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Evaluation of wood characteristics of tropical post-mid rotation plantation *Eucalyptus cloeziana* and *E. pellita*: Part (b) Accelerated seasoning of sawn timber

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Evaluation of wood characteristics of tropical post-mid rotation plantation *Eucalyptus cloeziana* and *E. pellita*: Part (b) Accelerated seasoning of sawn timber

Prepared for

Forest and Wood Products Australia

by

A.L. Redman and R.L. McGavin

Executive summary

Drying trials were conducted using two species of plantation grown eucalypt timbers: 19-year-old *Eucalyptus cloeziana* (Gympie messmate) and 15-year-old *Eucalyptus pellita* (red mahogany). Three conventional kiln trials, including two for 38 mm thick *E. cloeziana* (trials C1 and C2) and one for 25 mm thick *E. pellita* (trial C3), and two vacuum kiln drying trials, one each for 38 mm and 25 mm thick *E. cloeziana* (trials V1 and V2), were conducted. Due to limited resource no vacuum trials were conducted for *E. pellita*. For trials C1, C2 and V1, boards were sawn from up to three radial zones within a log; inner, intermediate and outer. The objective of this study was to gain an understanding of the drying potential of young plantation grown material using accelerated seasoning methods, a process expected to be critical to the success of plantation hardwood products entering value added markets.

The conventional trials used a 0.2 m^3 research kiln and the vacuum drying trials were conducted using a 2 m^3 superheated-steam vacuum drying research kiln.

The conventional drying schedule for conventional trials C1 and C3 were based on the schedules recommended by Rozsa and Mills (1991). A slightly milder schedule was developed for the second conventional trial C2 because of unacceptable surface check results recorded for trial C1. The schedule for vacuum drying trial V1 was based on a previous, successful schedule used by the Department of Primary Industries and Fisheries' (DPI&F) Salisbury Research Centre (SRC) to dry *Corymbia citriodora* (spotted gum). As a result of marginal surface checking recorded for trial V1, a milder schedule was selected for vacuum trial V2 from the kiln's pre-set schedules based on a European species believed to have similar tendency to surface check. The target final moisture content (MC) for each trial was 10%. An equalisation phase was implemented at the end of drying for each trial for either 24 hours for 25 mm thick boards or 36 hours for 38 mm thick boards.

Cross-sectional MC was measured prior to and after kiln drying. In addition, MC gradient, internal and surface checking, and drying stress were evaluated after drying. The material was visually graded to determine dried quality ranking in accordance with *Australian and New Zealand Standard AS/NZS 4787:2001 – Timber – Assessment of drying quality* (Standards Australia 2001).

The drying times for conventional drying trials C1, C2, and C3, including the equalisation phase, were 20.3, 23.2 and 17.7 days respectively. For vacuum drying trials V1 and V2 the drying times were 13 and 12.2 days respectively. The time to vacuum dry 38 mm thick *E. cloeziana* was approximately 60% shorter than conventional drying. Conventional drying times reported by one industry spokesperson for 38 mm and 25 mm native forest *E. cloeziana,* are approximately 30 and 21 days respectively (Rankin, pers. comm. 2007), which are considerably longer than for the plantation material tested here.

Initial cross-sectional MC analysis gave significant differences between the mean initial MC for the zoned boards. The driest to wettest boards were generally from the outer, intermediate and inner zones, respectively. Final cross-sectional MC grade quality was acceptable for trials C2 and C3 but was unacceptable for the remaining trials. Similar results were recorded for MC gradient grade quality and drying stress. In the majority of cases unacceptable grade quality results were only marginally unacceptable and improvements to grade quality in all cases were due to schedule manipulation, particularly during the equalisation phase.

Surface checking was present for all trials. For the first conventional trial C1, an unacceptable number of boards were downgraded for surface check (80% select grade) in accordance with *AS2796.3:1999 Hardwood – Sawn and milled products – Part3: Timber for furniture components* (Standards Australia 1999). All other trials achieved acceptable grade quality for

surface checking with 100% of boards in trials C3 and V2 meeting select grade. All boards in every trial were free of internal checks.

The findings are encouraging, indicating that both species can be dried using conventional drying techniques much faster than industry is currently achieving when drying native forest timber. The results suggest there is a definite drying time advantage in vacuum drying over conventional methods for 19-year-old *E. cloeziana*. The findings have shown that through careful schedule manipulation and adjustment, the grade quality can be optimised to suit the desired expectation. As this study was limited to only a small number of trials, time and quality improvements are expected to be realised for both conventional and vacuum drying methods as more research is conducted.

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1. Introduction

The objective of this study was to gain an understanding of the potential for seasoning sawn timber produced from fast grown, well managed Queensland hardwood plantations using accelerated seasoning methods. A 19-year-old *Eucalyptus cloeziana* (Gympie messmate) and a 15-year-old *E. pellita* (red mahogany) plantation provided the trial material. To meet the project objective, three conventional kiln trials (two *E. cloeziana* and one *E. pellita*) and two vacuum kiln drying trials (*E. cloeziana* only) were conducted.

Seasoning is critical for many product applications including furniture components, flooring and decking. The seasoning process essentially removes most of the water from the timber. The benefits of seasoning include improved stability, improved control over visual and internal defects (such as checking), control of distortion, decrease in weight, increase in strength, improved gluability and improved thermal insulation properties. Timber dried to the equilibrium conditions of its surroundings is a much more valuable commodity than its green counterpart for the majority of value-added product applications.

Traditionally, timber has been air-dried in stacks, a method that requires very little energy input. Disadvantages of this method include a lack of control over drying conditions, long drying times (months or even years) and an increased potential for drying degrade. Kiln drying allows more control over the seasoning process, improving dried quality, often combined with reduced drying times. Additional capital and operating costs occur with kiln drying are potentially re-couped through higher recovery of useable material, higher product value and faster stock turn around.

Both conventional and vacuum kiln drying were used in this study. Conventional kiln drying is currently the primary method of kiln drying timber in Australia. Conventional drying kilns generally provide control over temperature, humidity and air-flow. This ensures that seasoning conditions are in line with an appropriate drying schedule for the particular species, section size and required quality. The rate of drying is increased by raising the drying temperature and/or lowering the relative humidity. Drying schedules generally utilise a range of different temperature and relative humidity steps throughout the seasoning process to ensure the drying rate is as fast as possible without compromising the required final quality.

In recent years, with emerging technological advancements in construction, computer control and less expensive materials, vacuum drying hardwood timber has proven to be an economical alternative to conventional drying methods in many applications (particularly in Europe and the USA). There are several vacuum drying systems available commercially, but one feature they have in common is the ability to operate at sub-atmospheric pressures. The level of vacuum generated varies between systems, but is generally in the range of 100 to 250 mbar (Ressel 1994). Under a vacuum, the temperature at which water boils is lowered which accelerates surface evaporation. Additionally, a pressure gradient is created between the core and the outside of the board, which improves mass transfer (Defo et al. 2004).

Low oxygen levels present under continuous vacuum drying can also greatly reduce the incidence of discolouration associated with tannin oxidation (Savard et al. 2004).

The main reason that drying in a vacuum kiln is faster than conventional methods, is because a pressure gradient is created between the core and the outside of the board. This pressure gradient is very effective in moving moisture, particularly free water, from the core to the board surface. As the ambient pressure is reduced, the internal moisture migration is improved due to favourable pressure gradients inside the wood and because water conductivity is higher under vacuum (Chen and Lamb 2001).

2. Literature review

Much research has been completed and is in progress to support the development of the plantation hardwood sector in Queensland. Focused seasoning research however has been limited. While hardwood plantations are being established in Queensland at an increasing rate, the limited volumes of currently harvestable material has limited product-based research. Increased volumes are expected to be made available to industry in future as newly established plantations mature. The following provides an overview of some of the relevant drying research conducted in Australia and overseas using sub-tropical and tropical plantation hardwood species of commercial relevance to Queensland.

2.1 Australia

Redman and McGavin (2007) evaluated the drying potential of 25 mm thick boards sawn from eight-year-old thinnings harvested from an *E. cloeziana* plantation growing at Federal, South East Queensland. Two conventional and one vacuum seasoning trials were conducted at the Department of Primary Industries and Fisheries' (DPI&F) Salisbury Research Centre using a 0.2 m^3 conventional kiln and a 2 m^3 superheated-steam vacuum drying kiln (both research size). The drying times from green off saw to 12% moisture content (MC), excluding the equalisation phase were 5.4 and 4.9 days respectively for the conventional trials and 5.3 days for the vacuum drying trial. Final cross-sectional MC and MC gradient grade quality results for each trial were reported to be within acceptable limits. Drying stress grade quality results were considered marginal for each trial. Low but acceptable levels of surface checking were recorded for each trial. Low but acceptable levels of internal checking were reported for the conventional drying trials although an unacceptable number of boards (14 %) exhibited internal checking in the vacuum drying trial. No drying induced end splitting was reported for any trial.

Redman and McGavin (2007) report 'the findings were encouraging, indicating that this material can be conventionally dried much faster than industry is currently achieving using mature native forest sawn timber. The results suggest minimal advantage in using vacuum drying over conventional, however the study was limited to only one vacuum drying trial'.

Armstrong *et al.* (2005) evaluated the wood quality and utilisation potential of plantation grown *Khaya senegalensis* (African mahogany) as a plantation candidate for the dry tropic climatic zone in Queensland. Thirty-eight 32-year-old trees from two sites near Darwin, Northern Territory were selected for the study. The boards were sawn into two thicknesses (25 mm and 12 mm) suitable for furniture applications. Three seasoning trials were conducted at the Salisbury Research Centre. One trial was air-dried under hessian in an air-dry shed before final drying in a solar kiln. Two small batch conventional kiln trials dried 25 mm thick material only, from green-off-saw. The air/solar kiln dried material was air-dried for 2½ months before final drying for 2 weeks to 10.3% MC. This 'conservative' approach produced very little drying induced degrade. The first conventional kiln trial dried material to 10.5% MC in four days (including one day equalising) but produced marginal dried quality. A number of boards failed to make grade in accordance with Australian and New Zealand Standard *AS/NZ 4787:2001 – Timber – Assessment of drying quality* (Standards Australia 2001) due to high final MC (most likely as a result of case hardening). The schedule used in the second conventional kiln trial was milder and successfully dried from green to 10.6% MC in approximately five days (including one day equalising) with very good dried quality.

A study on plantation grown *Eucalyptus argophloia* (western white gum) reported by Armstrong *et al.* (2003) included limited seasoning trials. Trees were selected representing final rotation age (32-year-old sourced from Biloela, Queensland) as well as thinning material (10-year-old from Mundubbera, Queensland). The logs were sawn into 25 mm thick boards of varying widths.

Full-rotation and thinning material was dried in a 7 m^3 conventional kiln in separate charges. Each charge used the same drying schedule which was based on the specific gravity of the material as recommended by Simpson and Verill (1997). The full-rotation material took approximately 19 days to dry from the green to approximately 10% MC while the thinnings material took approximately 17 days. Both trials produced minimal drying induced degrade. The selected schedule was reported as being mild with a harsher schedule expected to result in faster drying times while maintaining similar dried quality.

The sawing, drying and board quality assessment of 27-year-old plantation *Eucalyptus grandis* (rose gum) grown near Urunga, NSW was investigated and reported by Northway and Blakemore (1996). Backsawn boards of two different thicknesses (25 mm and 40 mm) were trialled using a 2.0 m^3 capacity experimental conventional kiln. Concrete weights were used to weight the top of the stack to reduce drying induced distortion. The drying trials used schedules incorporating periodic high humidity treatments. The high humidity treatments occurred every six hours for 20 minutes from the green condition to fibre saturation point (approximately 25% MC). The underlying assumption behind this technique was that periodically higher temperature and humidity conditions relax drying stresses and moisture gradients resulting in a reduction in the levels of drying degrade (mainly surface checking, distortion and collapse). A counter argument to this is that the high temperature and humidity treatments may act to plasticise or weaken the wood and promote the initiation of surface checks (Northway and Blakemore, 1996). Boards 25 mm thick were successfully dried to a structural grade (grade quality determined by level of surface checking) in 13 days and 40 mm thick boards in 27 days. It was reported that using milder initial drying conditions may lead to less surface checking and produce an appearance grade product, but is likely to increase drying times and therefore costs.

2.2 Overseas

In 2001, DPI&F completed a South American based project that investigated the productivity and wood quality of young, plantation grown sub-tropical eucalypts (Hopewell, 2001). Thirteen-year-old *Corymbia maculata* (spotted gum), 13 and 14-year-old *E. cloeziana*, 13 and 14-year-old *Eucalyptus pellita* (red mahogany), 14.5-year-old *Eucalyptus pilularis* (blackbutt), and 11-year-old *Eucalyptus grandis* x *Eucalyptus urophylla* hybrid were harvested, sawn, dried and graded.

The logs were sawn into 25 mm thick boards and dried together in a 20 m^3 capacity conventional drying kiln. The drying schedule used was based on earlier studies by Northway and Blakemore (1996). The schedule was considered a mild schedule for the sub-tropical species studied as it was originally developed to dry plantation *Eucalyptus globulus* (southern blue gum) which is notoriously difficult to dry. The timber was kiln dried from green to 10-12 % MC in 14 days, with limited downgrade resulting from the seasoning process. Some collapse was present in the *E. pilularis* boards, although in most cases this was removed during dressing and had little impact on final grade recovery (Hopewell, 2001).

Austin (2000) investigated the growth and utilisation of plantation eucalypts within eastern South America with the purpose of studying the challenges and opportunities for the Australian hardwood forest industry. It was reported that one of the sawmills investigated, namely Urufor S.A. in Uruguay, was processing plantation *E. grandis* (age unspecified) and indicated that boards with a nominal thickness of 32 mm took approximately 23 days to conventionally kiln dry to a final MC of between 8% and 12%.

3. Materials and methods

3.1 Sample material

The seasoning trials used boards sawn from plantation grown 19-year-old *E. cloeziana* and 15-year-old *E. pellita* and were part of a large portfolio of project work undertaken by DPI&F on the two plantation areas. Other project activities included evaluation of veneer and plywood production (Hopewell *et al.* 2007), physical and mechanical properties (McGavin *et al.* 2007) and natural durability trials (Francis and McGavin 2007).

Both these plantation areas were severely damaged by Cyclone Larry which passed through the North Queensland area in March 2006. Both plantation areas represented the age and growth performance expected from post-mid to final rotation plantations in North Queensland and are species relevant to future hardwood plantation establishment in the region. As plantations of this age and quality are rare, the opportunity to collect valuable wood quality, processing and product information was seized and suitable logs were salvaged soon after the cyclone. Details of the plantation history, tree selection, harvesting and sampling strategy has been provided by McGavin *et al.* (2007).

The limited log supply restricted the scope of the seasoning trials. Sixteen *E. cloeziana* and 12 *E. pellita* logs approximately 1.8 m in length were allocated for assessing the accelerated seasoning behaviour of the plantation sawn wood. Allocated logs were used to provide 100 mm wide boards, either 25 mm or 38 mm thick. Logs were processed using a standard sawing pattern commonly used by industry to process these species. Sawing produced an approximately even ratio of backsawn and transitionally sawn boards. In-log position data were recorded for the logs which provided the 38 mm thick boards. This was done by marking the log ends with different colours representing inner heart (blue), intermediate heart (red), outer heart (yellow), and sapwood (no colour) zones (Plate 1). Each heartwood zone represented approximately 1/3 of the heartwood radius. Processing aimed to provide boards with each zone represented, although as the proportion of wood decreased from the outer heartwood to the inner heartwood, so did the quantity of sawn boards. By targeting boards from known log zones, a preliminary comparison of drying behaviour in the juvenile core and the more mature heartwood could be investigated.

Plate 1 – Example of log with coloured zones

3.1 Drying properties and quality

The following property and quality measurements were done for all boards for each drying trial.

3.2.1 Moisture content

Before drying 25 mm long cross sections were removed while the boards were docked to the required lengths (governed by the kiln capacity) for initial green MC determination. Moisture content was determined using the oven-dry method in accordance with Australian and New Zealand Standard *AS/NZS 1080.1: 1997 Timber – Methods of test – Method 1: Moisture content* (Standards Australia 1997).

Final dried MC was determined from sections removed from each board, no closer than 400 mm from the board end. Two 25 mm long sections per board enabled cross-sectional MC and MC gradients to be calculated (by ripping into approximate 1/3 thickness pieces and calculating MC in accordance with *AS/NZS 1080.1:1997*).

3.2.2 Surface and internal checks

When kiln drying was complete, each board was assessed for surface checking in accordance with Australian Standard *AS2796.3:1999 Hardwood – Sawn and milled products – Part 3: Timber for furniture components* (Standards Australia 1999).

The presence of internal checking was determined on a present or absent basis by visually inspecting the freshly sawn end of each board (i.e. after the 400 mm and MC sections were removed).

3.2.3 Drying stress

When drying was complete, a 25 mm cross section was removed (from the same locations as the MC samples) and used to quantify residual drying stress in accordance with Australian and New Zealand Standard *AS/NZS 4787:2001– Timber – Assessment of drying quality* (Standards Australia 2001).

Drying stress was quantified by measuring the width of each cross section before ripping the section down the middle and measuring the gap between the freshly sawn concave/convex faces. The degree of drying stress is the ratio of gap width and section width expressed as a percentage as follows:

$$D_{stress} = (D_{gap} / W) \times 100 \qquad (1)$$

where,

D_{stress} = degree of residual stress as a percentage

D_{gap} = gap between concave / convex faces

W = board width

3.2.4 Drying quality class descriptions

In accordance with *AS/NZS 4787:2001*, drying quality classes were assigned for cross sectional MC, MC gradient and drying stress qualities. Quality classes are based on 90% of samples adhering to predetermined allowable limits dependent on the final target value for each property measured. The 10% balance can fall within any criteria of lower classes. Classes are ranked from A to E and are described as follows:

Class A – caters for specific end uses and very specific requirements for drying quality;

Class B – applies where tight control over drying is required to limit 'in service' movement resulting from changes in equilibrium moisture content;

Class C – applies where higher drying quality is required and the final use environment is clearly defined;

Class D – applies when the final use environment is more clearly defined but the drying quality requirements are not considered high; and

Class E – applies when the final use and drying quality requirements are not high.

For the purpose of this study, dried quality was deemed acceptable if 90 % of samples fell into quality class B or above. Table 1 shows the allowable limits for each quality class for cross sectional MC and MC gradient (target final MC of 10%), and drying stress in accordance with *AS/NZS 4787:2001*.

Table 1 – MC and drying stress allowable limits per quality class.

Quality class	Allowable range for 90 % of samples		
	Average MC	MC gradient	Drying Stress (D_{stress})
A	9 - 12	1	0.5
B	8 - 13	2	1
C	7 - 14	3	2
D	6 - 15	4	3
E	5 - 16	5	4

3.3 Kiln drying

A total of five drying trials were conducted, consisting of three conventional kiln trials (trials C1 to C3) and two vacuum kiln trials (trials V1 and V2). A 0.2 m^3 (research sized) kiln was used for the conventional drying trials and a 2.0 m^3 (research sized) superheated-steam vacuum kiln was used for the vacuum drying trials. The nominal board dimension (i.e. targeted dimension of dried rough sawn boards), number of boards seasoned in each trial, zone origin (if applicable), kiln type and species are provided in Table 2.

Table 2 - Number of boards and dimension per trial

Trial	Kiln type	Species	Nominal dimension (mm)	# of boards	# boards per zone		
					inner	intermediate	outer
C1	conventional	*E. cloeziana*	38 x 100 x 900	30	-	15	15
C2	conventional	*E. cloeziana*	38 x 100 x 900	30	-	15	15
C3	conventional	*E. pellita*	25 x 100 x 900	40	n/a	n/a	n/a
V1	vacuum	*E. cloeziana*	38 x 100 x 1900	55	7	22	26
V2	vacuum	*E. cloeziana*	25 x 100 x 1900	55	n/a	n/a	n/a

n/a indicates that no zone specific material was used.

3.3.1 Kiln charge preparation

Immediately after the boards were docked to length and the initial MC cross sections removed, each end of each board was coated with Aftek End Check™ wax emulsion. This coating reduces the development of end drying defects and helps ensure that the results gained from short board length trials are transferable to the industry practice of seasoning longer lengths. Boards allocated for trials C1 and V1 were stripped into the respective kilns immediately after preparation. Boards for the remaining trials were plastic wrapped and stored in a cool room at

10ºC. Plates 2 and 3 illustrate the conventional and vacuum kilns with similar stack preparation methods implemented for this study. The number of boards available for use in the vacuum trials only partially filled the vacuum kiln chamber. To maintain air flow integrity during drying, boards were stripped centrally in the vacuum kiln between dry ‘fill’ boards of a similar thickness. To reduce distortion, a concrete stack weight of 444 kg was used.

Plate 2 - Conventional kiln stack

Plate 3 - Vacuum kiln stack

3.3.2 Drying schedules

For each of the five trials (Table 2), the target, final cross-sectional MC was 10 %. The cross-sectional MC was monitored in the conventional kiln trials using a load cell to weigh the whole kiln stack (i.e. calculating MC based on known starting MC and weight loss during the trial). For the vacuum drying trials, resistance probes were used to monitor the cross-sectional MC.

Conventional drying

In the absence of a published recommended drying schedule for 38 mm *E. cloeziana*, the schedule used for trial C1 (Table 3) was developed by adjusting a recommended schedule reported by Rozsa and Mills (1991) for 25 mm *E. cloeziana*. The 38 mm schedule was milder than the recommended 25 mm schedule and was developed from schedules published for 25mm and 38 mm thick boards for *Eucalyptus camaldulensis* (river red gum).

Due to the unacceptable levels of surface checking recorded for dried boards from conventional trial C1, a milder drying schedule was chosen for trial C2. Table 4 shows this schedule used the same dry bulb temperatures as trial C1 (Table 3) but higher relative humidities were adopted. This modification was expected to reduce MC gradients during drying, resulting in reduced surface checks.

The schedule adopted for conventional trial C3 for 25 mm *E. pellita* was recommended by Rozsa and Mills (1991), and coincidentally was identical to the schedule used for conventional trial C1 (Table 3).

The equalisation conditions for each conventional trial are shown in Table 5. A 24 hour equalisation phase was used for trial C3 instead of the 36 hour phase adopted for C1 and C2 given the smaller board thickness. As the average final cross-sectional MC recorded for trial C1 was slightly higher than the target MC, the equalisation equilibrium moisture content (EMC) conditions were lowered from 11.5% to 11% for trials C2 and C3.

Table 3 – Trials C1 and C3 conventional drying schedule

Moisture Content Change Points (%)	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
Green	45	42	83	16.0
60	45	41	78	14.0
40	50	45	75	12.5
35	50	45	75	12.5
30	55	47	60	10.0
25	60	50	58	8.5
20	70	55	45	6.5
15 to final	70	50	35	5.0

Table 4 – Trial C2 conventional drying schedule

Moisture Content Change Points (%)	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
Green	45	42	83	16.0
60	45	42	83	16.0
40	50	46	80	14.0
35	50	46	80	14.0
30	55	50	75	12.5
25	60	52	65	10.0
20	70	60	60	8.5
15 to final	70	55	45	6.5

Table 5 – Conventional drying equalisation conditions

Trial label	Time (hrs)	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
C1	36	65	59.5	75.0	11.5
C2	36	65	59.0	73.0	11.0
C3	24	65	59.0	73.0	11.0

Vacuum drying

The vacuum kiln used for the study uses software which includes a number of pre-set schedules for various timber species (predominantly American and European species) of varying thickness. Only two pre-set schedules pertaining to native Australian eucalypts exist (*E. regnans* and *E. globulus)*. The drying properties of these 'ash' type species are very different from those for most sub tropical and tropical eucalypt species considered for plantation development in Queensland (including *E. cloeziana* and *E. pellita*). This difference is mainly due to ash's susceptibility to severe collapse. For this reason, existing vacuum drying schedules for Australian species were judged to be unsuitable.

The schedule chosen for the first vacuum drying trial V1 for *E. cloeziana* was the same schedule reported by Redman (2006) to have successfully vacuum dried native forest *Corymbia citriodora* (spotted gum). *Corymbia citriodora* and *E. cloeziana* have similar wood properties and are expected to have very similar seasoning characteristics. For example, Bootle (2005) published air dry densities of 950 kg/m^3 for mature *C. citriodora* and 1000 kg/m^3 for mature *E, cloeziana*. Similar drying behaviour for the two species is supported by Rankin (pers. comm. 2007) who uses the same drying schedule commercially for both species.

The schedule used to dry *C. citriodora* successfully was a preset schedule provided for *Hymenaea courbaril* (courbaril). The schedule was chosen on the understanding (supported by Simpson and Verill, 1997) that in general, timbers of similar densities often have similar drying characteristics. The average dried density of mature *H. courbaril* is 910 kg/m^3 (Lincoln 1991), which is similar to that reported for mature *C. citriodora*. Table 6 illustrates the schedule adopted for trial V1, and although presented as a conventional stepwise schedule, the dry and wet bulb temperatures were actually ramped between MC change points.

Due to marginal surface checking results recorded for dried boards from vacuum trial V1, a milder drying schedule was chosen for trial V2 (Table 7) using the preset schedule for *Acer saccharum* (sugar maple). The milder schedule was chosen because *Acer saccharum* has a tendency to develop surface check (Lincoln 1991). Although the V2 drying schedule appears harsher in terms of temperature and humidity than that used in trial V1, the schedules cannot be directly compared due to the different board thicknesses used between trials. Drying schedules can only be compared between trials drying boards of the same thickness. The recommended preset schedule to dry 38 mm *A. saccharum* is provided in Table 8 which is milder, in terms of temperature, when compared to the schedule used in trial V1.

Six, randomly chosen, sample boards were selected to measure MC using resistance probes at varying depths during the drying trials. Probes were inserted at depths of 5 mm (surface), 1/3 board thickness depth and 1/2 board thickness depth (core). The kiln was controlled using the average core MC to determine each change point, however, the kiln control software also combines MC gradient information from all the resistance probes to ensure MC gradients aren't too excessive for the required dried quality. The vacuum pressure was controlled by the standard kiln control software and ranged between approximately 200 and 300 mbar (0.2 to 0.3 atmospheres).

The vacuum kiln equilibrium moisture content conditions shown in tables 6, 7, and 8 were calculated and provided by the kiln control software. The relative humidity values were calculated using the Hailwood and Horrobin sorption theory (Hailwood and Horrobin 1946). Simpson (1971; 1973) and Chen (1997) used the formula to estimate EMC for sitka spuce and red oak respectively. The Hailwood-Horrobin formula is:

$$EMC = (\frac{K_1 K_2 h}{1 + K_1 K_2 h} + \frac{K_2 h}{1 - K_2 h}) \times \frac{1800}{W}$$

where

$$K_1 = 4.737 + 0.04773 - 0.00050123T^2$$

$$K_2 = 0.70594 + 0.001698T - 0.0000055535T^2$$

$$W = 223.385 + 0.6942T + 0.018533T^2$$

where EMC is the equilibrium moisture content (%), T is the Kelvin temperature, and h is the relative humidity (%).

Table 6 – Trial V1 vacuum drying schedule

Moisture Content Change Points (%)	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
Green	58	53.4	91	13
70	60	54.4	89	12
60	61	54.5	87	11
40	62	55.5	87	11
35	64	56.3	84	10
30	65	56.5	83	9.5
25	67	56	76	7.7
20	71	54	65	5.6
15 to final	75	62	74	6.9

Table 7 – Trial V2 vacuum drying schedule

Moisture Content Change Points (%)	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
Green	60	54	86	11
70	61	54.8	87	11
60	62	55.7	87	11
50	62	55.5	84	10
40	63	55.7	84	10
30	64	55.3	82	9.3
25	66	55	77	7.9
20	68	52	67	6.1
15 to final	71	58	73	6.9

Table 8 – Vacuum drying schedule for 38 mm *A. saccharum*

Moisture Content Change Points (%)	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
Green	58	52.2	86	11
70	59	53	86	11
60	60	53.8	86	11
50	61	54.7	87	11
40	62	54.9	84	10
30	63	54.3	82	9.4
25	65	54	77	8
20	67	51	68	6.2
15 to final	69	56	72	6.9

The equalisation conditions for each vacuum drying trial are shown in Table 9. As with the conventional trials, the equalisation times varied according to the board thickness used for each trial.

Table 9 - Vacuum drying equalisation conditions

Trial label	Time (hrs)	Dry Bulb	Wet Bulb	Relative	Equilibrium
V1	36	72	65.5	88.0	11.0
V2	24	65	58.0	88.0	11.0

4. Results and discussion

Much of the quantitative data in this report is presented as box plots. A box plot is a chart that indicates the central tendency of the values, their variability, the symmetry of the distribution, and the presence of outliers (i.e. values very different from the others). Box plots are often used to compare several sets of data.

There are several ways to display a box plot. This report uses the following format:

- the box itself contains the middle 50% of the data;
- the upper end of the box indicates the 75^{th} percentile of the data set;
- the lower end indicates the 25^{th} percentile;
- the distance between the upper and lower edges of the box is known as the inter-quartile range;
- the black horizontal line represents the median; and
- the **red horizontal line** represents the average.

If the median line within the box plot is not equidistant from the ends of the vertical line, then the data is skewed.

The ends of the vertical lines indicate the minimum and maximum data values, unless outliers are present in which case the vertical line extends to a maximum of 1.5 times the inter-quartile range.

The outliers are represented as circles which are filled in when the values are more than 3 times the inter-quartile range, and are empty if they are within the 1.5 to 3 times inter-quartile range interval.

4.1 Drying properties and quality

4.1.1 Moisture content

Initial moisture content

The initial cross-sectional MC results for each trial are presented in Figure 1.

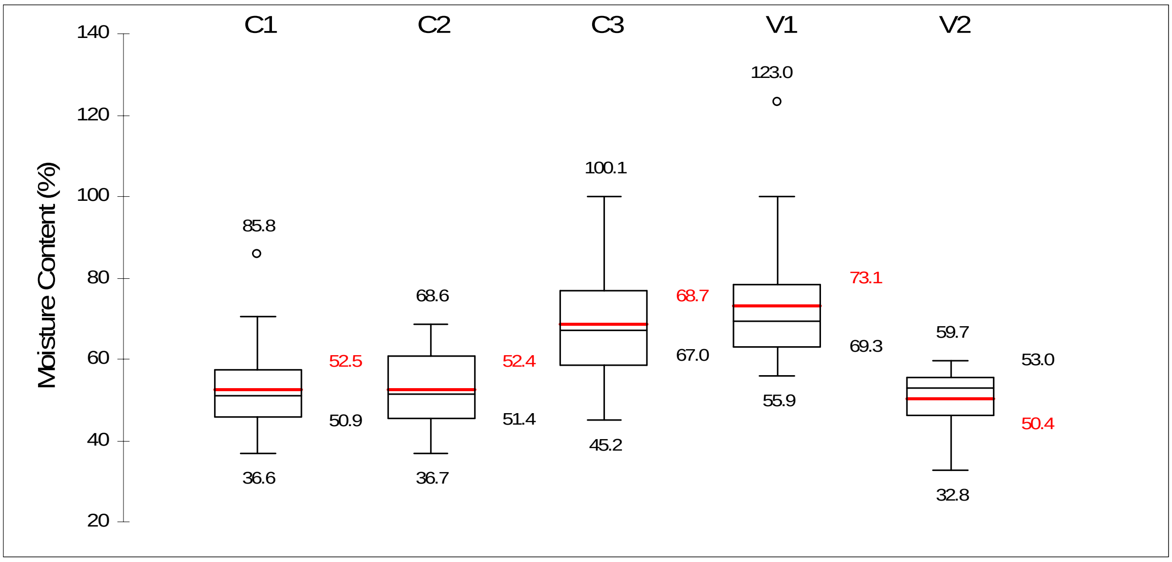

Figure 1 - Initial MC results for each trial

Including boards of known heartwood zone origin in trials C1, C2 and V1 allowed comparison of initial cross sectional MC between heartwood zones. Conventional trials C1 and C2 contained boards sourced from the intermediate and outer heartwood log zones. The zoned initial cross-sectional MC results for conventional trials C1 and C2 are presented in Figure 2. The results suggest that boards sawn from the outer heartwood zone tend to have a lower mean initial MC compared with boards sawn from the intermediate heartwood zone. An unpaired t-test confirms the differences in mean initial MC between the two zones are significant for both trials ($p = 0.05$ for trial C1 and $p < 0.001$ for trial C2).

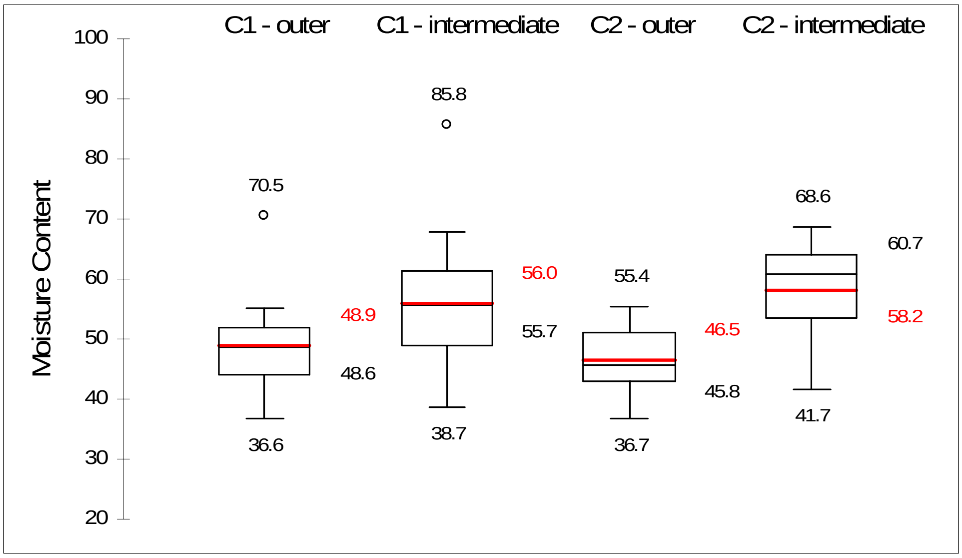

Figure 2 – Trials C1 and C2: zoned initial MC results for outer and intermediate heartwood zones (p = 0.05 for trial C1 and p < 0.001 for trial C2)

Figure 3 illustrates the zoned initial cross-sectional MC results for vacuum trial V1 which included representation from the inner, intermediate and outer heartwood log zones. As with the trend seen in trials C1 and C2, the mean initial MC of boards increases from the outer part of the log towards the inner. Analysis of variance (ANOVA) confirms that the difference between the mean initial MC of the three zones is significant ($p < 0.001$) and pairwise least significant difference (LSD) tests show that the initial MC means for each zone are significantly different from each other ($p \leq 0.05$).

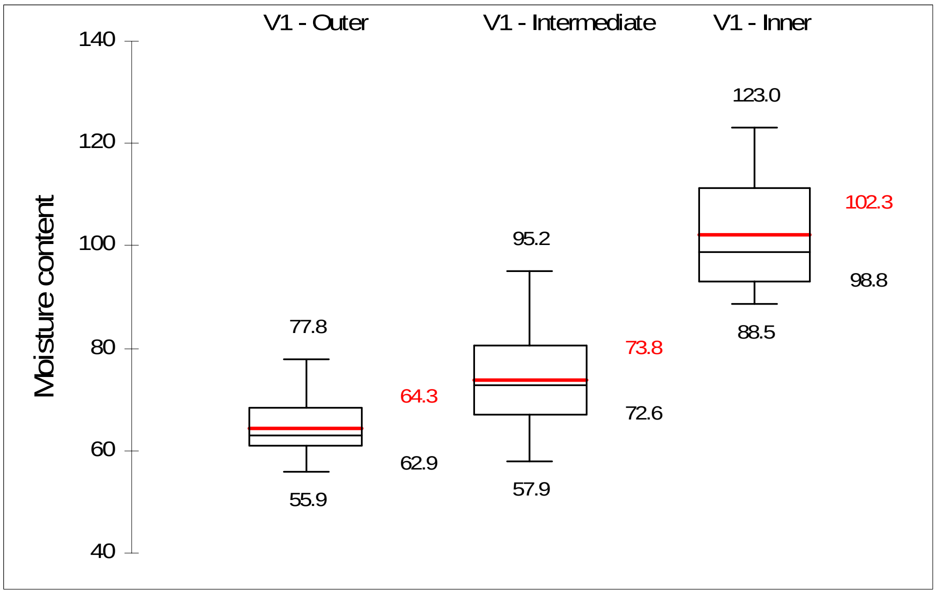

Figure 3 - Trial V1: zoned initial MC results for different heartwood zones ($p \leq 0.05$)

Final moisture content

The final cross-sectional MC and MC gradient results for each trial are presented in Figures 4 and 5 respectively. Table 10 shows the final measured cross-sectional MC and MC gradient grade quality breakdown in accordance with *AS/NZS 4787:2001* for each trial. Results are represented as the percentage of boards in each class along with the final assigned grade quality rating.

The results indicate that the average, final cross-sectional MC recorded for the 38 mm *E. cloeziana* material dried in trial C1 was 11.9 % which was unacceptably high given the target for all trials was 10%. This resulted in a final MC grade quality of 'C'. This was improved to an acceptable grade quality 'B' for trial C2 with an average final cross-sectional MC of 11.3 % being achieved. The improvement was attributed to lower equalisation EMC conditions used, resulting in the final MC being closer to the target MC. The overall cross-sectional MC range for trial C2 was also improved. The same EMC conditions from trial C2 were used to equalise the 25 mm *E. pellita* material in trial C3 which also achieved the acceptable final cross-sectional MC grade quality 'B'.

The final, cross-sectional MC results for vacuum trial V1 achieved acceptable grade quality 'B', however four 'wet' outliers were present (Figure 4). It is interesting to note that the three wettest outlier boards were all sawn from the same log. Due to a kiln malfunction, the final MC results for trial V2 were unacceptably low achieving grade quality 'C'. The humidity control during the equalisation phase failed resulting in 24 hours of extra drying at an EMC of approximately 6 % instead of equalising at the 12 % EMC setpoint. The malfunction is illustrated in the drying curve in Figure 7.

The MC gradient grade quality results for trials C1 and C2 were similarly improved from the unacceptable low grade quality for trial C1 to acceptable grade quality 'B' by using a milder schedule and adjusting the EMC conditions for trial C2. Unacceptable MC gradient grade quality results were recorded for trials C3, V1 and V2.

ANOVA tests show no significant difference ($p > 0.05$) between the final MC and MC gradient means within the zoned material for trials C1, C2 and V1.

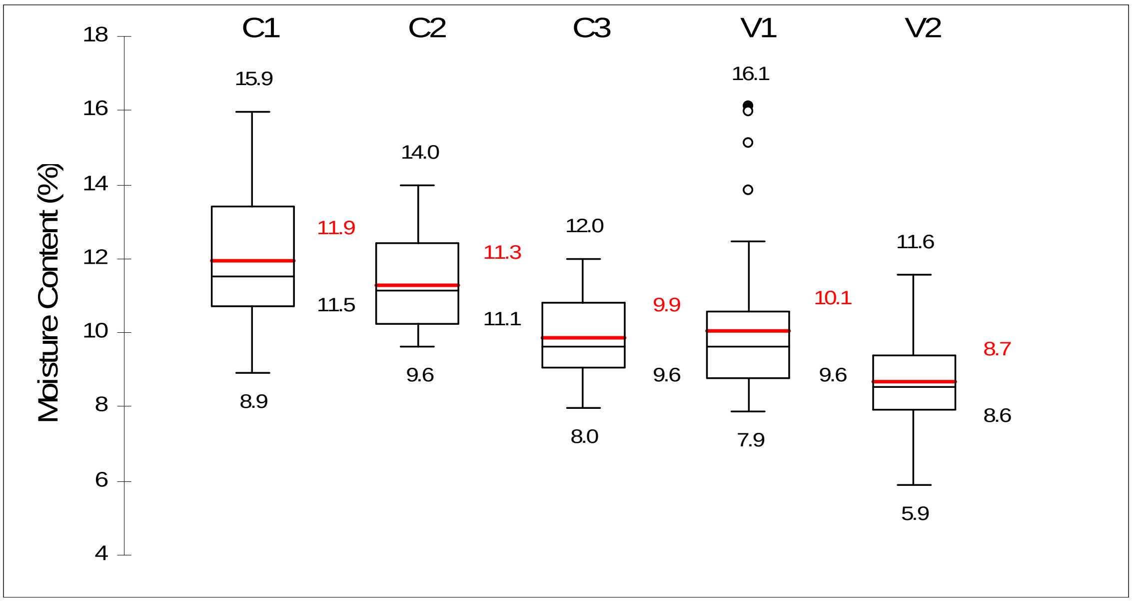

Figure 4 – Final, cross-sectional MC results for all trials ($p > 0.05$ between zones for trials C1, C2 and V1)

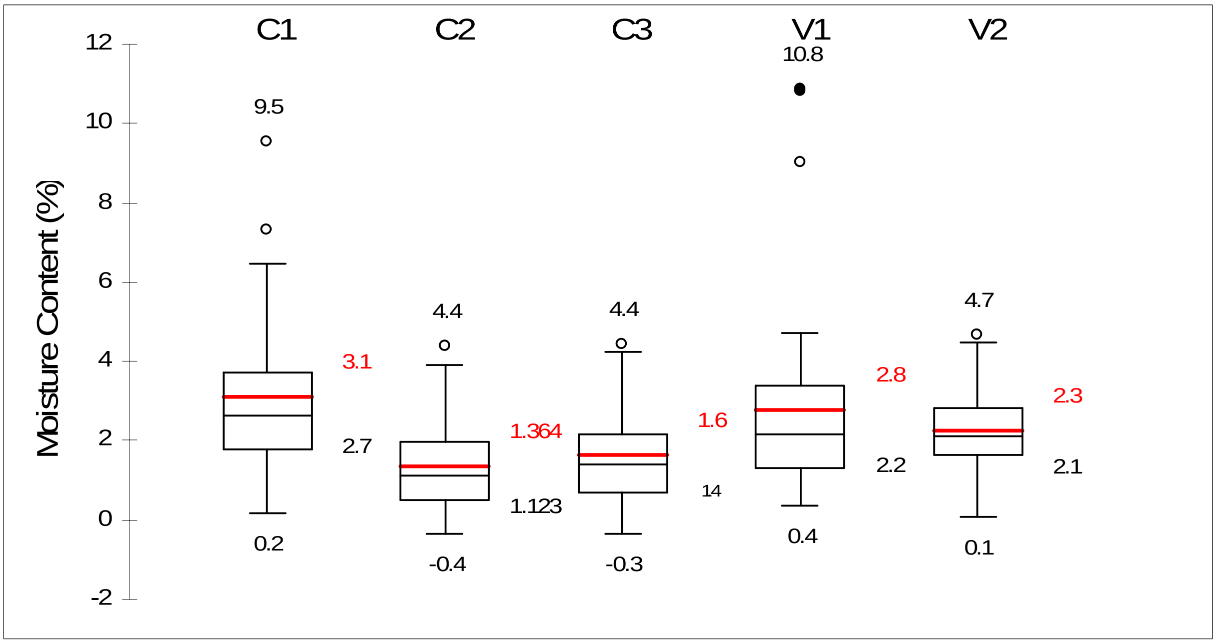

Figure 5 – Final MC gradient results for all trials (p > 0.05 between zones for trials C1, C2 and V1)

Table 10 – MC grade quality results

Grade	Grade percentage									
	Average MC					MC gradient				
	C1	C2	C3	V1	V2	C1	C2	C3	V1	V2
A	56.7	63.3	75.0	63.5	43.6	33.3	80.0	72.5	38.5	47.3
B	13.3	33.3	25.0	32.7	29.1	26.7	10.0	10.0	21.2	34.5
C	20.0	3.3	-	3.8	21.8	10.0	3.3	10.0	21.2	9.1
D	3.3	-	-	-	3.6	10.0	3.3	2.5	5.8	3.6
E	6.7	-	-	-	1.8	6.7	3.3	5.0	13.5	5.5
Fail	-	-	-	-	-	13.3	-	-	-	-
Final Grade	C	B	B	B	C	Fail	B	C	E	C

4.1.2 Surface and internal checks

Surface and internal checking are caused by a tension failure across the grain of the wood. Surface check formation usually occurs during the initial stages of drying (from green MC to approximately 2/3 green MC) due to the surface tension created by large MC surface to core gradients which are in turn caused by excessive drying rates (Wengert, 2006).

Internal checking can occur from a number of mechanisms. The most common include:

- the effect of surface tension set due to high initial drying rates causing internal checks to develop after stress reversal;
- extension of end checks; and
- those associated with collapse (McMillen 1963).

Table 11 shows the percentage of boards check-free (surface and internal) and the percentage of select (best) grade boards in accordance with *AS2796.3:1999*. Surface checking was present in all trials. For trial C1, an unacceptable 80 % of boards made select grade for surface checking. This result was improved for trial C2, where 90 % of boards made select grade, by adjusting the drying schedule such that higher relative humidities were used throughout. Even though the number of boards free of surface checks was slightly lower for trial C2 (43%) compared with trial C1 (57%), the checks were much smaller and less frequent along the length of the boards resulting in a better grade quality overall. Only 7 % of boards exhibited surface checks for trial C3, however they were not severe or frequent enough to prevent 100% of boards making select grade.

Acceptable surface checking was recorded for vacuum drying trial V1 with 64 % of boards free of surface checks and 93% of boards meeting select grade. A slightly milder schedule was used for vacuum drying trial V2 which improved the number of surface check-free boards recorded to 89% and resulted in 100 % of boards meeting select grade requirements.

All boards in each trial were free of internal checking which was encouraging.

Table 11 – Surface and internal checking results

	C1	C2	C3	V1	V2
Surface check-free boards (%)	57	43	93	64	89
Select grade for surface check (%)	80	90	100	93	100
Internal check-free boards (%)	100	100	100	100	100

4.1.3 Drying stress

Drying stress results for each trial are presented in Figure 6. Table 12 gives grade quality as the percentage of boards in each class along with the final allocated grade. For trial C2, the drying stress grade quality was improved to acceptable ‘B’ grade compared with the unacceptable ‘C’ grade achieved in trial C1. This improvement can be attributed to the milder drying schedule and adjustments to the EMC conditions during equalisation. Acceptable drying stress grade quality results were recorded for conventional trial C3.

The drying stress grade quality results for both vacuum drying trials V1 and V2 achieved the unacceptable ‘C’ grade. Fewer boards in trial V2 (81.1%) achieved the acceptable grade ‘B’than in trial V1 (5.5%), a result influenced directly by the equalisation stage failure during trial V2. This result is clearly evident in Figure 6.

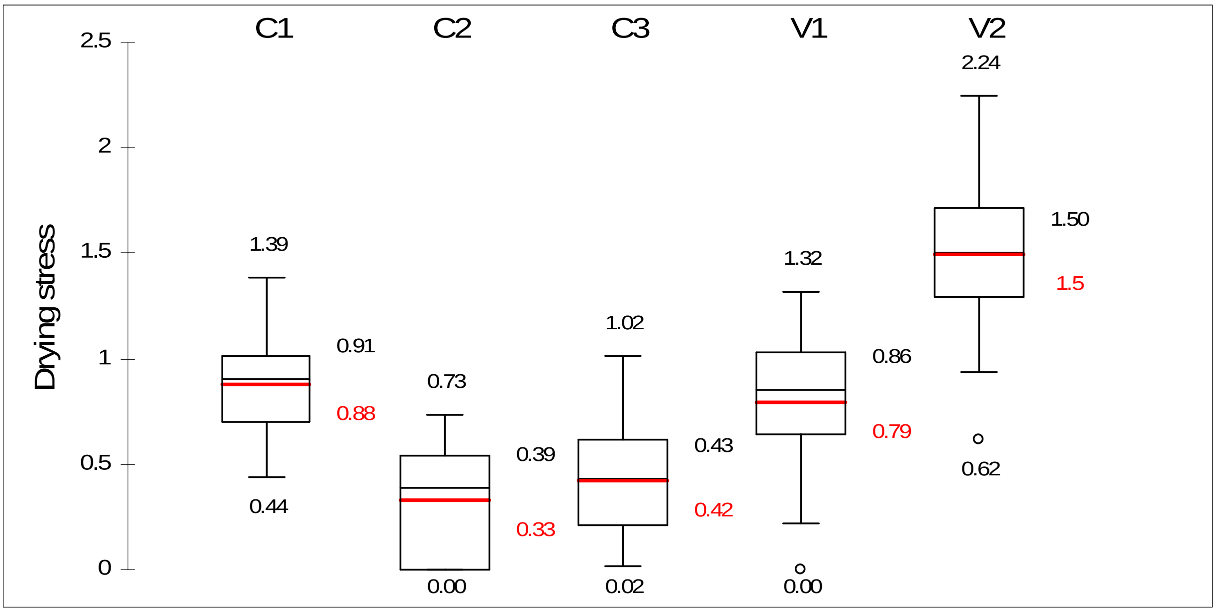

Figure 6 – Drying stress results for each trial

Table 12 – Drying stress grade quality results for each trial

Grade	Grade percentage				
	C1	C2	C3	V1	V2
A	13.3	76.7	65.0	15.1	-
B	70.0	23.3	35.0	66.0	5.5
C	16.7	-	-	18.9	89.1
D	-	-	-	-	5.5
E	-	-	-	-	-
Fail	-	-	-	-	-
Final Grade	C	B	B	C	C

4.2 Kiln drying

Moisture content as a function of drying time for each trial is shown in Figure 7. The MC values shown are the average values calculated from the load cell for the conventional kiln trials and the resistance probes for the vacuum kiln trials. Table 13 includes the final drying time (including the equalisation phase) and MC movement for each trial. The time to dry the 38 mm thick *E. cloeziana* in trial C1 was 20.3 days. This was lengthened to 23.2 days for similar material dried in trial C2 due to the milder drying schedule applied but did provide improved dried quality. The conventional drying time for the 25 mm thick *E. pellita* material was 17.7 days. The vacuum drying time for 38 mm thick *E. cloeziana* boards dried in trial V1 was approximately 60% shorter than that dried in conventional trials C1 and C2. The vacuum drying time for the 25 mm thick *E. cloeziana* boards dried in trial V2 was shorter than for the 38 mm thick boards as expected.

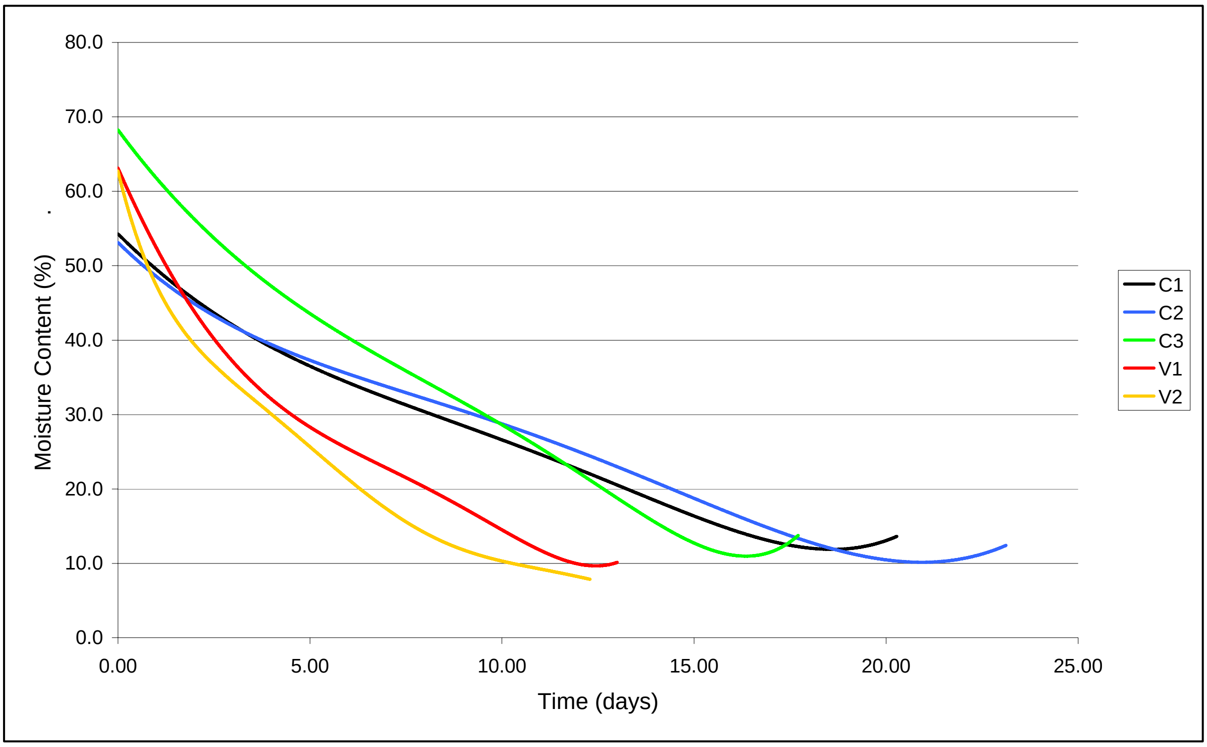

Figure 7 – Moisture content drying curves for each trial. Average values are calculated from the load cell for the conventional kiln trials (C) and the resistance probes for the vacuum kiln trials (V).

Table 13 – Initial and final drying times (including the equalisation phase) and MC movement for each trial.

	C1	C2	C3	V1	V2
Drying time (days)	20.3	23.1	17.7	13	12.2
Initial MC	52.5	52.4	68.7	73.1	50.4
Final MC	11.9	11.3	9.9	10.1	8.7

5. Conclusions

The drying schedule used to conventionally dry 38 mm thick plantation grown *E. cloeziana* for trial C1 was developed intuitively by adjusting a published schedule for 25 mm *E. cloeziana*. The slightly milder schedule used for the second conventional trial C2, drying the same species and thickness, was derived to improve the surface checking results experienced in the first trial. The drying schedule to conventionally dry 25 mm thick *E. pellita* for trial C3 was the same as that recommended by Rozsa and Mills (1991). The schedule used for the first vacuum drying trial of 38 mm *E. cloeziana* (trial V1) was the same schedule recently used by DPI&F to successfully vacuum dry native forest *Corymbia citriodora* in an earlier study (Redman 2006). This schedule was chosen on the knowledge that mature native forest *C. citriodora* and *E. cloeziana* have similar wood properties and that both species have similar drying properties, and this was supported by Rankin (pers. comm. 2007). Marginal levels of surface checking in trial V1 influenced the decision to use a milder schedule for the vacuum drying trial V2 to dry 25 mm thick *E. cloeziana*. The schedule was selected from the kiln's package pre-set schedule for European species *Acer saccharum* (sugar maple) known to have a similar tendency to surface check.

Statistical analysis demonstrated that the initial cross-sectional MC increased from the inner to the outer heartwood in the trials with known heartwood origin. For each trial, the target final cross-sectional MC was 10%. The average final cross-sectional MC for conventional trial C1 was unacceptably high (11.9%) resulting in a grade quality of 'C' being assigned. This was improved in trial C2 with schedule modifications which resulted in a final MC of 11.3 %, Combined with a tighter range, an acceptable grade quality 'B' was achieved. Conventional trial C3 and vacuum trial V1 also achieved the acceptable grade quality 'B' for final cross-sectional MC. Four wet outlier boards were present at the completion of trial V1, three of which belonged to the same log. The final cross-sectional MC of 8.6% was unacceptably low for trial V2 influencing the unacceptable grade quality 'C'. The over-drying of boards in trial V2 is a result of a kiln malfunction during the equalisation phase.

Schedule manipulation also improved the moisture gradient grade quality results from trial C1's failed grade to 'B' grade for C2. Unacceptable grade quality results were recorded for the remaining trials. Further schedule optimisation, particularly the equalisation phase, would be expected to achieve improvements by reducing MC gradients. As a result of the drying and equalisation processes, there was no statistical significance between the final MC and moisture gradient means between zoned material for trials C1, C2, and V1. This is a desirable outcome as the seasoning and equalisation processes are designed to produce material with a homogeneous final MC between and within boards.

Drying stress grade quality results for conventional drying trial C1 achieved an unacceptable grade quality 'C', however, this was improved through schedule adjustments to the acceptable grade quality 'B' for trial C2. Similar acceptable drying stress grade quality results were recorded for conventional trial C3 (grade 'B'). Both vacuum drying trials achieved unacceptable drying stress grade results (grade 'C'). The drying stress quality for trial V2 was much less than for trial V1 due to the lack of humidity control during the equalisation phase. For those trials not meeting acceptable drying stress grade quality, further schedule optimisation, particularly the equalisation phase, would be expected to make improvements.

Surface checking was present in varying quantities within all trials. An unacceptable proportion of only 80% of boards within trial C1 made select grade for surface checking, the highest grade quality within *AS2796.3:1999*. This result was improved as a result of schedule manipulation for conventional trial C2 where a marginal 90% of boards met the requirements of select grade. Excellent surface checking results were achieved for conventional drying trial C3 with all boards making select grade. Acceptable surface checking results were recorded for both vacuum drying trials. The milder schedule used for trial V2 improved the grade quality from 93% meeting select grade for trial V1 to 100% meeting the select grade requirements. The best possible result was achieved for internal checking whereby every board in all trials was free of internal checks.

The total drying time including the equalisation phase for 38 mm thick *E. cloeziana* for conventional trials C1 and C2 were 20.3 and 23.2 days respectively. The longer drying time experienced for trial C2 was due to the milder drying schedule used. The drying time to vacuum dry 38 mm thick *E. cloeziana* (trial V1) was approximately 60% shorter than conventional trials at 13 days. These drying times are considerably shorter than the 30 days needed to dry native forest material of the same species and thickness (Rankin, pers. comm. 2007). The drying time to vacuum dry 25 mm *E. cloeziana* was 8.2 days which is also considerably less than the 20-21 days to conventionally dry 25 mm thick native forest *E. cloeziana* (Rankin pers. comm. 2007). The drying time to conventionally dry the 25 mm thick *E. pellita* was 17.7 days (trial C3).

The findings are encouraging and indicate that young, fast grown plantation *E. cloeziana* and *E. pellita* can be dried rapidly using conventional or vacuum drying technology. The results suggest that drying plantation grown material is considerably faster than the drying times expected for drying native forest material of the same species. The results indicate that vacuum drying appears to be considerably faster than conventional drying for drying plantation grown 19-year-old *E. cloeziana* although drying quality needs improving. The findings also allude to the substantial benefits of conducting multiple trials where careful schedule manipulation and adjustment can be completed. The study has demonstrated that plantation *E. cloeziana* and *E. pellita* can be dried quickly and has provided a useful schedule benchmark.

Additional research is required to refine these schedules to ensure acceptable grade qualities can be reliably achieved across all drying criteria and exploit opportunities to reduce drying times further.

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