GROWTH RESPONSE AND WOUND OCCLUSION IN PRUNED *CORYMBIA TORELLIANA*

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Received February 2011

LIU Q, CHEN SX, LI ZH & ARNOLD RJ. 2012. Growth response and wound occlusion in pruned *Corymbia torelliana*. A field trial to examine growth and wound healing of pruned *Corymbia torelliana* was established in a 40-month-old plantation in western Guangdong, China. It included: (1) pruning all branches up to stem diameters of 5, 6, 7 or 8 cm, (2) wound protection with wax or paint and (3) a control with no pruning. Measurements of growth and wound occlusion taken at various intervals up to 12 months after pruning showed that pruning generally impeded height growth, promoted diameter at breast height (dbh) growth and slightly increased taper. The optimal pruning intensity for tree growth was pruning up to stem diameter of 8 cm. Lower wound occlusion rates occurred in heavier pruning intensities. The optimal intensity for rapid wound occlusion was pruning up to stem diameter of 7 or 8 cm. Paint resulted in better occlusion than wax. The fastest wound occlusion occurred in stem section of height 2.51 to 5.35 m above the ground. Rate of wound occlusion up to 12 months showed correlations with dbh increment, initial wound size and pruning intensity.

Keywords: Pruning intensity, protection, growth, southern China

LIU Q, CHEN SX, LI ZH & ARNOLD RJ. 2012. Gerak balas pertumbuhan dan katupan luka dalam *Corymbia torelliana* yang dicantas. Ujian lapangan bagi mengkaji pertumbuhan dan penyembuhan luka *Corymbia torelliana* yang dicantas dijalankan di ladang berusia 40 bulan di barat Guangdong, negara China. Rawatannya adalah (1) mencantas kesemua dahan sehingga diameter batang berukuran 5 cm, 6 cm, 7 cm atau 8 cm, (2) melindungi luka dengan lilin atau cat dan (3) kawalan tanpa cantasan. Pertumbuhan dan katupan luka disukat pada selang tertentu sehingga 12 bulan selepas pencantasan. Pada umumnya, pencantasan menghalang pertumbuhan tinggi, menggalak pertumbuhan diameter pada aras dada (dbh) dan menjadikan bentuk batang tirus sedikit. Pencantasan yang optimum untuk pertumbuhan pokok adalah mencantas sehingga diameter batang berukuran 8 cm. Kadar pencantasan yang tinggi menyebabkan kadar katupan luka yang rendah. Pencantasan yang optimum untuk kadar katupan luka yang cepat adalah mencantas sehingga diameter batang berukuran 7 cm atau 8 cm. Cat mengakibatkan katupan luka yang lebih baik daripada lilin. Katupan luka paling cepat pada batang antara ketinggian 2.51 m hingga 5.35 m di atas tanah. Kadar katupan luka sehingga 12 bulan menunjukkan korelasi dengan pertambahan dbh, saiz luka asal dan kadar pencantasan.

INTRODUCTION

Eucalypts were first introduced to China in the 1890s. During the last half of this period, they were predominantly planted for the production of fuel and fibre, rather than for production of solid wood end-products (Yu et al. 2007). Only a small proportion of eucalypt plantations in China is now managed primarily for solid wood end-products (Chen 2002).

In China, there is now increasing interest in developing fast-growing plantations, including eucalypts, specifically to supply quality timbers for higher value solid wood end-products (Cai et al. 1998, Chen et al. 2010). At present, most of the log demand in China for manufacturing hardwood sawn timbers and higher quality surface veneers is met by imported logs. Based on experience and industry developments in other countries, selected eucalypt varieties are seen to have good potential for sustainable plantation production of logs in China to supply such markets (Chen et al. 2010).

However, the value and suitability of plantation eucalypt timbers for higher value solid wood applications can be limited by the presence of knots (Lin 1992). Knots and associated defects are important indicators of wood quality both

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for appearance-grade products and structural timbers. From the perspective of wood quality, knots reduce the value of the raw material because they decrease the strength and stiffness of wood intended for structural uses (Whiteside et al. 1977, Briggs 1996, Gartner 2005). Size and location of knots are important characteristics in determining the grade of solid wood products such as structural lumber (Haygreen & Bowyer 1996).

Pruning is a silvicultural treatment that can help optimise the yield of knot-free timber from fast-grown eucalypt plantations (Pinkard & Beadle 1998, Pinkard 2002). However, the intensity of pruning can influence both subsequent growth and stem shape (Fujimori 1993). Moreover, the pruning method can influence the potential for subsequent stem decay. In oak species, pruning branches flush to the stem (i.e. without retaining branch stubs) is known to result in less internal stem decay and faster occlusion than when protruding stubs remain after pruning (Giefing et al. 2011).

Time of pruning, relative to tree development, has also been shown to influence the potential yield of quality clear wood in a number of species. If trees are pruned too young, particularly prior to canopy closure, tree growth may be significantly reduced (Montagu et al. 2003). Thus, development of an appropriate pruning regime that optimises post-pruning responses is critical to optimising yields of the desired end-products (Uotila & Mustonen 1994, Pinkard & Beadle 1998, Pinkard 2002, Montagu et al. 2003, Smith et al. 2006, Dieter & Marta 2007).

Pruning can reduce subsequent growth if too much live crown is removed. Schlesinger and Shigo (1989) provided a rule-of-thumb guide that no more than 25% of the live crown should be removed at any one pruning and a 50% live crown/bole ratio should be maintained in order to reduce the impact on growth. Pinkard (2002) demonstrated that the more severe the pruning of green crown in eucalypts, the greater the effect on stem volume, thus affecting site productivity. Many studies have found diameter growth to be more sensitively affected by loss of green crown due to pruning or insect defoliation than height growth (Langstrom & Hellqvit 1991, Majid & Paudyal 1992, Pinkard 2002).

In eucalypts, pruning wounds can be problematic as they provide increased risk of entry of fungal diseases into the interior of the bole and problems can also arise during wound occlusion (Mohammed et al. 2000). Damage to the branch collar (where the branch joins the stem) in the process of branch pruning may slow the healing process and promote internal decay (Mohammed et al. 2000). Thus, reducing the risk of fungal infections often associated with eucalypt pruning wounds is considered to be of paramount importance in designing pruning regimes. The protection of exposed wounds/cut surfaces resulting from the pruning process has been suggested as a means to reduce risks.

The speed at which pruning wounds occlude can have important impacts on subsequent wood quality. A long period of branch occlusion can lead to the occurrence of undesirable discoloration and/or rot inside the stem with significant losses in log value (Hein 2008). The time required for occlusion of wounds of pruned branch relates to the diameter of branch and stem diameter increment during the occlusion period (Polli et al. 2006, Hein & Spiecker 2007, Hein 2008). Silvicultural factors which enhance stem diameter growth, such as decreasing stand density, can help shorten the time required for occlusion (Mäkinen 1999, Hein & Spiecker 2007).

In order to develop effective pruning regimes for optimising yields of eucalypt timbers from fast-growing plantations in southern China, a field study was initiated in a young *Corymbia torelliana* plantation. The objectives of this study were to (1) quantify the effect of alternative pruning intensities and branch sizes on both occlusion rates and subsequent tree growth and (2) examine the effect of two wound protection methods on occlusion rates.

This study assessed indicators of growth response after pruning, i.e. increments of height, diameter at breast height (dbh), height/dbh ratio and crown area together with indicators of wound occlusion. We reported the results up to 12 months after pruning.

MATERIALS AND METHODS

Sample plots

The young *C. torelliana* plantation in South China Experimental Nursery was located in Zhanjiang of western Guangdong province, at latitude of 21° 16' N and longitude of 110° 05' E. This site has tropical climate with mean annual temperature of 23.1 °C, mean maximum temperature of 38.1 °C and mean minimum temperature of 13.6 °C. It has mean annual rainfall of 1567 mm, mean annual relative humidity of 80.4%, with wet season from May till September, accounting for 85.5% of the mean annual rainfall.

The topography of the site is flat. The soil is brick red, deeply weathered and derived from basalt parent material. The plantation was established under 2 × 2 m spacing with 4-month-old and 30 cm high seedlings. It was systematically thinned resulting in 2 × 4 m spacing. Pruning was done when trees were 40 months old.

Experimental design

The two treatment factors applied were pruning intensity and wound protection method. Four levels of pruning intensity were used—pruning all live branches up to height limits defined by stem diameters (over bark) of 5, 6, 7 or 8 cm (Figure 1). With these limits, the smaller the diameter the more intense or severe the pruning was. Two methods of wound protection were used, namely, covering the wound surface (i.e. the cut branch stub) with either a layer of wax or oil-based paint.

The two treatments were combined in a factorial manner to give a total of eight treatments. A control (no pruning) treatment was also included. The treatments were applied to 10 tree plots (two rows of five trees) and nine treatments were assigned randomly to plots within each of three complete replicates (randomised complete block design), giving a total of 27 plots in the trial.

Assessments

Growth was assessed immediately prior to pruning and then at 7 and 12 months after pruning. The traits assessed were total tree height, dbh, crown size and height to the first live branch. Tree height and height to the first live branch were measured using height sticks (average total height of 3-year-old *C. torelliana* stand before pruning was about 6 m). Dbh was measured at height of 1.3 m using metal tape. Crown size was obtained by measuring crown horizontal dimensions in both east–west and south–north directions.

Horizontal width (diameter) of the pruning wounds was evaluated at 0, 3, 7, 9.5 and 12 months after pruning. Initial wound diameters were categorised as small (0–10.0 mm), medium (10.1–20.0 mm), large (20.1–25.0 mm) and extra large (> 25.0 mm). Wounds were also classified according to height above ground, with stem height sections being defined as I (0–1.00 m), II (1.01–2.50 m), III (2.51–4.00 m) and IV (4.01–5.35 m height above ground).

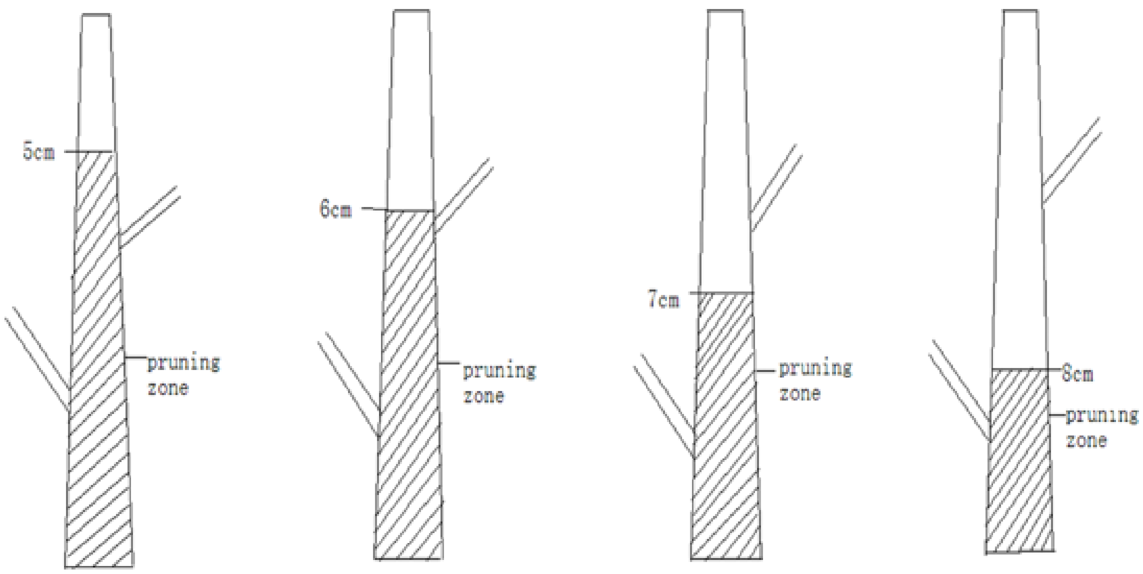

Figure 1 Diagrammatic depiction of the four levels of pruning intensity used in this study; all live branches were pruned up to height limits defined by stem diameters (over bark) of 5, 6, 7 or 8 cm

The changes in wound diameters over time provided data for calculation of occlusion rate and the proportion of wound that had occluded completely. These parameters were calculated on a plot mean basis as follows:

$$OCR = \frac{IWW - CWW}{IWW} \times 100 \qquad (1)$$

where

OCR = occlusion rate (%)
IWW = initial wound width (mm)
CWW = current wound width (mm)

$$COP = \frac{COW}{TWN} \times 100 \qquad (2)$$

where

COP = proportion of wounds that had occluded completely (%)
COW = number of completely occluded wounds
TWN = total number of wound

Statistical analysis

Analyses of variance were carried out to evaluate if there were significant differences between treatments for growth, stem form and wound occlusion traits using the SAS statistical software package. Stepwise regression was used to reveal key factors associated with wound occlusion.

RESULTS AND DISCUSSION

Tree growth response

At 12 months after pruning, the average values for height (8.04 m), dbh (10.0 cm), height to the first live branch (3.11 m), crown area (9.24 m^2) and individual tree volume (22.58 cm^3) showed increments over the pre-pruning averages of 28.4, 29.6, 12.1, 53.9 and 122.3% respectively (results not shown). At this age, only height increment differed significantly with pruning intensity.

Despite the lack of significant differences between pruning treatments (including the control) for dbh and volume increment, dbh growth appeared to be more affected by pruning than height growth. This was consistent with other studies (Lückhoff 1967, Sutton & Crowe 1975, Langstrom & Hellqvit 1991, Majid & Paudyal 1992, Pinkard 2002).

Wound occlusion

The total number of pruned branches assessed in this study was 545 (Table 1). Medium and large wounds accounted for 83.7% of the total, indicating that most branches up to the various pruning heights had basal diameter within the range of 10.1 to 25.0 mm. Most branches (87%) were found within height sections II and III (1.01 to 4.00 m above the ground).

Pruning intensity, method of wound protection and height of the stem all influenced wound occlusion rate, as judged by the proportional differences in wound diameters between immediately after pruning and 12 months later. For medium-sized wounds, occlusion rates differed significantly between pruning intensity, protection method and height section, while occlusion rates for large wounds differed significantly only between the protection method and height (Table 2). For extra large wounds, there were no significant differences in occlusion rates.

For medium-sized wounds, the highest occlusion rates were observed with pruning intensity of 7 cm (86.9%), in height section III (86%) and wound protection with paint (80%) (Figures 2c, 3c and 4a). The lowest occlusion rates for medium-sized wounds occurred with pruning intensity of 6 cm, in height section I and wound protection with wax, with occlusion rates of 65.8, 55.7 and 70.4% respectively (Figures 2b, 3a and 4b). For large wounds, the highest occlusion rates occurred with pruning intensity of 7 cm, in height section IV and wound protection with paint, with occlusion rates of 93.6, 97.8 and 91.0% respectively (Figures 2c, 3d and 4a). The lowest occlusion rates for large wounds occurred with pruning intensity of 5 cm, in height section I and wound protection with wax, with rates of 72.6, 65.0 and 74.6% respectively (Figures 2a, 3a and 4b). The highest occlusion rates of extra large wounds occurred in the pruning treatments of 8 cm pruning intensity, in height section IV and wound protection with paint, with rates of 97.0, 100.0 and 94.7% respectively (Figures 2d, 3d and 4a). The lowest occlusion rates for extra large wounds occurred in treatments of 6 cm pruning intensity, height section II and wound protection with wax, with rates of 91.3, 89.3 and 91.6% respectively (Figures 2b, 3a and 4b).

Table 1 Number of branches pruned by branch diameter and pruning treatments on *Corymbia torelliana* trees

Parameter		Branch diameter class [b]				No. of pruned branch
		Small	Medium	Large	Extra large	
Pruning intensity	5 cm	0	67	28	12	107
	6 cm	0	68	84	41	193
	7 cm	4	78	38	19	139
	8 cm	0	64	29	13	106
Protection	Paint	4	142	67	32	245
	Wax	0	135	112	53	300
Height section[a]	I	0	35	21	13	69
	II	4	169	105	53	331
	III	0	76	65	45	186
	IV	0	2	4	2	8
Total		4	277	179	85	545

[a] Height section: I = 0–1.00 m, II = 1.01–2.50 m, III = 2.51–4.00 m, IV = 4.01–5.35 m; [b] branch diameter class: small = 0–10.0 mm, medium = 10.1–20.0 mm, large = 20.1–25.0 mm, extra large = > 25.0 mm

Table 2 Analyses of variance on wound occlusion rates at 12 months after pruning

Wound size category[a]	Factor	Df	Mean square	F-value
Medium	Pruning intensity	4	0.465	4.83**
	Protection	1	1.213	12.24**
	Height section	3	0.538	5.47**
Large	Pruning intensity	4	0.028	0.34
	Protection	1	1.060	13.23**
	Height section	3	0.299	3.64*
Extra large	Pruning intensity	4	0.027	0.71
	Protection	1	0.037	0.99
	Height section	3	0.024	0.65

[a]Wound size category: medium = 10.1–20.0 mm, large = 20.1–25.0 mm, extra large = > 25.0 mm;
* significantly different at $p \leq 0.05$, **significantly different at $p \leq 0.01$

Both occlusion rates and proportions of completely occluded wounds differed significantly between pruning treatments. For the former, these varied significantly between pruning intensity for medium-sized wounds and also between wound protection method for medium- and large-sized wounds ($p < 0.01$; Table 2). Pruning intensities of 7 and 8 cm generally proved superior to intensities of 5 and 6 cm and paint proved superior to wax for obtaining higher occlusion rates (Figure 2).

For the proportions of completely occluded wounds, pruning intensities of 7 and 8 cm proved superior to intensities of 5 and 6 cm (Figure 5). Studies on pruning of *Eucalyptus* showed that a minimum level of leaf and branch retention was required for the maintenance of stemwood production (Pinkard & Beadle 1998). Below such levels, carbon gets diverted from stemwood to increasing or maintaining leaf and branch development. The inference of their findings to our current study was that pruning intensities up to 7 or 8 cm would be the maximum level of pruning (i.e. minimum level of branch and leaf retention) to maintain stemwood production in *C. torelliana*. Although young eucalypts can compensate for moderate levels of leaf area removal without permanent growth reductions,

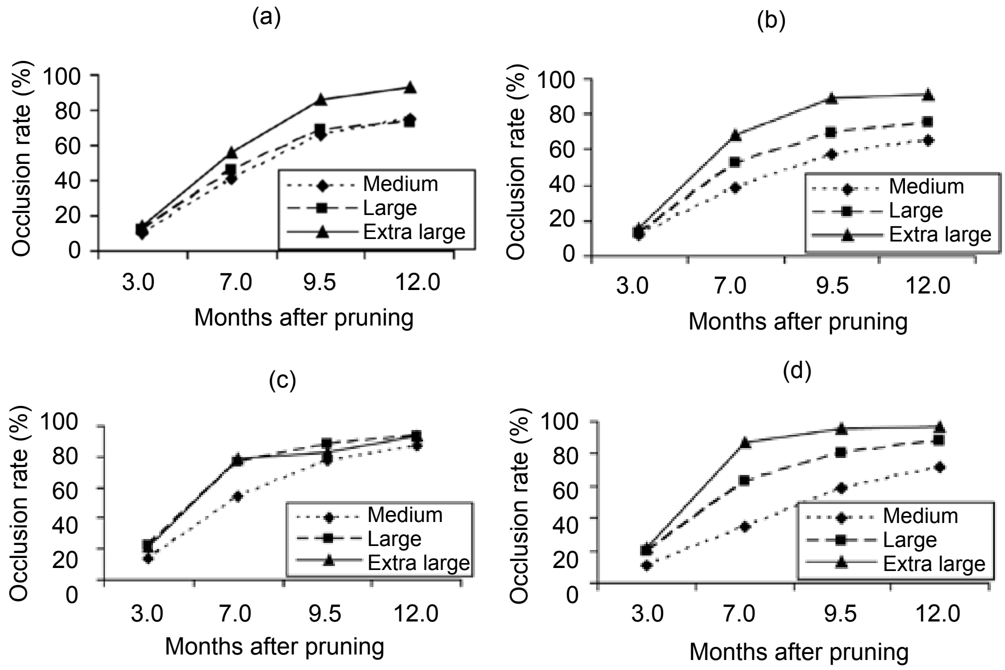

Figure 2 Occlusion rates of pruned wounds over time by wound size category for pruning up to stem diameters of (a) 5, (b) 6, (c) 7 and (d) 8 cm; results for small wounds (≤ 10.0 mm) were omitted due to the small number of data

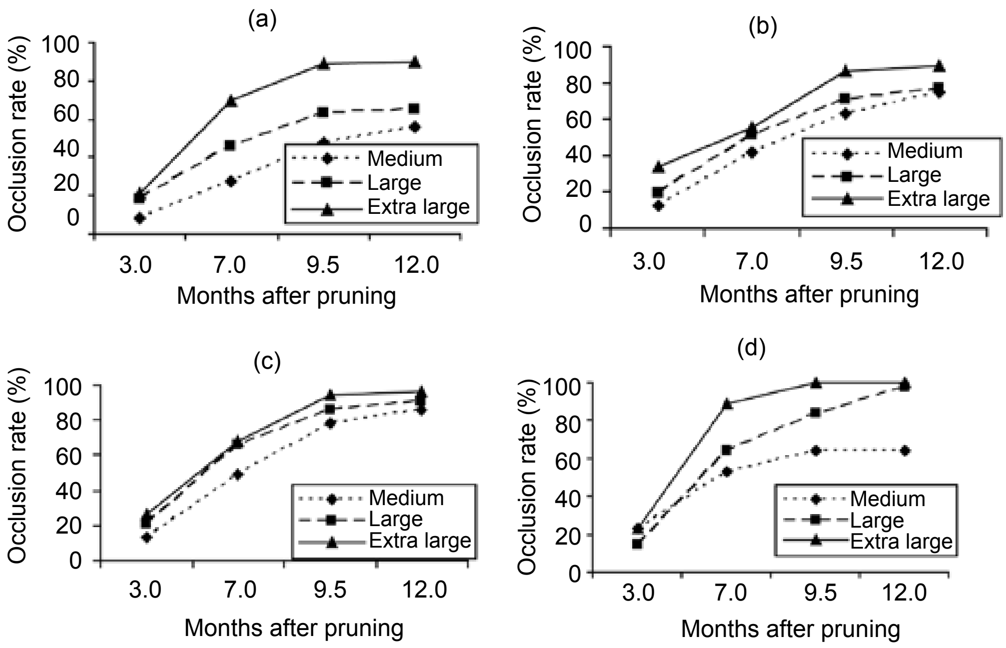

Figure 3 Occlusion rates of pruned wounds over time by wound size category for pruning up to stem height sections of (a) I = 0–1.00 m, (b) II = 1.01–2.50 m, (c) III = 2.51–4.00 m and (d) IV = 4.01–5.35 m; results for small wounds (≤ 10.0 mm) were omitted due to the small number of data

higher pruning intensities will significantly decrease tree growth. Recovery in stem growth rates is closely related to the capacity of green crown to supply assimilates, and such stem growth promotes occlusion of pruning wounds (Wang et al. 2003, Alcorn et al. 2008). Thus, moderate or lighter pruning favours high value knot-free clear wood cultivation.

While our study did not compare unprotected with protected pruning wounds, the results did show that occlusion rate and proportion of completely occluded wounds differed significantly

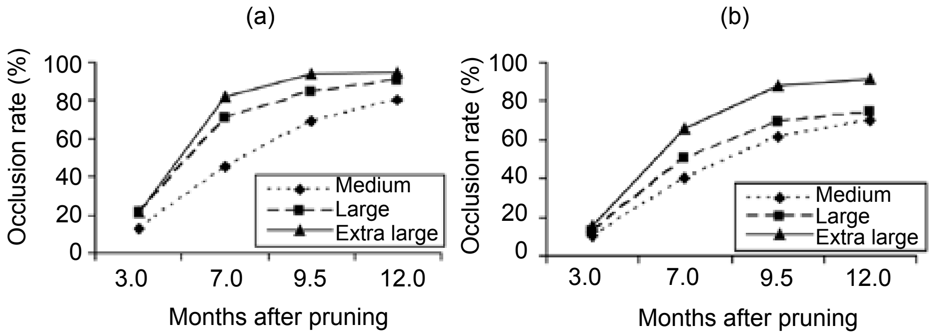

Figure 4 Occlusion rates of pruned wounds over time by wound size category for pruning with wound protections of (a) paint and (b) wax; results for small wounds (≤ 10.0 mm) were omitted due to the small number of data

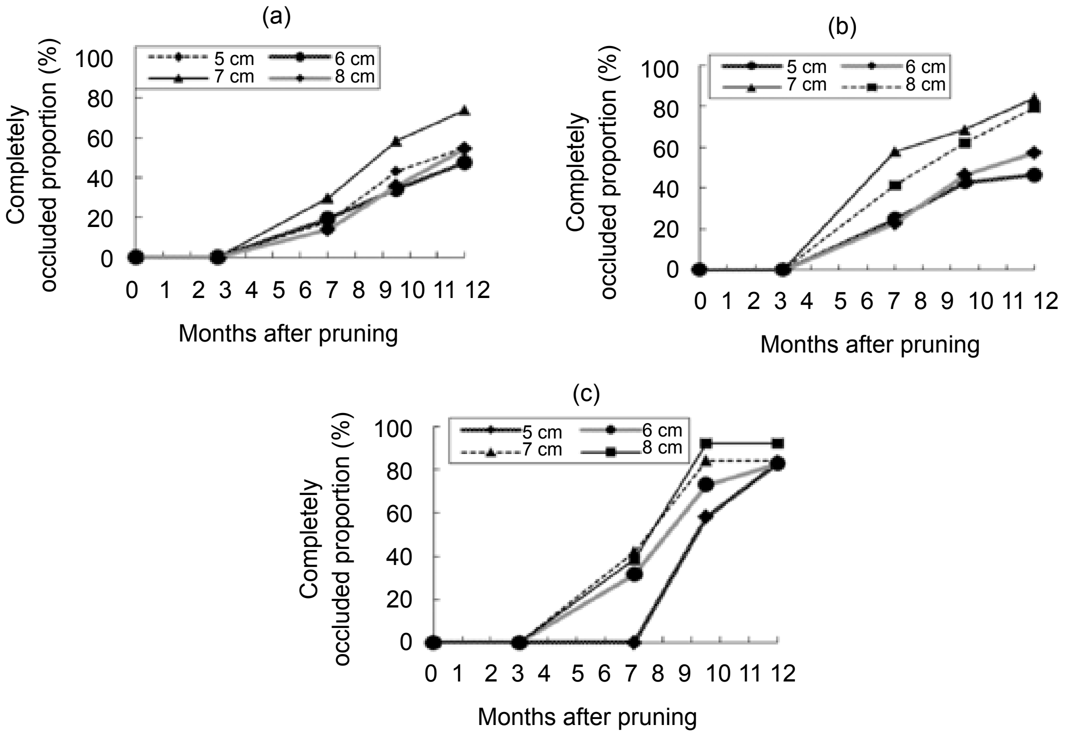

Figure 5 The proportion of completely occluded pruning wounds up to 12 months after pruning by pruning intensity (5, 6, 7, 8 cm), by initial wound size category of (a) medium, (b) large and (c) extra large; results for small wounds (i.e. ≤ 10.0 mm) were omitted due to the small number of data

between the two wound protection methods, with paint being superior to wax (Figures 6a and b). The possible explanation for faster occlusion of painted knots could be that paint had stronger ability to seal or waterproof wounds and provide a better environment for wound occlusion. However, Schlesinger and Shigo (1989) did not support the use of wound protection coatings after pruning. They thought that such treatments might actually be detrimental by promoting decay under the protected surface. It was beyond the scope of the current study to examine effects of wound protection method on subsequent wood quality with respect to decay and/or discoloration.

Another factor associated with differences in proportions of completely occluded wounds was the stem height section where the wounds were located (Figures 7a and b). The height sections where wound occlusion was fastest for medium and large wounds were sections III and IV (i.e. from 2.51 to 5.35 m). Studies on patterns of carbon allocation in a number of species have demonstrated that lower branches tend to

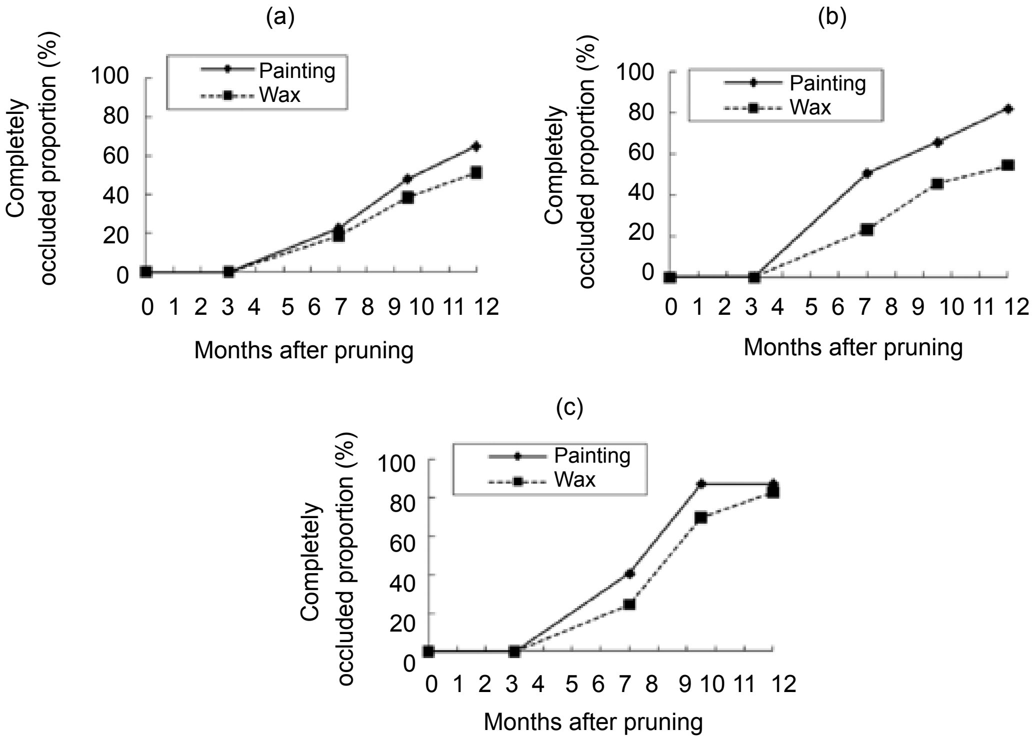

Figure 6 The proportion of completely occluded pruning wounds up to 12 months after pruning by protection methods (painting, wax) and by initial wound size category of (a) medium, (b) large and (c) extra large; results for small wounds (i.e. ≤ 10.0 mm) were omitted due to the small number of data

provide more carbon and assimilate for lower stem growth and root expansion, while upper branches tend to provide carbon and assimilate for shoot expansion (Dickson & Isebrands 1991, Sprugel et al. 1991). As the process of occlusion after pruning is related to the supply of assimilates and the height section where wounds are located (as it affects distance from the key source of assimilates—the green leaves), wounds closest to leaves (i.e. higher stems sections) will occlude faster than those lower on the stem.

An interesting result obtained in the present study was that extra large wounds showed faster occlusion rates and the highest rate of complete occlusion (84.7% of extra large wounds were completely occluded after 12 months) than medium and large wounds (Figures 5c, 6c and 7c). The fact that the largest wounds occluded the fastest was contrary to other studies which reported that occlusion rate was generally related to branch size, with wounds of smaller branches occluding faster (Smith et al. 2006). One possible explanation for the inverse results obtained in this study could be due to the suggestion presented by Gerrand et al. (1997) that occlusion of pruned branch stubs in *E. nitens* varied not only with stem diameter and diameter of the pruned branch but also with other factors not directly related to tree and branch size, including site conditions and relative suppression of individual branches at the time of pruning. Thus, differences in occlusion rates could result in part from environmental factors but they were not assessed in the current study. Another factor which may possibly have contributed to the faster occlusion of bigger wounds is the amount of branch collar remaining after pruning. Neely (1988) found that using 'Shigo' cuts, which resulted in leaving branch collars intact on the primary branches and providing small wounds resulted in smaller wounds but slower callus production. In comparison, larger wounds of conventional flush pruning resulted in more rapid callus production than the smaller wounds of 'Shigo' pruning. Rapid callus production is desirable to cover the exposed wood as quickly as possible (Neely 1988). While we did not attempt to assess the branch collar remaining around the wounds, it was possible that extra large wounds might have had less remaining branch collar compared with smaller wounds and this might have resulted in faster callus production and faster subsequent wound occlusion.

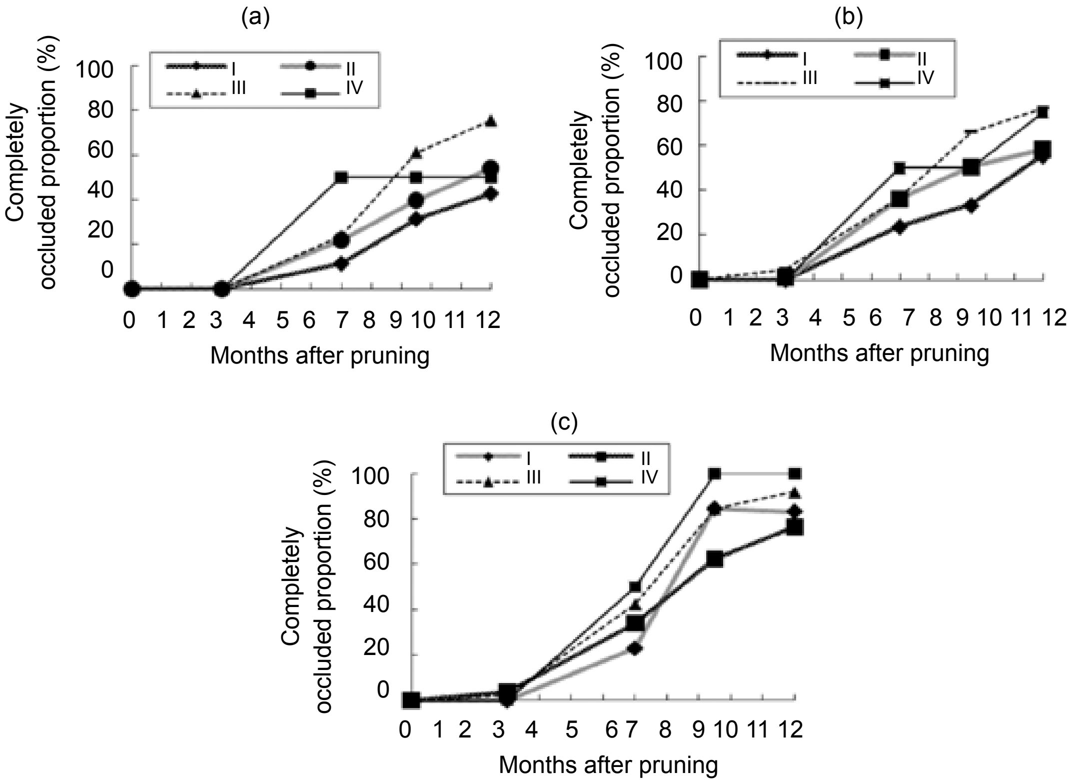

Figure 7 The proportion of completely occluded pruning wounds up to 12 months after pruning by pruning height sections (I, II, III, IV) and by initial wound size category of (a) medium, (b) large and (c) extra large; results for small wounds (i.e. ≤ 10.0 mm) were omitted due to the small number of data

The association between tree growth and pruning wound traits with the rate of occlusion is shown in Table 3. The only traits showing significant association ($p < 0.05$) in these analyses with the rate of occlusion were dbh increment during the 12-month period, initial size of the pruning wound and pruning intensity. Pruning intensity showed the strongest association with occlusion rate (partial $r^2 = 0.088$), with less intense pruning (i.e. pruning to a larger dbh limit) being associated with faster occlusion. Less intense pruning resulted in retention of more green crown and possibly greater subsequent availability of assimilates for wound healing. Dbh increment serves as a measure of the availability of assimilates produced by photosynthesis and these are required to promote wound occlusion. Despite the apparent higher occlusion rates observed in wounds protected with paint compared with those with wax, when combined with the other traits, the association between method of wound protection and occlusion rate was not significant.

CONCLUSIONS

Pruning intensity, wound protection method, wound height section and wound size influenced wound occlusion, with pruning intensity showing the strongest association with rate of occlusion. Overall, it was found that the optimal pruning intensity for wound occlusion was pruning up to stem diameter of 7 or 8 cm. The best wound protection method was paint and the fastest wound occlusion occurred in stem height sections III and IV (2.51–5.35 m height).

At 12 months after pruning, only height increment differed significantly with pruning intensity. The optimal pruning intensity for maintaining tree growth was pruning up to stem diameter of 8 cm. The faster wound occlusion rates observed for larger wounds suggested that changing pruning methods in order to encourage greater (or faster) callus production around the pruning wounds might facilitate more rapid occlusion to benefit post-pruning production of clear wood.

Table 3 Stepwise regression analyses to examine the association of growth and pruning wound parameters with occlusion rate 12 months after pruning

Variable	Partial r-square	Model r-square	F-value for individual variable
Dbh increment	0.069	0.069	6.51*
Wound size	0.054	0.123	5.33*
Crown increment	0.034	0.157	3.48
Height section	0.028	0.184	2.86
Height increment	0.022	0.206	2.28
Protection method	0.009	0.215	0.33
Lift (pruning intensity)	0.088	0.303	10.41**

*Significantly different at $p \leq 0.05$, ** significantly different at $p \leq 0.01$

ACKNOWLEDGEMENTS

This research was assisted financially by the Ministry of Science and Technology of the People's Republic of China (National Key Project of Scientific and Technical Supporting Program 2006BAD24B02) and the Ministry of Agriculture of the People's Republic of China (Technological Outcome's Transformation Project: 2007GB24320 418). We thank the China Eucalypt Research Center and the South China Experimental Nursery for providing and supporting the trial site. Thanks are also due to FY Han, SQ Ren, HL Zhang, LL He, PJ Zhang and DY Wei for collection of data.

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