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EFFECT OF SITE AND GROWTH ATTRIBUTES ON LOG END-SPLITTING OF *EUCALYPTUS PELLITA* GROWN IN NORTHERN BORNEO AND ITS REMEDIAL MEASURES

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Eucalyptus pellita is currently the predominant tree species deployed for tree plantation establishment in many parts of Borneo, particularly in the state of Sabah, Malaysia. This study evaluates the occurrence of end-splitting in four-year old plantation grown *E. pellita* in Sabah as affected by site and growth attributes. An existing progeny tree breeding trial, involving seeds originated from Papua New Guinea, China, Vietnam, Australia and Sabah with 101 individual families, was used to carry out the split assessment. The trial trees were planted on two contrasting sites which differed significantly in soil type, soil texture, soil physical conditions, effective rooting depth and drainage capacity. Logs from the second thinning were cut into 2.2 m long sections. The end splits were evaluated by using a designated split scoring system. Plastic s-hooks, a wax emulsion end sealer and a bitumen end sealer were used as remediation measure and were compared against a control of no remedial application. The study showed that significant variation exists in log end-splitting, comparing the two sites, in combination with significant variation in tree growth. The variation in log end-splitting is attributed to the variation in tree growth as a response to the different growing conditions. Application of plastic s-hooks reduced split occurrence and severity significantly (49.62%), while the wax and bitumen end sealers had no effect on reduction of growth strain related splits. The findings suggested that end-splitting is caused by complex genetic-environment/site-growth interactions. It is vital to better understand factors involved in log end-splitting to optimise *E. pellita* plantation management.

Keywords: Wet tropic, log end-split, split scoring system, family, tree height, remedial measures, site conditions

INTRODUCTION

Within the last 10 years *Eucalyptus pellita* has become the predominant tree species deployed for commercial tree plantation development in Sabah, Malaysia and other regions of Borneo Island (Paridah et al. 2018). Previously *Acacia mangium* was the main plantation tree species deployed in Malaysia, but due to the emergence of *Ceratocystis* vascular wilt disease, the species is seen today as unsuitable for plantation development by most forestry companies (Tarigan et al. 2010, Brawner et al. 2015, Chi et al. 2023). Until 2020, Sabah had planted about 36,200 ha with *Eucalyptus*, with the main species being *E. pellita* along with other eucalypts and eucalypt hybrids. In its natural range, *E. pellita* occurs naturally in North Queensland and the Island of New Guinea and it is well adapted to wet tropical climates (Brooker & Kleinig 2012). For this reason, *E. pellita* is less susceptible to fungal leaf pathogens when planted as an exotic species in similar environments (Harwood et al. 1997, Nazirah et al. 2021). Its low pest and disease susceptibility, in combination with good growth and advantageous wood property traits, make it one of the most suitable species for plantation establishment in many parts of Borneo (Prasetyo et al. 2017, Japarudin et al. 2020, Lee et al. 2022).

Peeling and saw milling trials in Sabah and Sarawak confirmed that *E. pellita* possesses good properties and appearance for solid wood end products. However, end-splitting in logs and boards adversely affect the recovery of viable volumes of produced (Hii et al. 2017). Solid wood recovery of *E. pellita* was reduced by as much as 50% of the viable log length due to splits (Japarudin et al. 2021). In order for *E. pellita* to succeed in solid wood markets, issues of recovery loss due to growth stress related log end-splitting and splitting of finished end products is one of the most important issue to be addressed (Sharma et al. 2017). A related study in Northern Borneo revealed that log end-splitting in *E. pellita* is heritable ($h^2 = 0.24$ at $p \leq 0.05$) and therefore it should be possible to alter incidence and severity of log splitting via genetic selections as a breeding strategy (Espey et al. 2021). In the same study, log end-splitting was also significantly related to tree growth, i.e. tree height was significantly related to log end-splitting. The same applies to diameter at breast height (DBH), but at a lower significance level compared to tree height (Espey et al. 2021).

Eucalyptus pellita is a relatively recent plantation tree species in Malaysian Borneo and to date there are only few studies concerning this crop under Malaysian growing conditions (Japarudin et al. 2022). There is limited information available on how far log end-splitting stands in relation to environmental factors in the Malaysian context, i.e. soil type and soil texture or soil physical characteristics. Soil type and physical soil characteristics have a significant impact on growth. Good or poor growth of a certain species, genotype or family is dependent on the environmental conditions and genetic by environment interactions. Growth and buildup of growth stress is strongly related to site conditions, particularly soil characteristics. End-splitting for *E. grandis* on good quality sites increased about 50% in comparison to low quality sites in South Africa (Malan 1984). In the case of *E. nitens* in Tasmania, Australia, regional differences in splitting have been reported, associated with different environmental conditions (Vega et al. 2016). If an environment-split relationship exists for *E. pellita* in Malaysia, it is not known and no information has been published. This study reports on *E. pellita* log end-splitting, influenced by site/environment and growth factors.

Knowledge on suitable remedial measures to reduce *E. pellita* wood degradation due to end-grain splitting is very limited. No research has been carried out in Malaysia, and published research data pertaining the topic does not exist. Remediation measures are designed to prevent, reduce or mitigate splitting of plantation logs or finished solid wood end products. Generally, two methods can be identified: 1) Products that physically hold or bind the wood together (S-hooks) and 2) Products which are applied to reduce moisture loss and therefore reduce split formation (Rice 1995, Hernandez and Wengert 1997). The first group of products usually comprises of metal s-hooks, rings or gang nails which are driven into the wood by hammer. It is a common practice in Malaysia, as well as in other countries, to apply metal s-hooks to the large and small end of the log (Guyana Forestry Commission 2012). Limitation of metal s-hooks is that they need to be removed before log processing. Usually, the log portion containing the s-hook is cut off and becomes a waste product, which increases the operational cost. Plastic s-hooks are relatively soft and can be cut by saws or other machinery, thus, they don't need to be removed. Plastic s-hooks are smaller compared to metal s-hooks and appear to be more suitable for smaller sized plantation logs.

Although s-hooks seem to reduce the severity and occurrence of splitting in round logs, they do not alter the residual growth stresses and the wood is still very likely to split during downstream processing (Yang and Waugh 2001). The second product group comprises of different emulsion pastes such as paraffin, silicon, petroleum jelly, wax, bitumen or oils which are sprayed or applied by a brush to the wood surface (Rice 1995, Hernandez and Wengert 1997). Use of end sealers appears to be common during downstream processing and is described as a standard practice in sawmills to prevent splitting (Hernandez and Wengert, 1997). Coatings reduce and delay the moisture loss from log ends or wood surface, allowing even drying and shrinkage of the wood core and its periphery, thus resulting in reduced drying stresses and low splitting (Yang and Normand 2012). Most commercial log and lumber sealers are described as being effective in split reduction with little statistically significant variation (Rice 1995). Suitable operational timing of end sealer application is crucial and should be carried out within seven days after felling (Yang and Normand 2012).

Uncertainty surrounds the occurrence of end-grain splitting in planted *E. pellita* logs in Malaysia. Very few reports have been published on this topic, which may be due to the lack of research conducted on the subject. In order to ensure long-term productivity, high-grade log recovery, and optimal utilisation of *E. pellita* wood products, it is essential to have a thorough understanding of end-grain splitting incidents in Malaysia so as to secure higher economic returns from *E. pellita* plantations. This study aims to evaluate the incidence and severity of end-grain splitting in *E. pellita* in relation to environmental/site variables. Also investigated was the effectiveness of three split remedial methods in reducing end-grain splitting in *E. pellita* logs. In this study, plastic s-hooks, a wax emulsion end sealer, and a bitumen end sealer were compared with no remedial application, serving as a control.

MATERIALS AND METHODS

Location of the trial site

An *E. pellita* progeny trial established in 2015 within the Acacia Forest Industries (AFI) project area was used for this study. The site is situated on the Bengkoka Peninsular, Pitas District in the North of Sabah state, in the Malaysian region of Borneo Island (N 06° 30' E 117° 07'). The region is characterised by low lying coastal terrain with undulating hills of low elevation (30 to 70 m), where 99% of the area has slope degrees of less than 25 °. The mean annual temperature is 27.4 °C with little variation. Soils are mainly derived from sediment bedrock material such as sand and mudstone. The project area including the trial site was prior stocked with mature *Acacia mangium* of around 20 years of age (Acacia Forest Industries 2017).

Soil type/texture

The *E. pellita* progeny trial in AFI is planted on two contrasting sites which differ significantly in soil type and soil texture and are distinguished in this study as AFI site 1a and 1b. The two sites are physically separated by a small valley and lie on two separate hills. Five replications were planted on site (AFI 1a) which has Tanjong Lipat as soil type and is considered high productive. The soil is derived from sandstone parent material, and soil texture is a sandy loam in the A-horizon and a loam in the B-horizon. The sand content is estimated at 55%, silt is about 25% and the clay fraction size is around 20%. Due to the high sand content, the soil contains many pores and is friable and soft. This allows for easy root penetration, good drainage with no waterlog issues and aeration of the soil. Due to the porous, soft soil, rooting is effective with an estimated depth of 137 cm, resulting in better site exploitation (Figure 1).

Figure 1 Soil pits at Acacia Forest Industries (AFI), (left) site 1a showing Tanjong Lipat soil type with sandy loam-loam soil texture, classified as highly productive, (right) site 1b showing Kumansi soil type with silty clay-clay soil texture, classified as low productivity

A further three replications were planted on site (AFI 1b) which is significantly different compared to site 1a, and is considered a lower productive site (Figure 1). The parent soil material is mudstone and the soil type is classified as a Kumansi. The soil texture within the A-horizon is a silty clay and for the B-horizon, it is clay. In contrast to site 1a the clay content is high (ca. 55%), while the sand content is only around 10% and the silt content is estimated at 35%. Due to the different clay, sand and silt content, site 1b has significant different physical properties. The soil is compact, firm and hard with less air filled pores which results in a reduced effective rooting depth and therefore lower site exploitation. The lower oxygen content of the soil results in reduced root gas exchange. Site 1b has poor drainage capacity especially during the rainy season and has periodic waterlog issues, especially in combination with the low slope (11.5 °, Table 1). In summary site 1a and 1b are significantly different and therefore significant different growth as well as wood property traits can be expected. Soil related details are illustrated in Table 1.

Table 1 Genetic material, trial design and site variation within the Acacia Forest Industries (AFI) progeny trial 2015

Details	*Eucalyptus pellita* progeny trial 2015 in AFI	
	Site AFI 1a	Site AFI 1b
Type of trial	*E. pellita* progeny trial 2015	
Trial coordinates	N 06° 30’ 8.82” E 117° 07’ 47.60”	
Planting date	July 2015	
Assessment date	July 2019	
Age at split assessment	4 years	
Spacing (m)	3 x 3	
Soil type	Tajong lipat	Kumansi
Soil parent material	Sandstone	Mudstone
Soil texture	Sandy loam-loam	Silty clay-clay
Estimated clay content (%)	20	55
Estimated sand content (%)	55	10
Estimated silt content (%)	25	35
Soil consistency	Friable	Firm
Effective rooting depth (cm)	137	64
Waterlog	None	Periodic waterlog
Average slope degree	17.2	11.5
Altitude (masl)	27.5	12.0
Mean annual rainfall (mm)	2631	
Mean annual temperature (°C)	27.4	
Trial design	Randomised incomplete block design (RIBD)	
Treatments/ families of *Eucalyptus pellita*	101	
Replications	10	
Replications sampled	8	
Replications sampled per site	5	3
Blocks per replication	17	
Families/ plots per block	6	
Trees per family per block/ plot	3	
Trees per block	18	
Origin of seed material	China, Vietnam, PNG, Australia, Sabah, Sarawak	

Soil description

Three soil pits were established at upper, middle and lower slope in each site. The soil type was classified by use of Sabah and Sarawak terminology (Figure 1). The soil texture was assessed by use of a soil texture triangle (Soil Texture Tringale 1979) and the USDA Soil Texturing Field Flow Chart (1992) to estimate clay, sand and silt content by hand feel test. Effective rooting depth was measured to the last visible root in the soil profile. Other soil parameters such as soil structure, soil consistency, stone and root abundance were assessed by use of FAO guidelines for soil description (Jahn et al. 2006). Other aspects such as waterlog or drainage characteristics were recorded. The background information of soil parameters is summarised in Table 1.

Rainfall pattern of the trial project area

The mean annual rainfall (7-year average) shows a pronounced seasonality of precipitation and an uneven distribution of rainfall throughout the year. Most of the precipitation occurs from November to February, the local rainy or monsoon season with a maximum of around 490 mm monthly rainfall. The rest of the year can be relatively dry with monthly rainfall of around 100 mm and below (Figure 2). The total average annual rainfall received is 2,631 mm.

Families and trial design

The 2015 *E. pellita* progeny trial in AFI was established as part of the Borneo Forestry Cooperative (BFC) *E. pellita* breeding program. The BFC member companies implemented the progeny trial by use of the same standardised trial design and largely share the same genetic material. More than one hundred improved families were tested on each trial site, specifically 101 families in the 2015 AFI trial. The genetic material used originated from progeny tree breeding trials in China, Vietnam and Papua New Guinea. These progeny trials have been established with improved material from other breeding programs such as Ingham SSO, Danbulla SSO, Kairi SSO in Australia and material from Vietnam ex Bao Bang SSO. The trials also contain material from wild collections of individual mother trees harvested in Queensland as well as material from AFI seed orchard production. The trial was laid out using a randomised incomplete block design. One incomplete block contains 6 families, with each family being represented with 3 trees (3 tree line plot). One replication contains the total number of incomplete blocks and therefore all of the treatments (AFI and BFC). The details and genetic material as well as trial design used in this study are shown in Table 1.

Height, diameter measurement and conversion to seed orchard

Prior to thinning, trees were measured for height and diameter at breast height (DBH), as well as an assessment of tree form at 3 years of age. The first inferior tree per family in each replication was then removed. At 4 years of age the trial area was converted to a seedling seed orchard (SSO) by removal of the second inferior tree, within

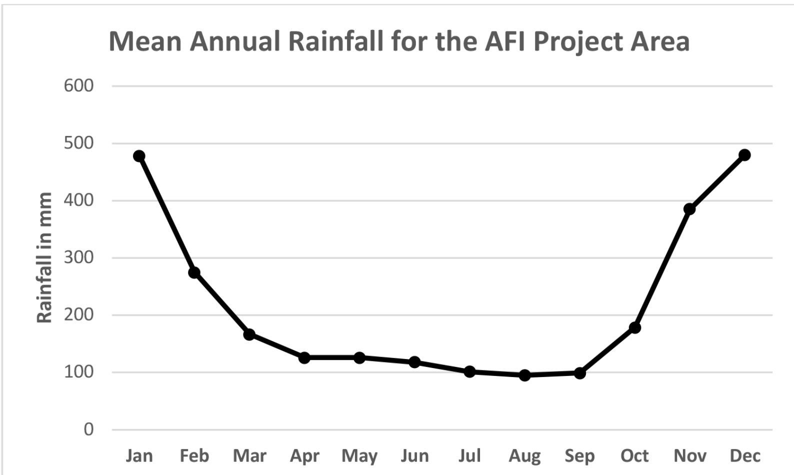

Figure 2 Mean annual rainfall for the trial project area, 7 year average (Acacia Forest Industries)

the 3 tree line plot (Table 1). Trees felled during this stage are denoted as second thinning and were used for the split assessment. A total of 499 trees were felled and the corresponding height and diameter measurements were recorded and assessed for splitting.

End-splitting assessment

The end-splitting assessment was conducted according to the study by Espey et al. (2021). Seventy-two hours (three days) after felling and cross cutting, the incidence and severity of end-splitting was assessed at both large and small log ends using a modified scoring system developed by the Council for Scientific and Industrial Research, South Africa (CSIR) (Figure 3) (Conradie 1980).

A total of 499 trees were felled and assessed, providing 1819 log sections of 2.2 m length resulting in 3638 split observations (large and small log ends were assessed). Trees felled during the second thinning operation were used to carry out the split assessment. Immediately after felling, the trees were cut into 2.2 m long billets up to a small end over bark diameter of 10 cm (Figure 4). Each log was labelled with treatment number at both ends by using crayon (Figures 5–8). Splits were classified according to the radial distance impacted by the split. The scores were determined according to Table 2.

During the field assessment, the number of splits per each split's category, n, was recorded. The total scores for each log section were calculated for large and small end as:

$$\text{Split score} = \Sigma\,[n_a(1) + n_b(1.5) + n_c(2) + n_e(1) + n_f(2) + \Sigma_d(1)] \quad (1)$$

where n = the number of splits per each split's category, a, b, c, d, e, f = categories of split according to Table 2, Σ_d = sum of width of split (mm) at outer circumference, and value in ( ) = scoring points according to categories of split in Table 2.

Determination of split sample size

Prior to the analysis the required split sample size per family was determined by use of the Yamane formula (Yamane 1967) as follows:

$$n\ \text{Yamane} = \frac{N}{1+N(e^2)} \quad (2)$$

where n = split sample number/size, N = population, e = confidence level. The Yamane formula is suitable to determine the sample numbers required for studies with a known population size (Yamane 1967). All families with a total split sample amount below the

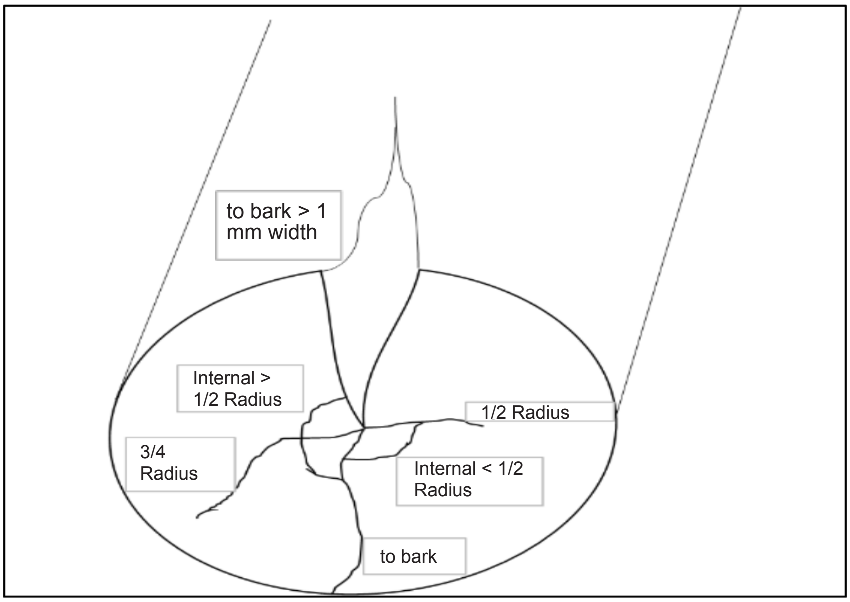

Figure 3 Modified Council for Scientific and Industrial Research (CSIR) split scoring system showing type of splits in *Eucalyptus pellita* (Espey et al. 2021)

Figure 4 Felled 2nd inferior tree of the 3 tree line plot, cross cut into 5 log sections of 2.2 m length

Table 2 Split scoring points assignment (Espey et al. 2021)

Description	Category (split type)	Scores
A split extending from the pith to half of the log radius	Half radial split (a)	1
A split extending from the pith to 70% of the log radius	Three quarter radial split (b)	1.5
A split extending from the pith to the outer periphery of the log	Full radius split (c)	2
Pith to bark splits can open up at the outer circumference of the log and are measured in width and length, if the width of the open up is ≥ 1 mm, by use of an electronic caliper (Figures 5, 7, 8, 9).	Radial split (d)	1 for every one millimeter (1/mm)
Internal splits tangentially connect the radial splits, if they reach half the arc-circumferential length or part thereof	Internal split (e)	1
If the internal split is longer than half of the log radius	Internal split (f)	2

80% confidence level were excluded from the statistical analysis.

End-grain split remediation measures assessment

In AFCS, two replications of the *E. pellita* progeny trial series 2013 (planted May 2014) were used to carry out the remediation measures assessment. Trees were felled and cross cut as described under section 3.4. Split remediation was carried out by applying three different products: S-hooks, wax emulsion and bitumen paste. Log end-grain splitting was compared against a control treatment of no remediation methods applied (in total four treatments), as shown in Table 3 and Figures 10 to 13. Each remedial method was applied at both, large and small log end of one 2.2 m long log section, immediately after the logs were cross cut. A minimum of 100 samples/cut surfaces were taken for each of the four treatments. This is equivalent to a minimum of 50 logs per treatment. The sequence in which the four treatments were applied to the logs was determined by use of random numbers (one to four), generated by a free online research randomiser as a service of Social Psychology Network. The split assessment was carried out

Table 3 List of treatments for end-grain split remediation measures assessment

No.	Treatment	Product name	Description
1	Control	-	No remediation applied
2	Wax emulsion	Anchorseal 2	Water-based wax emulsion end sealer, applied by brush to the cut surface
3	Bitumen paste	Atlaskote 103	Water-based bitumen end sealer, applied by brush to the cut surface
4	S-hooks	S-hooks	Plastic S-hooks driven into the wood by use of hammer

two weeks after application of remedial measures using the same method as described under section 3.4. The mean split score was calculated for each log section, resulting in a minimum of 50 values for each treatment.

Statistical analysis

Statistical analysis incorporated the randomised incomplete block design of the progeny trial, with data organised according to replication, block, plot and treatment/family. The Statgraphics Centurion 18 software package was used for data analysis. Analysis of variance (ANOVA) was applied to determine the relationship between growth factors and sites as well as split and sites at 95% confidence level. Multiple range test with 95% Tukey's honestly significant difference (HSD) procedure was used to determine significant differences for growth factors and split, sites and split.

RESULTS & DISCUSSION

Effects of site 1a and 1b on end-splitting and growth

The two contrasting sites, 1a and 1b at AFI, showed significant effect on log end-splitting and growth of *E. pellita*. Site 1a with friable sandy loam-loam soil texture (5 replications) with a low clay content is considered high productive with good growing conditions. Site 1b with firm silty clay-clay soil texture (3 replications) with a high clay contents results in inferior growing conditions, is considered low productive. The difference in height growth for the two sites was statistically significant at $p < 0.001$ (Table 4).

Based on the assessment data at 3 years of age, the mean tree height for the high productive site, 1a, was 15.75 m in comparison to the low productive site 1b with 14.53 m (Table 5). The mean tree height for site 1a was significantly higher compared to site 1b (Table 5). Similar results were observed for diametric growth. Site 1a had a mean DBH of 13.25 cm in comparison to site 1b with an average DBH of 12.80 cm (Table 5). The variation in mean DBH for the two sites was statistically significant (Table 4). The mean DBH for site 1a was significantly higher compared to site 1b (Table 5). The *E. pellita* plantation logs grown on the high productive site, 1a, exhibited a mean split score of 4.33 (Table 5).

Whereas the mean split score for logs grown on the low productive site, 1b, was 3.93 (Table 5). The different growing conditions of the low and high productive site, 1a and 1b, led to differences in *E. pellita* log end-split occurrence and severity (Figure 14). The difference in log end-splitting for the two different sites was statistically significant (Table 4). End-split occurrence and severity in *E. pellita* was significantly higher for the high productive site, 1a, in comparison to the low productive site, 1b (Table 5). The significant variation in log end-splitting for the two sites was caused by the significant variation in height and DBH growth (Table 4 and 5) caused by different environmental/soil conditions. The effects of tree height on log end-splitting were more pronounced (Table 4) compared to DBH (Table 4).

This study has shown that variation in growth caused by different sites with varying soil type, soil texture and soil physical characteristics are important factors related in the incidence of end-splitting observed in 4-year-old plantation-grown *E. pellita* in Sabah, Malaysia. The AFI 2015 *E. pellita* progeny trial results revealed significant differences in tree growth as well as significant differences in observed severity of log end-splitting distinguished by site. Variation in site and growing conditions had a more prominent effect on tree height compared to DBH. The significant variation in end-splitting for the two sites was caused by the variation in growth. A related study by the Asian Forestry

Table 4 Analysis of variance for the effects of site 1a & 1b on height, diameter at breast height (DBH) and split as well as effects of height and DBH on split of *Eucalyptus pellita*

Type of effects	Sum of squares (between groups)	Df	Mean square	F-ratio	P-value
1. Effects of Site 1a & 1b on height (m) of *Eucalyptus pellita*	163.07	1 (498)	163.07	38.37	0.0000***
2. Effects of Site 1a & 1b on DBH (cm) of *Eucalyptus pellita*	22.1835	1 (498)	22.1835	4.85	0.0282*
3. Effects of Site 1a & 1b on split of *Eucalyptus pellita*	58.2838	1 (1818)	58.2838	16.17	0.0001***
4. Effects of Tree Height (m) on split for *Eucalyptus pellita*	392.016	98 (498)	4.00017	1.76	0.0001***
5. Effects of DBH (cm) on split of *Eucalyptus pellita*	314.825	95 (498)	3.31395	1.35	0.0245*

*Significant at p ≤ 0.05, ***Significant at p ≤ 0.001

Table 5 Significance levels for the effects of site 1a & 1b on tree height, diameter at breast height (DBH and split of *Eucalyptus pellita*

Site	Count height & DBH	Count split	Mean height (m)	Mean DBH (cm)	Mean split score
Site 1b	163	505	14.5344^{b}	12.8043^{b}	3.93396^{b}
Site 1a	336	1314	15.7533^{a}	13.2539^{a}	4.33367^{a}

Means followed by the same letters a, b in each column are not significantly different at p ≤ 0.05 according to Least Significant Difference (LSD) test

Company in North Sabah confirmed that growth factors are significantly related to end-splitting where tree height had a more pronounced effect on the occurrence and severity of splitting in comparison to DBH. The same study further concluded that end-splitting is heritable (h^2 = 0.24 at $p \leq 0.05$) with significant variation of end-splitting on an individual family level for *E. pellita* grown in Northern Borneo (Espey et al. 2021).

Matching species requirements with site conditions is vital for sustainable, successful plantation forestry and variation in growth, as well as wood property traits depending on site conditions (Lu et al. 2020). For instance, plantation growth of *Eucalyptus urophylla* × *grandis* hybrids in China significantly varies with different site factors i.e. soil type, soil depth and soil texture (Lu et al. 2020). Similarly, differences in growth exist for four *E. pellita* seedling seed orchards located in Sumatra and Kalimantan associated with different site and growing conditions (Leksomo et al. 2008). A study in Australia has shown that soil type has a major impact on growth rates of *Flindersia brayleyana* and *E. grandis*. Both species had reduced growth development on poorly drained and clay rich soils, with reduced tree height development in particular (Manson et al. 2013).

To date, knowledge on how genetic and environmental factors influence wood characteristics along the stem is still limited (Rocha et al. 2019). A study conducted with *E. nitens* in Tasmania concluded that log end-splitting increased with increased DBH Splitting is significantly increased for logs from higher productivity, fast growing sites compared to lower productivity, slow growing sites (Vega et al. 2016). Another study on *E. nitens* in Tasmania resulted in significant variation in sawn board splitting comparing different sites. The observed splitting was reduced by 20% on low growth sites which had higher basic density and cellulose content of 4 to 5% (Kube & Raymond 2005). It is vital to understand a wider range of aspects involved in *E. pellita* log end-splitting in order to assure long-term productivity and optimisation of higher grade recovery, and thus higher economic returns. Simultaneous improvement of growth and wood property traits is imperative if *E. pellita* end products are to succeed in solid wood or veneer markets.

Assessment of end-grain split remediation measures effectiveness

End-grain split occurrence and severity were significantly different depending on the remedial techniques examined (Table 6). In logs from an *E. pellita* plantation, the use of plastic s-hooks was found to significantly reduce log end-grain splitting. S-hooked logs had a 49.62% lower splitting rate than control treatment. For plastic s-hooks, the decrease in log end-grain splitting was statistically significant (Table 7). The two end sealer products, a wax emulsion and bitumen paste, ranked roughly equal to the control of no preventive measures being used and had no discernible impact on the decrease of log end-grain splitting in *E. pellita* (Table 7 and Figures 11, 12 and 13).

The use of plastic s-hooks significantly reduced split occurrence and severity in *E. pellita* plantation logs by 49.62%. Whereas the two end sealer products, bitumen paste and wax emulsion, did not have a significant effect on reduction of end-grain splitting, both products rank about the same as the control treatment of no remediation applied. The application of wax emulsion resulted even in a slight increase in end-grain splitting whereas the use of bitumen paste slightly reduced end-grain splitting. For the evaluation of suitability and effectiveness of remedial methods, the root cause for split formation need to be put in consideration. The two main reasons for splits to form are uneven shrinkage of inner and outer wood layers due to drying and growth stress release. Both factors are not related to each other but are likely to interact. Eucalypts are reported to have particularly high growth stress levels. In addition to the general high growth stress levels of eucalypts, short rotation plantation trees have higher growth stress levels due to a larger proportion of juvenile wood and reaction wood compared to trees of higher age (Maeglin 1987). In relation to this it can be assumed that end sealer products, which are designed to mitigate splitting by reducing moisture loss, will not be effective in reduction of splits caused by growth stress release. It further can be assumed that methods which physically hold or bind the wood together, i.e. s-hooks or gang nails, are more effective in mitigation of growth stress related split formation in round logs of *E. pellita*. This may explain the significant differences in effectiveness of the three end-grain split remedial methods used in this study. Published research data provides varying information with regard to the effectiveness of end coatings. However, research findings obtained from end sealer application trials with eucalypts are in agreement with the results of this study. In the case of *E. dunnii*, logs treated with end sealant had the highest split severity and boards produced showed the highest bow rate (Matos et al. 2003).

Table 6 Analysis of variance for the effects of split remediation method on split score values

Source	Sum of squares	Df	Mean square	F-ratio	P-value
Between groups	803.675	3	267.892	13.59	0.0000***
Within groups	3924.07	199	19.7189		
Total (Corr.)	4727.74	202			

***Significant at $p \leq 0.001$

Table 7 Effects of split remediation method on split score values

Type of split remediation	Count	Mean
4 - S-hooks	52	4.725^{b}
3 - Bitumen paste	50	8.636^{a}
1 - Control	51	9.380^{a}
2 - Wax emulsion	50	9.608^{a}

Figure 5 Measurement of split width (4.58 mm) for splits from pith to bark ≥ 1 mm width

Figure 6 No splitting was observed in family 39

Figure 7 Severe splitting of family 88

Figure 8 Severe splitting of family 48

Figure 9 Split length measurement for splits from pith to bark of ≥ 1 mm width (135.92 mm)

Figure 10 Plastic s-hook applied to the cut surface

Figure 11 Application of wax emulsion (Anchorseal 2) at log end

Figure 12 Application of bitumen paste (Atlaskote 103) at log end

Figure 13 Control treatment of no remedial methods applied

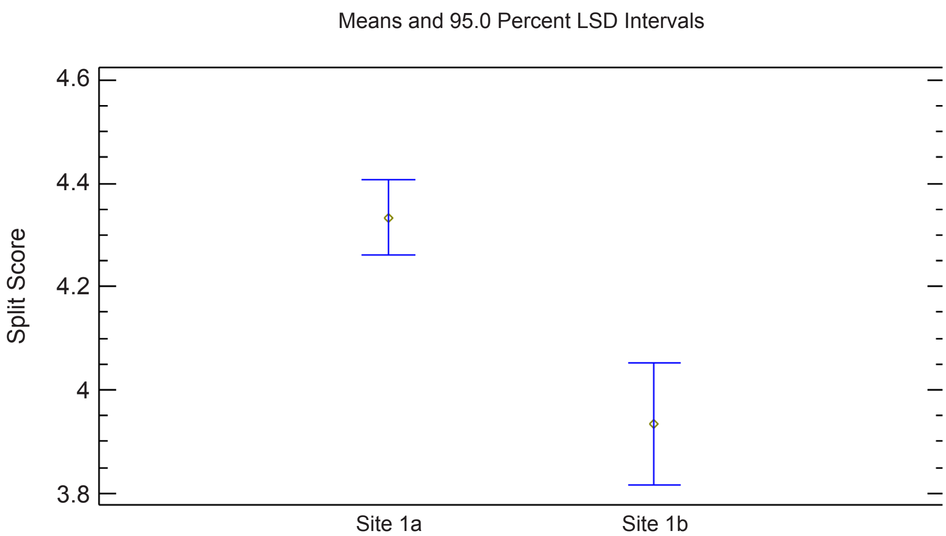

Figure 14 The occurrence of end-splitting in *Eucalyptus pellita* logs planted on different sites and varying growing conditions

Similar with *E. urophylla*, application of end coating resulted in significant increased board cracking and has proven to be ineffective (Silva et al. 2017). The fore mentioned findings do stand in contrast to research results obtained from Hungary with *Q. petrarea* (oak), where four different end sealer products had significant effect on reduction of split formation. It was concluded that water based products performed significantly better compared to aqueous paraffin and alcohol based products (Szeles et al. 2015). In this context, slow grown (cold climate) hardwood species certainly have different wood properties compared to fast grown, tropical eucalypt species. Thus, growth strain levels and tangential shrinkage rate, both resulting in wood splits, can be expected to vary widely.

There is no published research data available for the effectiveness of s-hooks on reduction of log end-grain splitting. Although usage of s-hooks showed positive results in this study, this method does not alter the residual growth strain levels in round logs and the wood is still very likely to split during downstream processing (Yang & Waugh 2001). Injections of herbicides into still standing/alive *E. dunnii* and *E. urophylla* trees, resulting in a slow death of the tree, has been reported as very effective in reduction of growth stress related defects and splits (Matos et al. 2003, Silva et al. 2017). However, this method appears to be not suitable from an environmental and operational cost point of view.

In summary, knowledge on suitable and effective split remedial methods is very limited. More research is required to determine which split preventive measures are suitable for tree harvesting operations and downstream processing industries, especially for fast grown eucalypt species. The results of this study provide useful information on which end-grain split remedial measures can be applied to *E. pellita* logs after tree felling and log making in harvesting operations. Plantation managers are advised to incorporate s-hook application into the annual harvesting planning to maintain log quality and value.

CONCLUSIONS

Four-year-old *E. pellita* planted in Sabah, Northern Borneo, has significant variation in growth and log end-splitting on different sites. In high productivity sites with low clay content, soft-friable soil, increased effective rooting depth and good drainage capacity showed significantly higher severity and occurrence of log end-splitting combined with superior growth. In contrast, low productivity sites, characterised by high clay content, hard-firm soil, reduced effective rooting depth and poor drainage capacity, resulted in significantly lower observations of log end-splitting as well as poor growth. Log end-splitting is caused by complex genetic–environment/site–growth interactions. It is important for forest management to better understand factors influencing wood quality including end-splitting of plantation logs. Application of suitable remedial measures i.e. metal s-hooks is advised, especially on high productive sites. In the future, it may be of interest to identify the genes responsible for log end-grain splitting. The log production and downstream processing industries require additional research into suitable remediation techniques.

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