Subsequent removal of all trees resets forest age to 0, while a thinning resets only the fraction thinned to age 0. Alternatively, the effects of release from competition and stimulation of growth in a stand after thinning can be simulated by reducing the average age of the stand.

Review of the residuals from lines of best fit that define the pivotal relationship of biomass to productivity indicate that more data are needed in the high-biomass forest types. The other priority is the determination of growth patterns of lower-productivity (generally non-commercial) forest types so that the age of maximum CAI can be determined more accurately. Few yield tables are available for these types of forests.

The method as applied has provided a biomass account with a high degree of spatial and temporal specificity. It takes account of key environmental and physiological factors, as well as long-term physical disturbance, in determining standing biomass. There is potential to test further applications of this modelled approach to plantation systems and to the estimation of wood product.

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A modelled carbon account for Australia's post-1990 plantation estate

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Summary

Australia's national carbon account for afforestation and reforestation activities qualifying under Article 3.3 of the Kyoto Protocol between 2008 and 2012 can be estimated using a carbon accounting model supported by a range of forest-related data. Using inventories of current plantation areas and projected expansion of the plantation estate, it is possible to project carbon sequestration in 36 known plantation management regimes to give an annual national account of net (sequestration minus emissions) carbon stock change.

Data for the modelling were provided through a range of studies undertaken for the development of the National Carbon Accounting System (NCAS). These included compendiums of available information on management regimes, plantation growth and yield, wood density, carbon contents and allocations to non-stem components of trees.

Future refinements of the modelling will include the extraction of a 'mask' of relevant afforestation and reforestation activities from the continental multi-temporal Landsat satellite coverages of Australia developed for the NCAS. Other improvements will include the use of the NCAS national annual 1 km grid productivity mapping to determine variability in growth associated with variability in climate and soil characteristics. Soil carbon modelling capability using the Roth C model will also be possible when the spatial mapping is complete and details of plantation areas can be merged with the relevant maps of soils and climate.

Keywords: carbon; carbon sequestration; models; accounting; inventories; remote sensing; forest plantations; forest management; area; projections; productivity; growth rate; increment; thinning; Australia

Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change introduces, via Article 3.3, a requirement to account for carbon stock change due to afforestation (establishment of forest on land that has not been forested for at least 50 y), reforestation (establishment of forest on land that was not forested in 1990) and deforestation (removal of forest, except for temporary destocking, since 1990). This paper is the third in a series of three in this issue of *Australian Forestry*. It provides for a description of methods used in the FullCAM model to estimate continental carbon stocks for the NCAS. The other two papers in the series:

(i) describe the development of the integrated carbon accounting model FullCAM, and
(ii) provide a detailed overview of the site biomass productivity-based method developed for estimating continental biomass stock and stock change.

Australia's national account for afforestation and reforestation will be largely delivered from the expanding commercial plantation estate, while the account for deforestation will be largely due to emissions from agricultural land clearing.

The Australian Government's capacity for current accounting and account projections has been developed in the initial phase of Australia's National Carbon Accounting System (NCAS). This initial phase included four principal sectors: remote sensing of land cover change, biomass estimation, soil carbon estimation, and system development. A brief synopsis of each of these programs follows.

Land cover change

Twelve continental coverages of Landsat MSS (50 m resolution, 1972–1988), Landsat TM (25 m, 1988–1998) and Landsat ETM+ (25 m, 2000–2002) were geographically co-registered and spectrally calibrated to provide a history of change in land cover at a fine resolution from 1972 to 2002 (Furby 2001a,b). Change was identified via an objective and automated thresholding procedure on a pixel-by-pixel (25 m) basis. These satellite 'change' data were then merged with the vegetation mapping contained in the National Vegetation Information System and other climate and resource maps (e.g. soils, rainfall). The analysis can also identify areas of afforestation and reforestation capable of being detected as change; that is, providing sufficient change in signal, within each 25 m pixel.

Biomass

Several data synthesis activities were performed for this program, including collation of published and unpublished literature on biomass estimation, partitioning of biomass into various tree elements, carbon contents of tree types and components, and wood density. Plantation growth (yield) data were calculated from the published wood yield estimates of the National Forest Inventory (NFI 1997a) by Turner and James (2001).

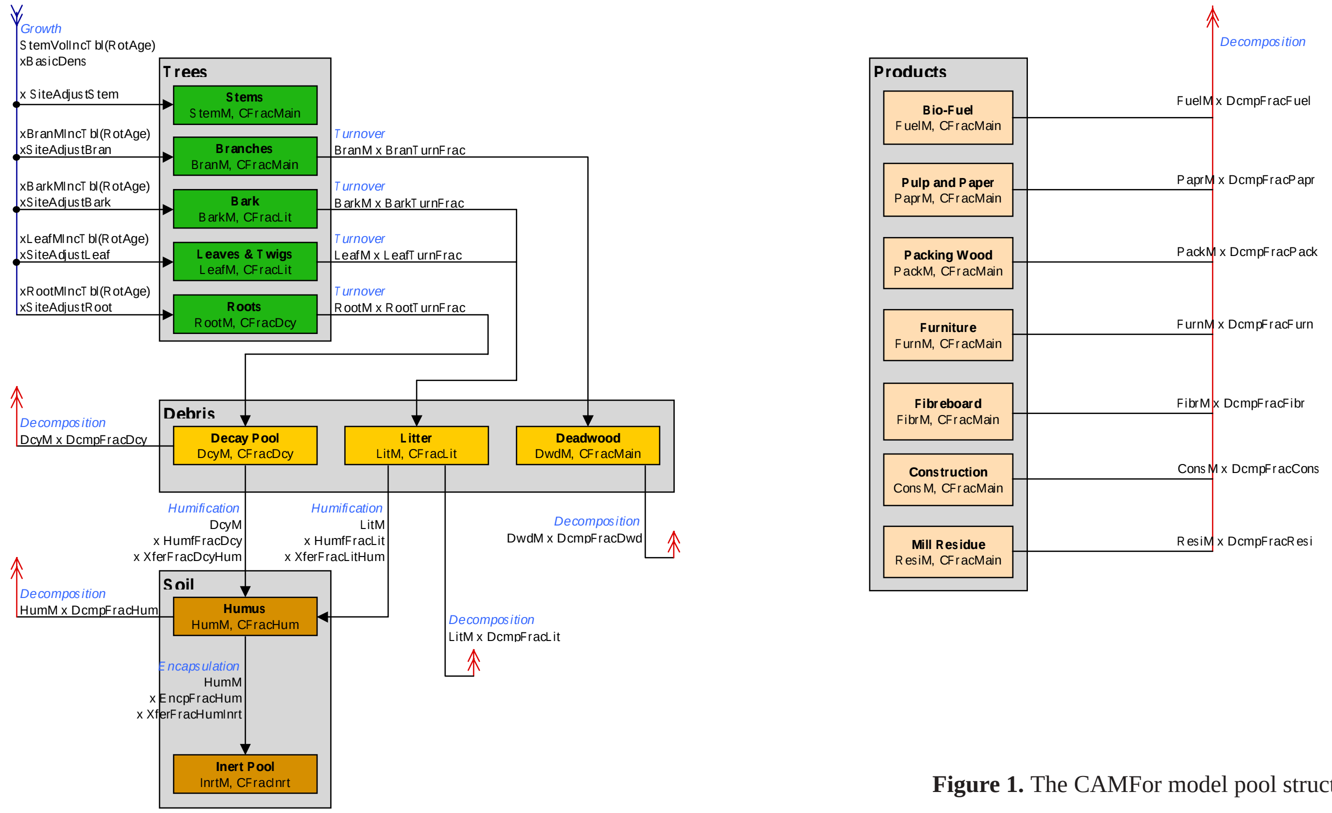

Figure 1. The CAMFor model pool structure

For native forests a modified version of 3PG (Landsberg and Waring 1997; Coops *et al.* 1998; Coops *et al.* 2001; Landsberg and Kesteven 2001; Landsberg *et al.* 2001) was applied spatially to provide relative indices of productivity (1970–2000 and long-term average) at 1 km resolution. A 250 m slope-and-aspect-corrected productivity surface was also produced. Regressions with productivity developed around known measures of mass in native forests were subsequently fitted to generalised yield curves. The spatially and temporally variable productivity indices provide a moderator to achieve 'real time' estimates of biomass accumulation which vary by age as derived from the Land Cover Change program. The productivity mapping will be used to estimate growth when spatial modelling is implemented.

Estimation of soil carbon

The agricultural soils program considered several elements including calibration of the Roth C model (Jenkinson *et al.* 1987, 1991), development of a national land use and management database (Swift and Skjemstad 2001), preparation of a pre-disturbance soil carbon map of Australia (Webb 2002), standardisation of analytic (laboratory) methods and correction of historic results (Skjemstad *et al.* 2000), yield estimation for different crop types by region over time, and extensive field verification of modelled results (Skjemstad and Spouncer 2003).

Forest soils have been treated independently, albeit drawing relevant information from the agricultural soils program and following technically and conceptually similar processes. State-of-knowledge and model development have been reported (Polglase *et al.* 2000; Paul *et al.* 2001). Development of model calibration programs has progressed (Paul *et al.* 2003a,b) and will be applied when the spatial modelling is implemented.

System development

The system development for the NCAS started with the point-based and spatial 'estate' Excel versions of the CAMFor model (Richards and Evans 2000). CAMFor (Fig. 1) was then integrated with the RothC soil carbon model which is independently calibrated and verified in the soils program, the 3PG forest growth model and the GENDEC litter decomposition model (Moorhead and Reynolds 1991; Moorhead et al.1999) in an Excel application (GRC3). The individual models can be applied independently or in various combinations within the model framework. For example, CAMFor can take data inputs from user-entered data tables, from 3PG or from a generalised, productivity-driven growth formula.

Once testing of the GRC3 model was complete, an equivalent agricultural model was developed around a new model CAMAg (Richards 2002), which replicated the role of CAMFor. The forest and agricultural applications were then integrated in the FullCAM model (Richards 2001, 2002), providing the capacity for spatial (GIS) application, with transitions between agricultural and forest systems, or mixed systems such as agroforestry and grazed woodlands. The ability to change agricultural and forest species over time was also introduced into FullCAM (Fig. 2). The FullCAM model provides the framework for integrating the model calibration and verification activities, data on land use and management systems, remotely-sensed information on land cover change, and collated (tabular) data such as crop yield and wood density.

The approach to post-1990 plantations

The approach to estimating carbon accumulation in plantations established after 1990 will evolve and be refined as the NCAS

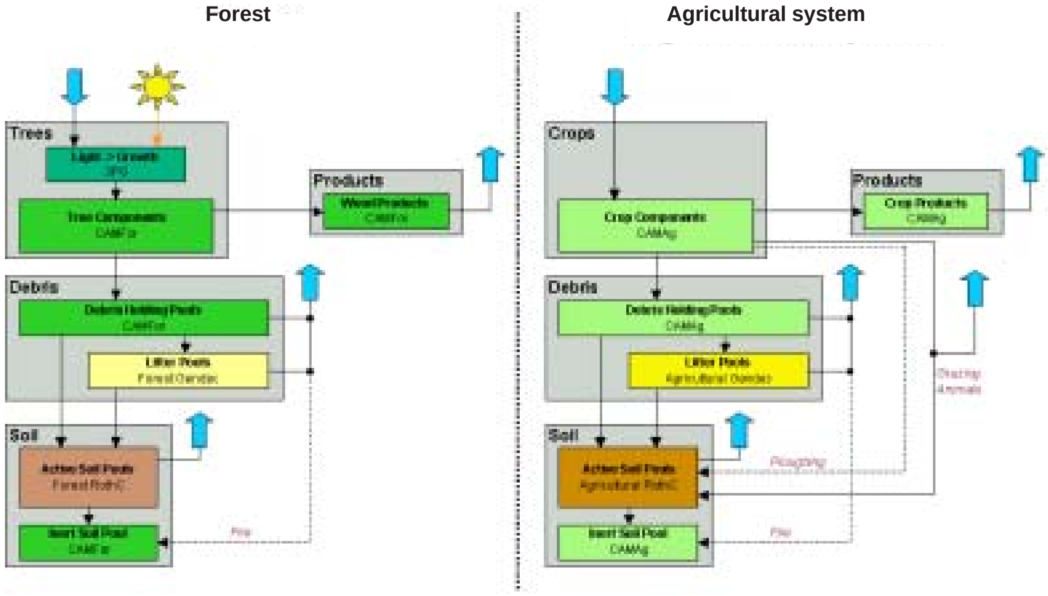

Figure 2. The FullCAM model principal pool structure

develops. In this initial implementation, growth increment tables based on the work of Turner and James (2001) as developed from the National Forest Inventory (NFI 1997a) estimates of wood flow, are used as a basis for growth modelling (Brack 2001; Brack and Richards 2001). Areas of relevant (to the Kyoto Protocol) plantation types have been derived by Spencer (2001) from the National Plantation Inventory establishment estimates (NFI 1997b, 2000). Overall estimates were discounted by the estimated areas of establishment subsequent to the clearing of native forests and second-rotation plantations, neither of which are compliant with the afforestation and reforestation definitions of Article 3.3 of the Kyoto Protocol. Spencer (2001) also provides estimates for the projected expansion of the plantation estate to 2019. These estimates and the growth tables of Turner and James (2001) underpin the current approach as reported in this paper.

The next significant stage of model development will be the use of the multi-temporal remote sensing program to spatially define the expansion of the plantation estate. Such an approach will allow for the linking of areas of establishment to the productivity mapping previously described. This will allow the generation of growth tables according to variable productivity (over both space and time) and for informed allocation of management regimes as affected by site productivity.

While soil carbon contents for most plantations do not change in the medium to long term (Polglase *et al.* 2000), there are frequently short-term losses (later recovered in most situations) and some instances of long-term losses (Paul *et al.* 2002). Work is underway to develop capacity for soil carbon accounting for the range of plantation situations. Initial work (Paul *et al.* 2003a,b) shows the potential to develop this capacity.

The model capability for the NCAS is also being extended to include the non-CO_2 gases which may arise from activities, such as fertiliser application and decomposition, producing nitrous oxide and methane under moist conditions. These gases and their potential impact have not been considered in the current analyses.

Model implementation

The data provided by Spencer (2001) are reported on the basis of the 14 National Plantation Inventory regions (Fig. 3). Three classes of forest are defined: short rotation hardwood (SRH), long rotation hardwood (LRH) and softwood (SW). Projected areas of establishment (beyond 2000) are a medium (mid-range) expectation (Table 1) for projected establishment rates. Data are generally presented as an average over five-year areas of establishment.

These data were subsequently annualised (cumulative area divided by number of years) within the blocks of years reported by Spencer

Figure 3. The National Plantation Inventory regions: 1 Western Australia; 2 Tasmania; 3 Green Triangle; 4 South Australia Lofty B1ock; 5 Central Victoria; 6 Murray Valley; 7 Central Gippsland; 8 East Gippsland/ Bombala; 9 Southern Tablelands; 10 Central Tablelands; 11 Northern Tablelands; 12 North Coast;13 South-east Queensland; 14 Northern Queensland; 15 Northern Territory

Table 1. Estimated plantation areas (ha) post-1990 (after Spencer *et al.* 2001)

Region	1990–1994			1995–1999			2000–2004			2005–2009			2010–2014			2015–2019		
	SRH	LRH	SW	SRH	LRH	SW	SRH	LRH	SW	SRH	LRH	SW	SRH	LRH	SW	SRH	LRH	SW
Western Australia	33814	37	6389	106722	364	12470	73700	700	5900	37900	3800	11400	31000	5200	25900	20700	5200	5900
Tasmania	2385	666	2247	9674	2100	5273	14700	7400	7400	11400	7600	7600	10300	10300	10300	10300	5200	0300
Green Triangle	2786	154	4766	22842	504	6772	88500	6300	8300	37900	9500	9500	10300	10300	10300	5100	8300	5100
Central Victoria	392	177	1234	5537	400	1782	25100	3200	900	7600	1900	1900	10300	2100	2600	5200	2100	2600
Murray Valley	7	136	7123	2018	773	12142	4800	4800	4800	2900	2900	2900	3800	3800	3800	3900	3800	3800
Central Gippsland	4971	1279	2957	7420	224	4286	8100	2000	900	5100	1700	1900	6900	2300	2600	6900	2300	2600
East Gippsland	411	82	639	1157	255	5387	2600	0	3700	2700	0	3800	2100	0	2100	2100	0	2100
Sourthern/Central Tablelands	0	6	5006	0	69	8397	0	1900	23600	0	1900	24200	0	2000	16600	0	1500	6600
Northern Tablelands	51	491	1257	569	16198	2918	3700	22100	2900	3800	17000	3000	5200	18600	2000	5200	14000	2000
Queensland	0	674	2357	0	4807	7539	7300	14700	7300	7500	22700	7500	5200	20700	8200	5200	20700	8200
TOTAL	44817	3702	33975	155939	25694	66966	228500	63100	65700	116800	69000	73700	85100	75300	84400	64600	63100	79200

SRH: Short-rotation hardwood; LRH: Long-rotation hardwood; SW: Softwood

Table 2. Typical plantation management regimes in each National Plantation Inventory (NPI) region

Species	NPI region	Regime
Pinus pinaster	Western Australia	Average sites — 65% thin @ 18 y, 37% @ 25 y and clearfall @ 40 y
Pinus radiata	Western Australia	Average sites — 51% thin @ 12 y, 39% @ 18 y, 32% @ 24 y, clearfall @ 35 y
Pinus radiata	Victoria, New South Wales	Poor sites — clearfall @ 30 y
Eucalyptus globulus	Western Australia	Clearfall @ 10 y
Pinus radiata	Victoria, New South Wales	Average sites — 65% thin @ 16 y,m 57% @ 24 y, 27% @ 30 y, clearfall @ 35 y
Pinus radiata	Victoria, New South Wales	Poor sites — 26% thin @ 18 y, 32% @ 24 y, clearfall @ 30 y
Pinus radiata	Victoria, New South Wales	Average sites — 65% thin @ 16 y, clearfall @ 30 y
Pinus radiata	Victoria, New South Wales	Average sites — 65% thin @ 16 y, 57% @ 24 y, clearfall @ 30 y
Pinus radiata	Murray Valley	Very good sites — 44% thin @ 14 y, 31% @ 18 y, 27% @ 23 y, clearfall @ 30 y
Pinus radiata	Victoria, New South Wales	Average sites — clearfall @ 30 y
Pinus radiata	Murray Valley	Average sites — 47% thin @ 14 y, 35% @ 22 y, 29% @ 29 y, clearfall @ 30 y
Pinus radiata	Murray Valley	Average sites — 47% thin @ 14 y, 35% @ 22 y, clearfall @ 30 y
Eucalyptus spp.	Vic (Central Gippsland)	All sites — clearfall @ 35 y
Pinus radiata	Vic (Central Gippsland)	Average sites — 33% thin @ 15 y, 37% @ 20 y, clearfall @ 30 y
Eucalyptus spp.	Vic (Central Gippsland)	All sites — clearfall @ 20 y
Eucalyptus spp.	Vic (Central Gippsland)	All sites — clearfall @ 30 y
Pinus radiata	Victoria (Central)	Average sites — clearfall @ 30 y
Eucalyptus spp.	Victoria (Central)	All sites — clearfall @ 25 y
Pinus spp. (not *P. radiata*)	Tasmania	All sites — clearfall @ 35 y
Pinus radiata	Victoria (Central)	Average sites — 34% thin @ 15 y, 18% @ 22 y, 24% @ 28 y, clearfall @ 35 y
Eucalyptus nitens	Tasmania	All sites — clearfall @ 25 y
Pinus radiata	Tasmania	Average sites — clearfall @ 35 y
Eucalyptus nitens	Tasmania	All sites — clearfall @ 30 y
Eucalyptus nitens	Tasmania	All sites — clearfall @ 15 y
Eucalyptus spp.	South Australia	All sites – clearfall @ 25 y
Pinus spp. (not *P. radiata*)	South Australia	Average sites — 54% thin @ 13 y, 25% @ 18 y, 28% @ 23 y, clearfall @ 30 y
Eucalyptus spp.	South Australia	All sites — clearfall @ 25 y
Pinus spp. (not *P. radiata*)	South Australia	Average sites — 54% thin @ 13 y, 25% @ 18 y, 28% @ 23 y, clearfall @ 30 y
Eucalyptus spp.	South Australia	All sites — clearfall @ 20 y
Eucalyptus spp.	South Australia	All sites — clearfall @ 15 y
Eucalyptus spp.	Queensland	All sites — clearfall @ 20 y
Southern pines	Queensland	All sites — 35% thin @ 18 y, clearfall @ 35 y
Eucalyptus spp.	NSW	All sites — clearfall @ 20 y
Eucalyptus spp.	Queensland	All sites — 67% thin @ 20 y, 47% @ 35 y, clearfall @ 45 y
Southern pine	NSW Northern Tableland	Average sites — 27% thin @ 14 y, 47% @ 20 y, clearfall @ 30 y
Eucalyptus spp.	NSW	All sites — 67% thin @ 20 y, 47% @ 35 y, clearfall @ 45 y
Pinus radiata	Green Triangle	Average sites — 54% thin @ 13 y, 25% @ 18 y, 28% @ 23 y, clearfall @ 30 y
Pinus spp. (not *P. radiata*)	Green Triangle	Average sites — 54% thin @ 13 y, 25% @ 18 y, 28% @ 23 y, clearfall @ 30 y

(2001). The changing trends in data are often quite dramatic, and averaging often leads to large ‘step’ functions in the data. This will be refined when the spatial application is implemented.

Allocations of the SRH, LRH and SW classes are made to the region and species-specific management regimes described by Turner and James (2001). Table 2 shows the 38 management regimes for which growth increment (yield) tables are available.

Within the FullCAM model, as implemented to derive a carbon account for the national plantation estate, CAMFor equivalent models for each of the 38 identified management regimes were developed. Additional information, beyond the growth tables and thinning regimes of Turner and James (2001) shown in Table 2 and the example datasheets (Figures 4a,b,c), for each Forest Type included:

- wood density
- conversion of stem mass to whole-tree mass
- carbon contents
- destinations of wood product, and
- estimates of leaf and root turnover.

For each of the management regimes, Figure 4 shows snapshots of the relevant inputs and the resultant carbon balances on a per-hectare basis. These snapshots are integrations of the information collated by the NCAS as individual implementations of the model for each management regime.

The ‘Estate’ module of CAMFor, as contained within the FullCAM, is then used to determine the consequence of implementing the individual management regime models on the basis of the new areas of forest established under each regime over time. To do this, the model interrogates the carbon balance for each management regime at the relevant point in time to derive the overall account. The per-hectare outcome, by the relevant age (as determined by the year of planting for each regime), is multiplied by the number of hectares planted in the corresponding year to calculate the change for the whole of the estate in any one year. A fuller explanation of the operation of the ‘Estate’ module of CAMFor can be found in Richards and Evans (2000).

Growth tables and thinning regimes

Turner and James (2001) were commissioned by the NCAS to reinterpret their previous work for the NFI wood flow estimates (NFI 1997a) to provide current annual increments (CAI) of stem volume for each management regime represented. To determine the CAI, estimates of total volume produced (from either a thinning or a clearfall) by age were fitted to growth curves. The method of fitting growth curves to the known points of wood yield for each management regime is described in Turner and James (2001).

The information to support the estimates of wood flow was collected through grower survey, and would largely be the result of actual inventory. As such, the estimates would generally reflect inventory data collected to the point of plantation maturity. The data would therefore be representative of the growing stock, site and silvicultural treatments over the life of the plantation, many aspects of which will have improved since that time. As growth projections, the estimates are therefore likely to be conservative

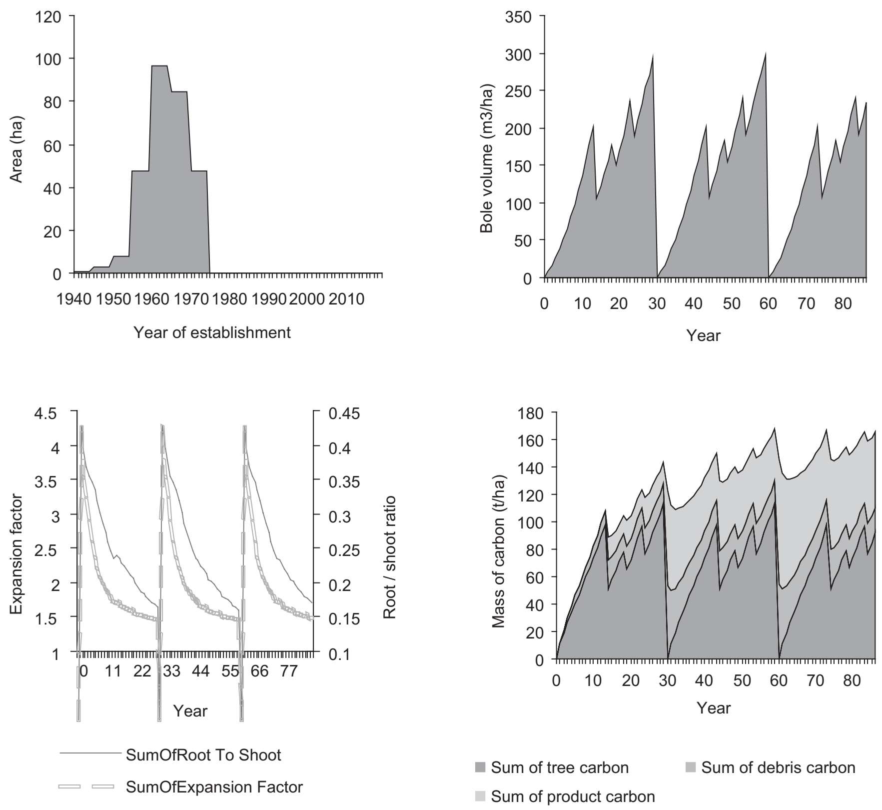

Figure 4a. Example model inputs and carbon balances for short-rotation hardwood (SRH): *Eucalyptus* plantation, NSW9101112 (All sites: 67% @ 20y; 47% @ 35 y; CF @ 45 y)

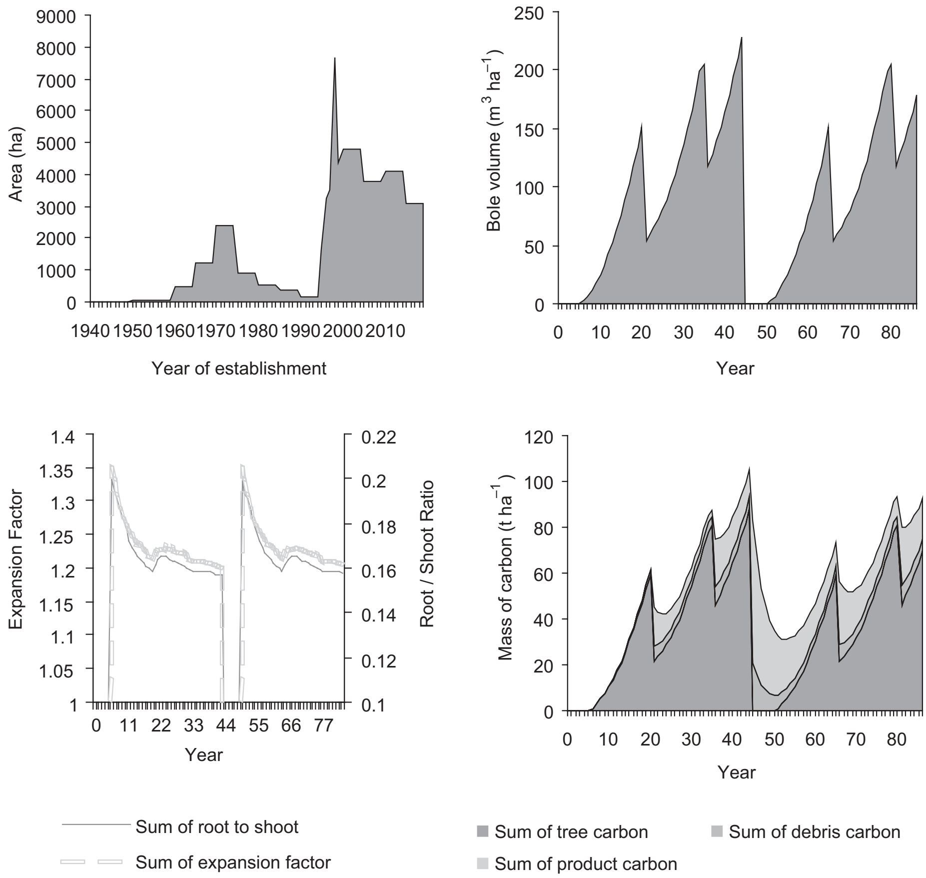

Figure 4b. Example model inputs and carbon balances for long-rotation hardwood (LRH): *Eucalyptus nitens* plantation, Tasmania (All sites: CF @ 30y)

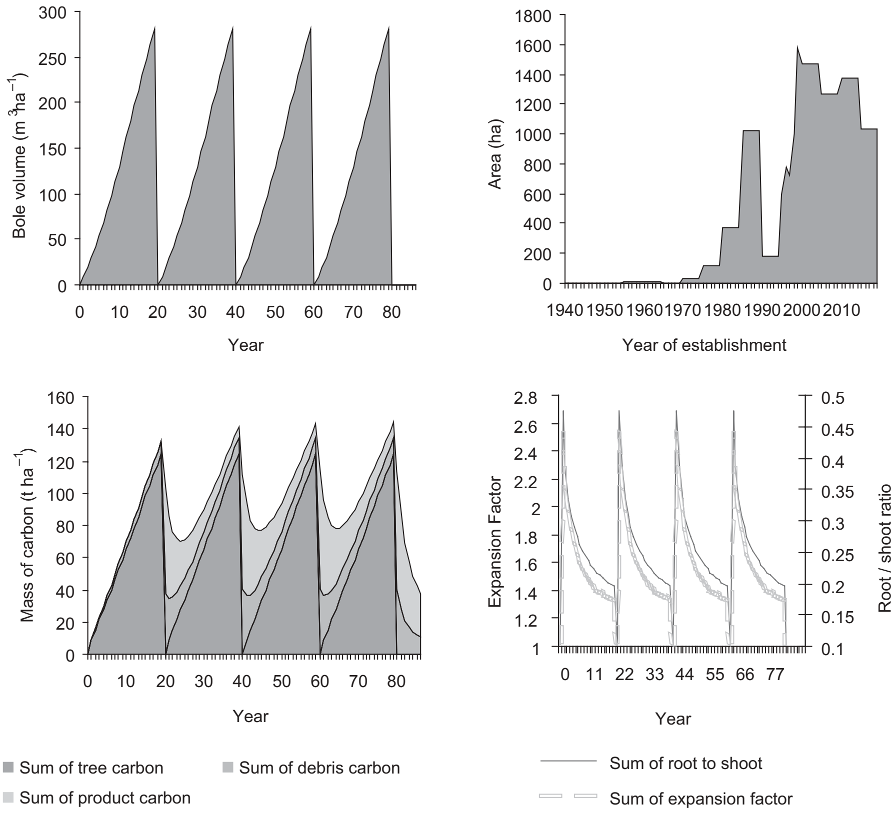

Figure 4c. Example model inputs and outcomes for softwood (SW): *Pinus* spp. (not *P. radiata*) plantations, Green Triangle (Average: 54% thinning @ 13 y; 25% @ 18 y; 28% @ 23 y; CF @ 30y)

because of expected improvement in plantation performance. However, this benefit may be moderated by a constrained availability of optimum sites for future plantation establishment.

The empiricism of the estimates also masks the influences of climate variability over the time of measurement. A variable climate is associated with a variability in growth over time. While it is unlikely that the volume at maturity (reflecting the longer-term climate average) would be much affected, over a shorter period such as the first Commitment Period of the Kyoto Protocol (2008–2012) yield may be above or below the expected growth due to the prevailing climate conditions. The potential impact of prevailing climate conditions during the time of reporting has been studied and is reported in Brack and Richards (2002).

Estimates of wood density and carbon content

Wood density estimates were extracted from the compendium prepared by Ilic *et al.* (2000) for the NCAS. While many native forest species have few —in some instances no — reported wood density estimates, plantation species are relatively well studied and reported. However, wood density is most commonly measured at the time of harvest, reflecting a mature state.

As it is commonly accepted that wood density increases with tree age, up to a certain point, it is possible that the adopted wood densities are over-estimates for the early stages of plantation growth. However, the overall effect is unlikely to be significant as lower densities occur when mass is least; that is, during early growth stages. Also, as plantations are generally harvested well before individual tree maturity (generally before annual growth increment begins to decline) it is possible that the maximum potential density may not be achieved by the time of harvest. Table 3 shows the wood density values used for the major plantation species in the management regimes.

The carbon contents of various tree components below and above ground were examined by Gifford (2000a) and Gifford (2000b) respectively in studies for the NCAS. Carbon contents were tested for various species and growing conditions, with recommended estimates given within the range of values yielded in test results. There was little variability in the results and more importantly no cause to suspect bias in any set of environmental conditions or plant groups. These results could be considered as robust and reliable estimates, providing little uncertainty in the carbon models.

Stem to whole-tree mass conversions

Studies completed for the NCAS on the above- and below-ground partitioning of biomass (Grierson *et al.* 2000; Keith *et al.* 2000; Eamus *et al.* 2000; Snowdon *et al.* 2000) have shown that both below-ground and non-stem allocations reduce as site biomass increases. Greatest uniformity, and therefore least variability, tends to occur in even-aged and productive stands. Figures 4a,b,c illustrate the non-stem allocations (root/shoot ratio) used in each management regime model.

The ratio of stem (merchantable) quantities to non-merchantable components is particularly important for the calculation of the amounts of forest slash generated by thinning and harvesting activity. The potential accumulation of slash can make a considerable contribution to increased carbon stock, particularly on former pasture sites.

Wood product destinations

Jaakko Pöyry Pty Ltd (1999, 2000) were contracted by the NCAS to develop a life-cycle analysis model for forest products. The timber pool descriptions developed (e.g. timber framing, furniture, pulp and paper, mill residue) were subsequently incorporated into the CAMFor model, and hence FullCAM. The pool turnover rates (Table 4) were also incorporated, providing a stand-based wood product life cycle capacity within CAMFor / FullCAM. These turnover rates are applied annually, so the trajectory of decomposition is exponential.

The principal limitation of the approach as used is that the turnover rates are estimates with potentially large variability. A number of factors such as building engineering design life and rates of recycling can produce vastly different turnover rates. Also, only the serviceable life of products has been considered. As yet there is only a very preliminary understanding of the rates of breakdown after disposal.

Leaf and root turnover

The turnover rate of leaves affects both the amount of fine litter on the forest floor and subsequently most of the aboveground contribution to soil carbon. The turnover of roots (largely fine roots) is a direct input to soil carbon.

As this implementation of the model has not considered soil carbon, the rates of turnover of both leaves and fine roots are relatively unimportant. The key attributes of the assigned rates (Table 5) are that they are realistic and neither reduce the mass of attached leaves and live roots below reasonable expectation, nor create unrealistically high or low levels of litter.

A simple reality check can be performed directly from observations of model results. While leaf turnover rates have been the subject of measurement and can be compared to observations, the difficulty in measuring root turnover means that there are very few reported measures for comparison. However, as the stock of 'dead' fine root material is accounted for as soil organic matter, this becomes irrelevant until soil carbon accounting is attempted. Testing of the more comprehensive modelling capability of the Australian Greenhouse Office's GRC3 model by Paul et al. (2003a,b), and ongoing NCAS studies with CSIRO and the Australian National University, provide a basis for developing this capacity in future.

Slash decomposition

Subsequent to harvest there are often large quantities of slash (stumps, branches, etc.) left on the forest floor to decompose. The rates of decomposition applied in the model have been guided by the work of Mackensen and Bauhus (1999) for the NCAS. Table 6 shows the decomposition rates applied.

Harvesting sub-rule

Under Article 3.3 of the Kyoto Protocol, there is a harvesting sub-rule that plantations established after 1990 (with a positive carbon stock change since 1990) may, because of a thinning or harvest activity in the first Commitment Period (2008–2012), yield a negative carbon stock change result for that period.

Table 3. Wood densities and carbon contents for each management regime

Region(s)	Species	Density	Carbon content (%)								Regime description
			Leaf	Twig	Brch	Sap	Wood	Bark	Fine	Coarse	
Green Triangle	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — 54% thinning @ 13 y, 25% @ 18 y, 28% @ 23 y, CF @ 30 y
Green Triangle	*Pinus* spp. (not *P. radiata*)	440	52	52	51	51	52	53	46	49	Average sites — 54% thinning @ 13 y, 25% @ 18 y, 28% @ 23 y, CF @ 30 y
NSW Northern Tableland	Southern pine (*P. elliottii*, *P. taeda*), *Araucaria cunninghamii*	440	52	52	51	51	52	53	46	49	Average sites — 27% thinning @ 14 y, 47% @ 20 y, CF @ 30 y
NSW	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — 67% @ 20 y, 47% @ 35 y, CF @ 45 y
NSW	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 20 y
Queensland	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — 67% @ 20 y, 47% @ 35 y, CF @ 45 y
Queensland	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 20 y
Queensland	Southern pine (*P. elliotti*, *P. taeda*), *Araucaria cunninghamii*	440	52	52	51	51	52	53	46	49	All sites — 35% @ 18 y, CF @ 35 y
South Australia	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 20 y
South Australia	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 15 y
South Australia	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 25 y
South Australia	*Pinus* spp. (not *P. radiata*)	440	52	52	51	51	52	53	46	49	Average sites — 54% thinning @ 13 y, 25%@18 y, 28% @ 23 y, CF @ 30 y
Tasmania	*Eucalyptus nitens*	550	52	52	47	52	52	49	46	49	All sites — CF @ 30 y
Tasmania	*Eucalyptus nitens*	550	52	52	47	52	52	49	46	49	All sites — CF @ 15 y
Tasmania	*Eucalyptus nitens*	550	52	52	47	52	52	49	46	49	All sites — CF @ 25 y
Tasmania	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — CF @ 35 y
Tasmania	*Pinus* (not *P. radiata*)	440	52	52	51	51	52	53	46	49	All sites — CF @ 35 y
Victoria (Central)	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites —34% thinning @ 15 y, 18% @22 y, 24% @ 28 y, CF @ 35 y
Victoria (Central)	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — CF @ 30 y
Victoria (Central Gippsland)	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 25 y
Victoria (Central Gippsland)	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 20 y
Victoria (Central Gippsland)	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 30 y
Victoria (Central Gippsland)	*Eucalyptus* plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 35 y
Victoria (Central Gippsland)	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — 33% thinning @ 15 y, 37%@ 20 y, CF @ 30 y
Murray Valley	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — 47% thinning @ 14 y, 35%@22 y, 29% @ 29 y, CF @ 30y
Murray Valley	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — 47% thinning @ 14 y, 35% @ 22 y, CF @ 30 y
Murray Valley	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Very good sites — 44% thinning @ 14 y, 31%@ 18 y, 27% @ 23 y, CF @ 30 y
Victoria and NSW	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — CF @ 30 y
Victoria and NSW	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Av'ge sites – 65% thinning @ 16 y, CF @ 30 y
Victoria and NSW	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — 65% thinning @ 16 y, 57% @ 24 y, CF @ 30 y
Victoria and NSW	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — 65% thinning @ 16 y, 57% @ 24 y, 27% @ 30 y, CF @ 35 y
Victoria and NSW	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Poor sites — 26% thinning @ 18 y, 32% @ 24 y, CF @ 30 y
Victoria and NSW	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Poor sites — CF @ 30 y
Western Australia	*Eucalyptus globulus*	550	52.8	49.8	47	48.7	50.7	49	46	49	Clear fall @ 10 y
Western Australia	*Pinus pinaster*	470	52	52	51	51	52	53	46	49	Average sites — 65% thinning @ 18 y, 37% @ 25 y, CF @ 40 y
Western Australia	*Pinus radiata*	440	52	52	51	51	52	53	46	49	Average sites — 51% thinning @ 12 y, 39% @ 18 y, 32% @ 24 y, CF @ 35 y

Table 4. Decomposition rates for wood products

Product type	Decomposition rate (fraction y^{-1})
Biofuel	1.0
Pulp and paper	0.33
Packing wood	0.2
Furniture, poles	0.05
Fibreboard	0.07
Construction wood	0.02
Mill residue	1.0

Table 5. Turnover rates for tree components

Tree component	Turnover (fraction y^{-1})
Branches	0.03
Bark	0.1
Leaves and twigs	0.5
Coarse roots	0.05
Fine roots	0.1

Table 6. Decomposition rates for slash

Slash component	Decomposition rate (fraction y^{-1})
Deadwood	0.1
Bark litter	0.5
Leaf litter	1.0
Coarse dead roots	0.5
Fine dead roots	1.0

The sub-rule operates on a stand-by-stand basis, and any stand that qualifies for Article 3.3 afforestation or reforestation but has a negative stock change result will be excluded from the accounting.

To deal with this in CAMFor 'Estate' (as implemented within FullCAM), an additional reporting routine has been added whereby each age class (annual) for each management regime is reviewed for cases where the carbon stock in 2012 is less than the carbon stock in 2008. In such instances the negative stock change is automatically replaced with a zero stock change. This approach gives effect to the sub-rule in a stand-based approach.

Uncertainty analysis

Brack and Richards (2002) have provided the basis for uncertainty analysis using the @Risk (Palisade 1997) 'Monte Carlo' capabilities attached to the CAMFor model. The analysis described the potential 'variance' within many parameters in terms of a probability distribution.

Dealing with quantified variances within Monte Carlo analyses also makes it possible to consider the correlation between variables and parameters, and the likelihood of any single or interacting circumstance occurring. When the Monte Carlo analysis, running multiple variants of possible inputs in combination, is not guided by correlation, simplistic, yet unrealistic, scenarios may be induced. For example, under a high rainfall, growth rate will likely increase, as will decomposition rates. If the Monte Carlo analyses are informed that these parameters are positively correlated, then the random selection of high growth values will be associated with increased decomposition values.

If correlations are not prescribed, combinations such as increased growth and decreased decomposition rates (a negative correlation) are as likely to be selected as a positive correlation, although they are unlikely to occur in reality. The inclusion of unrealistic scenarios (i.e. presuming all variables are independent) in the Monte Carlo analyses will considerably increase uncertainty attributed to model outcomes by not acknowledging the frequently ameliorating effects of correlated inputs.

Brack and Richards (2002) modelled the performance of an individual stand, using growth rates determined according to the observed growth variance around rainfall variability, error in allocating a growth index for the relevant growth model, and known variance or uncertainty in other key parameters.

The 'tornado' diagram (Fig. 5) shows the sources of uncertainty of model parameters in order of their importance to uncertainty in the model outcome. It is clear from the analysis that, on an individual stand basis and in this instance, predictions are more prone to climate-based variation than any other influence.

Figure 6 shows the means and standard deviations for projected performance, providing the logical conclusion that stands established in the early 1990s and thus aged around their maximum potential growth rate during the first Commitment Period of the Kyoto Protocol would be most affected (with the largest standard deviation) by variability, largely driven by climate.

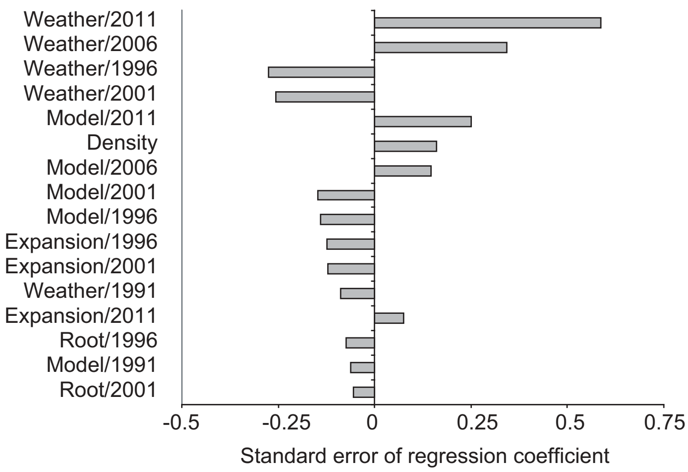

Figure 5. Tornado diagram derived from @Risk simulations of the correlation between uncertainty of the inputs and distribution of sequestration estimates between 2008 and 2012 for a plantation established in 1990. Weather/xxxx denotes the variation in weather during the 5-y period commencing xxxx. Model/xxxx denotes the variation in the modelled site index during the 5-y period commencing xxxx. Expansion/xxxx denotes the variation in the expansion factors (caused as a result of the variation in increment of bark, branches, twigs and leaves) during the 5-y period commencing xxxx. Roots/xxxx denotes the variation in root increment and decay during the 5-y period commencing xxxx.

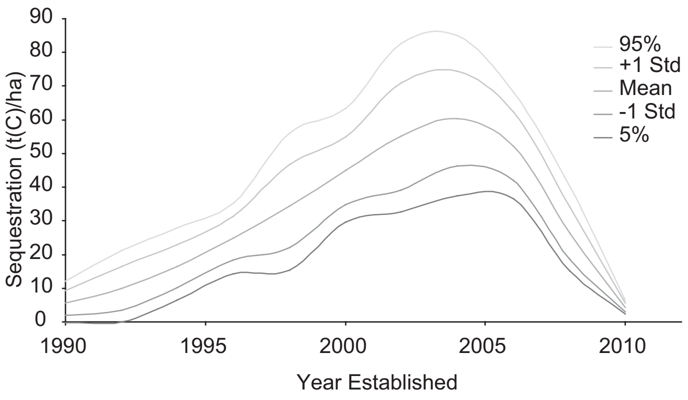

Figure 6. Variability in stand performance by age of stand (from Brack and Richards 2002)

To extrapolate such individual-stand-based analyses to a national scale by simplistically running high and low ranges of outcomes for the first Commitment Period would yield unrealistic results. The use of say a 'low' base and the lower standard deviation is founded on the unlikely potential for below-average rainfall for all plantation areas for the whole of the first Commitment Period across the whole continent.

The appropriate approach would be to determine the climate projections and uncertainties for each plantation region and apply that range of potential outcomes to the relevant forest types for each region. Despite their complexity, such analyses will still be unable to determine the effect of access to groundwater on plantation growth. The effects of groundwater availability are not widely understood and may considerably ameliorate the climate-induced variability shown in the example above.

Given the vast areas covered by plantations, it is a reasonable expectation that across the continent, over the first Commitment Period, 'near average' conditions will be achieved. Extreme climate events, like risks of fire or insect attack, are more appropriately dealt with by security / risk-based analyses than included in the uncertainty analysis. The results derived from the independent risk and uncertainty analyses would be mostly additive, although care may need to be taken that factors that increase risk, for example dry conditions, are not strongly correlated with particular uncertainty outcomes.

Of more concern in terms of uncertainty is the variability in the projected plantation establishment rates, and the uncertainty in the current estimates of plantation area. If the current figures for the area of the plantation estate are accepted, projected plantation areas are as presented in Table 1.

Model outcomes

The carbon outcomes for each management regime model by time are shown in Figure 4. The areas allocated to each management regime from each region for SRH, LRH and SW classes are given in Table 1.

The results for the carbon stock present each year in the post-1990 plantation estate are shown in Table 7. Table 8 shows the effect of the Kyoto Protocol harvesting sub-rule on the scenarios.

Table 7. Carbon stock (Mt C) projections for the post-1990 plantation estate

Year	Carbon stock: plantations + products	Carbon stock: wood products[a] only
1990	0.2	0
1991	0.7	0
1992	1.3	0
1993	2.0	0
1994	2.9	0
1995	4.0	0
1996	5.6	0
1997	7.6	0
1998	10.0	0
1999	12.0	0.4
2000	16.4	0.7
2001	20.2	0.9
2002	25.2	1.2
2003	30.3	1.4
2004	35.5	1.8
2005	40.2	2.8
2006	44.8	3.7
2007	49.5	4.6
2008	54.1	5.7
2009	59.0	6.3
2010	64.5	7.0
2011	70.2	7.7
2012	76.1	8.3
2013	83.5	9.1
2014	90.6	9.8
2015	96.9	11.1
2016	102.8	12.5
2017	108.5	13.9
2018	113.6	15.8
2019	118.9	17.3

[a]Wood products are materials moved offsite during harvest and include mill residues and material in service life. Wood products disposed of in landfill are already accounted for under the Waste sector reporting of national inventories.

The sub-rule specifies that for a forest stand, reported carbon stock losses (e.g. due to harvest) cannot be greater than the positive carbon stock change for that stand over the same period.

Conclusions

The development of the capacity to provide a credible current carbon account for Australia's plantations and capability to project future outcomes has been a major undertaking, requiring the collation, synthesis and interpretation of large and diverse data sets. The development of the accounting framework and models to assimilate this information to provide the systems capacity for carbon accounting has also been a complex task, requiring considerable iterative development and testing. Extensive and international reviews of the model have been undertaken (Brack 2000).

The national-level modelling can be considered as less subject to extreme risks and variability than stand-level modelling, as risks are spread and the large number of unbiased estimates and climate

Table 8. Impacts of the harvest sub-rule on the 2008–2012 carbon stocks of post-1990 plantations

Scenario	Plantation (Mt C)	Plantation + wood products (Mt C)
First Commitment Period with sub-rule	29.1	28.3
First Commitment Period without sub-rule	23.0	26.7

conditions over vast areas draw the results closer to the median estimated value. These moderating effects of scale do not equally apply to individual or small (particularly clustered) areas of plantations.

The modelling described here provides the first comprehensive review of plantation carbon accounting at a national scale. As such it provides a state-of-knowledge summary and sets benchmarks which can assist industry understanding of the possible implications of the emerging market in carbon trading. In particular, it provides the tools to allow individual growers an early opportunity to consider the implications of the Kyoto Protocol on their particular plantation estates, together with time to respond via their management and expansion activities.

Further developments in accounting for forest plantation activities will include:

- the use of remote sensing to determine the age, type and location of plantations (including previous land cover);
- comprehensive modelling on a spatial basis, including the use of annual forest productivity indices at a 1 km resolution to determine rates of forest growth, and the incorporation of soil carbon models.

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