UNIVERSITI PUTRA MALAYSIA

INFLUENCE OF GENETICS, GROWTH AND ENVIRONMENT ON ENDGRAIN SPLITTING OF EUCALYPTUS PELLITA F. MUELL. AND EFFECTIVENESS OF SPLIT REMEDIATION METHODS

MANUEL ESPEY

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By

MANUEL ESPEY

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Abstract of a thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree Master of Science

INFLUENCE OF GENETICS, GROWTH AND ENVIRONMENT ON END-GRAIN SPLITTING OF *EUCALYPTUS PELLITA* F. Muell. AND EFFECTIVENESS OF SPLIT REMEDIATION METHODS

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Chairman : Prof. Paridah Md Tahir, PhD
Institute : Tropical Forestry and Forest Products

Eucalyptus pellita is currently the predominant tree species deployed for tree plantation establishment in Sabah and Sarawak, Malaysia. Its low disease susceptibility, good growth and form, and desirable wood properties make *E. pellita* particularly suitable for plantation development in the wet tropical regions of south-east Asia. In spite the many positive traits, practical field observations indicate that the species is susceptible to end-grain splitting. This study evaluates the occurrence and severity of end-grain splitting in plantation grown *E. pellita* in Sabah and Sarawak as affected by genetics, environment and growth attributes. The study further evaluates the effectiveness of three split remedial measures. Four existing progeny tree breeding trials were used to carry out the split assessment. Logs from the second thinning were cut into 2.2 m long sections. The end splits were assessed three days later at large and small log end. Three split remedial measures were tested and compared against a control in a separate progeny trial in Sabah. Plastic s-hooks, wax and bitumen emulsions were applied to the cut surface and assessed two weeks later. In this study, *E. pellita* showed a high tendency towards end-grain splitting. About 96% of all logs showed some signs of splitting on its cross-sectional surface with an average of 2.7 splits per cut surface. In average 9.06% of the log volume is compromised due to end-grain splitting. Three-Quarter Radial Splits were the most frequently observed split types with 64% occurrence rate, followed by Pith to Bark Splits with 27%. End-grain splitting in *E. pellita* is heritable ($h^2 = 0.24$ at $p \leq 0.05$). This implies that about 24% of the observed splitting is due to genetics. The trait end-grain splitting therefore can be altered via genetic selections in breeding programs. End-grain splitting also is found to be significantly related to growth factors such as tree height, diameter at breast height (DBH) and tree volume. Increased growth is associated with an increase in split incidence and severity. The unfavorable relationship between growth and log end-grain splitting requires careful selections of high volume and low split genetic material for breeding purpose. Environmental factors, especially soil texture with varying clay- sand-silt content, were found to have a significant effect on log end-grain splitting as well as on growth comparing different sites. Application of plastic s-hooks reduced significantly (49.62%) split occurrence and severity, while the wax and bitumen end sealers had no effect on reduction of growth strain related splits. The findings suggest that end-grain splitting is caused by heritable, complex genetic–environment–growth interactions.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

PENGARUH GENETIK, PERTUMBUHAN DAN PERSEKITARAN PADA REKAHAN SERAT HUJUNG BAGI *EUCALYPTUS PELLITA* F. MUELL. DAN KEBERKESANAN DARIPADA KAEDAH PEMULIHAN REKAHAN

Oleh

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Pengerusi : Prof. Paridah Md. Tahir, PhD
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Eucalyptus pellita kini merupakan spesies pokok yang utama untuk industri penanaman pokok di Sabah dan Sarawak, Malaysia. Ketahanan terhadap penyakit, pertumbuhan, bentuk pokok yang baik, dan ciri-ciri kayu yang diterima umum menjadikan *E. pellita* sangat sesuai sebagai pembangunan ladang di kawasan tropika yang lembab terutamanya di Asia Tenggara. Walaupun terdapat banyak ciri-ciri menarik yang dilihat pada spesies pokok ini, namun beberapa pemerhatian di lapangan secara praktikal menunjukkan bahawa spesies ini mudah merekah. Kajian ini menilai masalah kayu merekah dan tahap keparahan masalah tersebut di ladang penanaman pokok *E. pellita* yang ditanam di Sabah dan Sarawak yang di mana dipengaruhi oleh sifat genetik pokok, persekitaran dan pertumbuhan. Kajian ini juga bertujuan untuk menilai keberkesanan tiga langkah-langkah pemuliharan masalah kayu merekah. Terdapat empat kawasan kajian terhadap baka pokok yang sedia ada bagi menjalankan kajian ini. Pokok yang ditebang semasa kerja penjarangan pokok yang ke dua dipotong kepada 2.2 m bahagian. Kayu merekah dinilai tiga hari kemudian pada setiap kedua bahagian hujung besar dan hujung kecil setiap kayu yang dipotong. Tiga langkah-langkah pemuliharan kayu merekah telah digunakan dan ia dibandingkan dengan jenis pemuliharan kawalan di dalam Kawasan kajian baka pokok di Sabah. Cangkuk plastic jenis S, wax dan bitumen telah digunakan pada permukaan kayu dan dinilai selepas dua minggu kemudian. Dalam kajian ini, *E. pellita* menunjukkan mempunyai risiko tinggi terhadap masalah kayu merekah. Kira-kira 96% daripada semua sampel kayu menunjukkan beberapa rekahan pada permukaan keratan rentas kayu dengan rata-rata 2.7 bahagian permukaan yang dipotong. Sederhana 9.06% daripada isipadu kayu adalah kurang bernilai oleh kerana rekahan kayu tersebut. Rekahan jejari tiga Suku adalah jenis kerosakan yang paling banyak diperhatikan dengan kadar 64%, diikuti oleh rekahan dari dalam hingga ke kulit dengan kadar 27%. Keparahan kayu merekah menunjukkan boleh mewarisi (h^2 = 0.24 pada $p \leqslant$

0.05). Bermaksud 24% dari rekahan kayu adalah kerana genetik pokok tersebut. Oleh itu rekahan kayu terebut boleh berubah dari pemilihan genetik dalam program pembiakan. Kejadian kayu merekah juga didapati ada kaitannya secara signifikan dengan faktor pertumbuhan seperti ketinggian pokok dan ukur lilit pokok (DBH). Faktor persekitaran, terutamanya tekstur tanah seperti campuran tanah liat-pasir-lumpur yang berbeza-beza juga mempunyai kesan yang signifikan terhadap kejadian kayu merekah dan juga factor pertumbuhan di Kawasan kajian yang berbeza. Bagi spesies *E. pellita* penggunaan cangkuk plastik jenis S dapat mengurangkan (49.62%) daripada masalah dan juga tahap keparahan kayu merekah, sementara itu wax dan bitumen tidak mempengaruhi kadar pengurangan kayu merekah yang dimana ianya disebabkan oleh tekanan dari pertumbuhan. Hasil kajian ini menunjukkan bahawa kejadian kayu merekah disebabkan oleh interaksi antara genetik pokok dengan persekitaran dan juga pertumbuhan yang sangat kompleks.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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This is to confirm that
- the research conducted and the writing of this thesis was under our supervision;
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LIST OF ABBREVIATIONS

AFCS	Asian Forestry Company (Sabah) Sdn Bhd
AFI	Acacia Forest Industries Sdn Bhd
ANOVA	Analysis of variance
BFC	Borneo Forestry Cooperative
BLUP	Best linear unbiased prediction
Corr.	Corrected
CSIR	Council for Scientific and Industrial Research
DBH	Diameter at breast height
Df	Degree of freedom
DRL	Longitudinal residual strain
E.	Eucalyptus
e	Confidence level/ error
F- Ratio	Fischer's ratio
f	Family
fr	Family by replication
GPa	Gigapascal
h^2	Narrow sense heritability
HSD	Honestly significant difference
ID	Identification
IRT	Amount of logs with end-splitting
JTH	Jaya Tiasa Holdings Bhd
LS	Least significant
LSD	Least significant difference
m^3	Cubic meter

MAI	Mean annual increment
m asl	Meters above sea level
MOE	Modulus of elasticity
MPa	Megapascal
N	Population size
n	Sample of population
p	Phenotype
PNG	Papua New Guinea
P- Value	Probability value
Qld	Queensland
spp.	Species
SSB	Sabah Softwoods Berhad
SSO	Seedling seed orchard
TCL	Longitudinal growth stresses
σ	Variance

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Eucalyptus pellita F. Muell., also known as red mahogany, occurs naturally in the tropical regions of north-eastern Queensland, Australia and the island of New Guinea. It can reach heights of up to 40 m and about 1 m diameter at breast height with a usually straight stem form. It grows in gentle to moderate sloping terrain mixed with other eucalypt species in tall open forest and at the fringes to tropical rainforest. It prefers sand to loam soil types with good drainage at altitudes from sea level to 800 m asl with moderate to high rainfall of 900 to 4000 mm annually (Brooker and Kleinig, 2012). It is one of the few eucalyptus species that is adapted to the wet tropical climate and is thus less susceptible to fungal leaf pathogens (Harwood et al., 1997). This adaptation together with other positive traits make it suitable for plantation establishment in wet tropical regions outside of its natural range.

The recent devastation caused by Ceratocystis vascular wilt disease (Tarigan et al., 2010 and Brawner et al., 2015), has resulted in almost all *Acacia mangium* Willd. plantations in the Malaysian states of Sabah and Sarawak being replaced by *E. pellita*. Since 2012, large scale *E. pellita* plantations and tree breeding orchards have been established in Sabah, as well as in Sarawak (Paridah et al., 2017). Japarudin et al. (2020) have shown *E. pellita* to have highly productive growth in Sabah (mean annual increment, MAI, 27.6 m3 ha-1 y-1) compared to other potential species in a taxa trial. Studies revealed that among the three species, namely E. grandis W. Hill, *E. urophylla* S.T. Blake and *E. pellita*, E. pellita has superior characteristics in both growth rate and wood properties (Prasetyo et al., 2017). Hii et al. (2017) and Japarudin et al. (2021) studied the properties of *E. pellita* from Sarawak and Sabah and found that it possesses good properties for solid wood and veneer which are consistent with those reported by earlier studies (Atyeo and Bailleres, 2008). Unfortunately, the studies also confirmed the tendency of *E. pellita* towards end-grain split formation with significant reduction in higher grade solid wood recovery (Japarudin, 2021). The solid wood recovery of *E. pellita* can be reduced as much as 50% as the viable log length decreases with larger aggregates of end-grain splits (Japarudin, 2021).

1.1.1 Incidence of End-Grain Split in Eucalyptus Logs

Many studies have associated growth stress with increase in severity of end-grain split in logs. Beltrame et al., (2015) investigated the relationships between level of longitudinal residual strain (DRL) and the longitudinal growth stresses (TCL) and their effects on the amount of logs end-grain splitting (IRT) of Eucalyptus spp. They discovered that there were significant and positive correlations between DRL/TCL variables with IRT. Thus, it is possible to predict the trend of IRT by performing an evaluation of DRL in the field. Owing to that, this variable becomes a reliable tool for the selection of clones less prone to splitting (Beltrame et al., 2015). High magnitude of longitudinal growth stresses has a significant implication on recovery and processing of high quality timber. Although the longitudinal growth stresses are inherent to all trees, their magnitude varies from species to species, and also within species. These stresses cause ring shake and brittle heart in standing trees, end-grain splitting in logs within a short time span of felling a tree, severe splitting in timber immediately after sawing, and twisting and cracking in timber during drying (Malan, 2009 and Yang, 2005). Hence growth stresses have become a major wood quality criterion in the selection of superior genetic material and also assessing the economic values of logs. Addressing log end-grain splitting and distortion of timber due to growth stress is necessary if Eucalypts are to succeed in solid wood or in veneer markets (Sharma et al., 2017).

1.1.2 Remedial Measures to Prevent or Mitigate End-Grain Splitting

Knowledge on suitable remedial measures to reduce *E. pellita* wood degradation due to end-grain splitting is very limited. It seems that no research has been carried out yet in Malaysia and published research data pertaining such 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 (Max Amrhein GmbH, S-hooks, company website) and 2.) Products which are applied to reduce moisture loss and therefore reduce split formation (Hernandez and Wengert, 1997; Rice, 1995). 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 (Guyana Forestry Commission, 2012), to apply metal s-hooks to the large and small end of the log. Usually this is carried out during log making or stockpiling of logs along the road side, awaiting transportation. Metal s-hooks are readily available in Malaysia and it is a relatively cheap method compared to end coating. Logging contractors and workers are familiar with the use of s-hooks and it is seen as a method that works. This is despite the fact that there is no clear evidence or prove for its effectiveness. It appears that there are no studies and publications regarding use and effectiveness of s-hooks. A 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, due to this they don't need to be removed. On the other hand, side plastic s-hooks are not as strong and solid as metal s-hooks and do not withstand larger wood stresses. 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 (Hernandez and Wengert, 1997; Rice, 1995). There are many different products available on the market which all promise to be effective. Applying end coatings to round logs after felling and log making is not a common practice in Malaysia and rarely can be observed in logging operations. Use of end sealers appears to be common during downstream processing and is described as a standard practice in sawmills to prevent splitting (Linares-Hernandez and Wengert, 1997). Coatings reduce and delay the moisture loss from log ends or the wood surface and allow an 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).

In this study plastic s-hooks, a wax emulsion end sealer and a bitumen end sealer are used and compared against a control of no remedial application.

1.2 Research Questions

This study intends to provide answers to the following research questions:

1. Is end-grain splitting in *E. pellita* related to genetics?
2. Is end-grain splitting in *E. pellita* related to environmental factors?
3. Is end-grain splitting in *E. pellita* related to growth factors?
4. Are there suitable remediation measures to prevent or mitigate end-grain splitting in *E. pellita* plantation logs?

1.3 Statement of Problems and Justifications

The occurrence of end-grain splitting in planted *E. pellita* logs in Malaysia is poorly understood. Reports published on this topic are very few which may be due to the lack of research being carried out concerning such topic. The research questions raised in this thesis are crucial in determining the true value of *E. pellita* as the future source of wood material. However, very little information pertaining to these questions have been reported so far. For instance, the published research mainly discussed about recovery loss due to splits and do not cover a wider range of aspects involved in log end-grain splitting, particularly the genetic influence on the extent of the end-grain splitting. In order to ensure long term productivity, high grade log recovery and optimum utilization of *E. pellita* wood products, comprehensive information and knowledge on the end-grain splitting incidents are vital so that higher economic returns of *E. pellita* plantations in Malaysia can be secured.

1.4 Objectives

It is the objective of this study to provide detailed answers to the raised research questions. The specific objectives of the study are:

i. To evaluate the occurrence and severity of end-grain splitting in *E. pellita* as affected by heredity and family.

ii. To evaluate the occurrence and severity of end-grain splitting in *E. pellita* as affected by growth factors.

iii. To evaluate the occurrence and severity of end-grain splitting in *E. pellita* as affected by environment/ site factors.

iv. To evaluate the effectiveness of three split remedial methods in reduction of end-grain splitting of *E. pellita* logs.

Knowledge gained from this study shall contribute to improve the management of *E. pellita* tree plantations and the maximization of value creation. It is intended to identify if statistically significant differences in log end-grain splitting do exist on an individual family level. In relation to this, it is targeted to determine if splitting as a wood property trait in *E. pellita* is heritable. This is important in order to determine in how far the occurrence and severity of log end-grain splitting can be altered via genetic selections as a breeding strategy.

It is further envisaged to clarify if different soil/ environment conditions contribute to end-grain splitting in *E. pellita* plantation logs. In combination to different site conditions, it is planned to identify if variation in growth rate has an effect on log end-grain splitting. Knowledge concerning this can be incorporated in annual harvesting planning and application of suitable split remediation measures. This study intends to provide information on suitable remedial measures which can be applied after tree felling and log making in order to reduce split occurrence and severity.

1.5 Organisation of Thesis

This thesis contains the following chapters:

1. Introduction
2. Literature Review
3. Materials and Methods
4. Results
5. Discussion
6. Summary, Conclusions and Recommendations for Future Research

REFERENCES

Aggarwal, P.K., Chauhan, S.S. and Karmarkar, A. (2006). Growth strain in *Acacia auriculaeformis* trees of different age: Their relationship with growth rate and height. *Journal of the Institute of Wood Science* 17: 212-215.

Anchorseal 2 end sealer product information from UC Coatings LLC. N.d. Retrieved 16 May 2010 from https://uccoatings.com

Atlaskote No. 103 end sealer product information from Atlas Industries SDN Berhad. N.d. Retrieved 22 May 2020 from atlaskote.com/product/bitumen-emulsion/

Atyeo, W.J., Hopewell G.P. and McGavin, R.L. *Evaluation of wood characteristics of tropical post-mid rotation plantation Eucalyptus cloeziana and E. pellita: Part (d) Veneer and plywood potential.* Project Report: Forest and Wood Products Australia Ltd, Victoria. 2008.

Bailleres, H., Hopewell, G.P. and McGavin, R.L. (2008). *Evaluation of wood characteristics of tropical post-mid rotation plantation Eucalyptus cloeziana and E. pellita: Part (c) Wood quality and structural properties.* Project Report: Forest and Wood Products Australia Ltd, Victoria. 2008.

Bandara, K.M.A. and Arnold, R.J. (2017). Genetic variation of growth and log end- splitting in second-generation *Eucalyptus grandis* in Sri Lanka. *Australian Forestry* 80: 264-271.

Beltrame, R., Peres, M.L.D, Lazarotto, M., Gatto, D.A., Schneid, E. and Haselein, C.R. (2015). Growth stress and its relationship with end splits in logs of Eucalyptus spp. *Scientia Forestalis* 43: 63-74.

Bennett, G.L., Pollak, E.J., Kuehn, L.A. and Snellig, W.M. (2014). Breeding: Animals. In *Encyclopedia of Agriculture and Food Systems*, ed. N.K.V. Alfen, pp. 173-186. Cambridge: Academic Press.

Biechele, T., Nutto, L. and Becker, G. (2009). Growth stress in *Eucalyptus nitens* at different stages of development. *Silva Fennica* 43: 669-679.

Brawner, J.T., Japarudin, Y., Lapammu, M, Rauf, R, Boden, D and Wingfield, M.J. (2015). Evaluating the inheritance of *Ceratocystis acaciivora* symptom expression in a diverse *Acacia mangium* breeding population. *Southern Forests* 77: 83-90.

Brooker, I. and Kleinig, D. (2012). *Eucalyptus pellita.* In *Eucalyptus: An Illustrated Guide to Identification*; pp. 230. Melbourne: New Holland Publishers.

Burdon, R.D. (2010). Wood properties and genetic improvement of *radiata* pine. *New Zealand Journal of Forestry* 55: 22–27.

Cassens, D.L. and Serrano, J.R. Growth stress in hardwood timber, In *proceedings of the 14th Central Hardwood Forest Conference*, Wooster, Ohio, March 16-19, 2004.

Conradie, W.E. *Part 1 Control of end splitting in veneer logs.* Utilization of South African grown *Eucalyptus grandis* (W. Hill ex Maiden) as veneer logs. CSIR Special Report, Hout 206. Council for Scientific and Industrial Research: Pretoria. 1980.

Davidson, J. *Ecological aspects of Eucalyptus plantations*. Proceedings. Regional expert consultation on eucalyptus, volume I. FAO. 2021.

Davies, N.T., Apiolaza, L.A. and Sharma, M. (2017). Heritability of growth strain in *Eucalyptus bosistoana*: a bayesian approach with left-censored data. *New Zealand Journal of Forestry Science* 47: 1-5.

Eldridge, K.G., Davidson, J., Harwood, C.E. and Wyk, G. van. (1993). Eucalypts natural and planted. In *Eucalypt domestication and breeding*. pp. 288. Oxford: Claredon Press.

Encyclopaedia Britannica. Eucalyptus, Major Species and Uses. N.d. Retrived on 23 July 2021 from https://en.m.wikisource.org

Free online research randomizer as a service of Social Psychology Network. N.d. Retrieved 16 September 2020 from https://www.randomizer.org

Florence, R.G. Perception of the eucalypt as an exotic: An ecological interpretation. In *International Symposium on Eucalyptus,* Zhanjiang, China, November 1990.

Food and Agriculture Organization of the United Nations 2006. *Guidelines for soil description*, 4th edition, pp. 67-71, Rome: FAO.

Google earth map information. N.d. Retrieved 27 January 2021 from google.com/earth/index.html

Grzeskowiak, V.; Turner, P. and Sefara, N.L. *Potential of screening tools for early prediction of splitting and brittleheard in Eucalyptus grandis.* CSIR international report. 2001.

Guayana Forestry Commission 2012. *Code of Practice for Wood Processing Facilities (Sawmills & Lumberyards)*, Version 2. Guayana Government.

Hannrup, B., Cahalan, C., Chantre, G., Grabner, M., Karlsson, B., Le Bayon, I., Jones, G.L., Mueller, U, Pereira, H. and Rodrigues, J.C. (2004). Genetic parameters of growth and wood quality traits in *Picea abies*. *Scandinavian Journal of Forest Research* 19: 14-29.

Harwood, C.E., Alloysius, D., Pomroy, P., Robson, K.W. and Haines, M.W. (1997). Early growth and survival of *Eucalyptus pellita* provenances in a range of tropical environments, compared with *E. grandis*, *E. urophylla* and *Acacia mangium*. *New Forests* 14: 203–219

Harwood, C.E. (1998). Eucalyptus pellita: An Annotated Bibliography. In *CSIRO Forestry and Forest Products publication*, Canberra: CSIRO Forestry and Forest Products.

Hettasch, M.H., Snedden, C.L., Lunt, K., Pierce, B.T. and Verryn D. (2004). Narrow Sense Heritability. In *Practical data analysis tools for tree breeders manual,* Pretoria, South Africa: Environmentk, CSIR, South Africa.

Hii, S.Y., Ha, K.S., Ngui, M.L., Ak. Penguang, S., Duju, A., Teng, X.Y. and Meder, R. (2017). Assessment of plantation-grown *Eucalyptus pellita* in Borneo, Malaysia for solid wood utilization. *Australian Forestry* 80: 26-33.

Hillis, W.E. Timber management towards wood quality and end-wood product value: Australia's experience, In *proceedings of the CTIA/ IUFRO International Wood Quality Workshop*, Division III, Quebec City, Canada, August 18-22, 1997.

Hillis, W.E., *Wood quality and utilization.* Eucalyptus for wood production. CSIRO: Canberra, Australia. 1984.

Iowa State University. *Wood drying*; Iowa State University 2000.

Ivkovic, M., Wu, H.X. and Kumar, S. (2010). Bio-economic modeling as a method for determining economic weights for optimal multiple-trait tree selection. *Silvae Genetica* 59: 77-90.

Japarudin, Y., Lapammu, M., Alwi, A., Warburton, P., Macdonell, P., Boden, D., Brawner, J.T., Brown, M. and Meder, R. (2020). Growth performance of selected taxa as candidate species for productive tree plantations in Borneo. *Australian Forestry* 38: 29-38.

Japarudin, Y., Meder, R., Lapammu, M., Alwi, A., Chiu, K.C., Ghaffariyan, M. and Brown, M. (2021). Veneering and sawing performance of plantation- grown *Eucalyptus pellita*, aged 7-23 years, in Borneo Malaysia. *International Wood Products Journal* 12: 1-12

Japarudin, Y., Meder, R., Lapammu, M., Alwi, A., Ghaffariyan, M. and Brown, M. (2021). Compression and flexural properties of plantation-grown *Eucalyptus pellita* in Borneo, Malaysia. Potential for structural timber end use. *Australian Forestry* 84: 139-151.

Kube, P.D. and Raymond, C.A. (2005). Breeding to minimise the effects of collapse in *Eucalyptus nitens* sawn timber. *Forest Genetics* 12: 23-34.

Kübler, H. (1959b). Die Spannungen in Faserrichtung. *Holz als Roh- und Werkstoff* 17: 44-54.

Kübler, H. (1987). Growth stresses in trees and related wood properties. *Forest Production Abstract* 10: 61-119.

Keey, R.B., Langrish, T.A.G. and Walker, J.C.F. (2000). Stress and strain behavior. In *Kiln-Drying of Lumber,* pp. 224-231, Berlin: Springer.

Laclau, J.P., Mareschal, L., Bouvet, J.M. (2020). Eucalyptus Plantations. In *Forest Ecology and Management*, ed. D. Binkley, pp. 87-98, Amsterdam, Netherlands: Elsevier.

Lamb, F.M. *Splits and cracks in wood.* Virginia Tech. Virginia Tech: Blacksburg, Virginia. 1992.

Linares-Hernandez, A. and Wengert, E.M. (1997). End coating logs to prevent stain and checking. *Forest Products Journal* 47: 65-70.

Leksomo, B., Kurinobu, S. and Ide, Y. (2008). Realized genetic gains observed in second generation seedling seed orchards of *Eucalyptus pellita* in Indonesia. *Journal of Forest Research* 13:110-116.

Lu, H., Xu, J., Li, G. and Liu, W. (2020). Site classification of *Eucalyptus urophylla x Eucalyptus grandis* plantations in China. *Forests* 11:1-15.

Maeglin, R. Juvenile wood, and growth stress effects on processing hardwood, In *proceedings of the 15th annual hardwood symposium of the Hardwood Research Council*, Memphis, USA, 1987, TN. 100-108.

Malan, F.S. (2009). Clonal differences in log end splitting in *Eucalyptus grandis* in relation to age, parent performance, growth rate and wood density in two even-aged trials in Mpumalanga, South Africa. *Southern Forests* 70:37-43.

Malan, F.S. and Hoon, M. (1992). Effect of initial spacing and thinning on some wood properties of *Eucalyptus grandis*. *South African Forestry Journal* 163: 13-20.

Malan, F.S. (1984). *Studies on the phenotypic variation in growth stress intensity and its association with tree and wood properties of South African grown Eucalyptus grandis (Hill ex Maiden),* PhD Thesis, University of Stellenbosch, South Africa.

Malan, F.S. (1979). The control of end splitting in sawlogs: A short literature review. *South African Forestry Journal* 109: 14-18.

Manson, D.G., Schmidt, S., Bristow, M., Vanclay, J.K. and Erskine, P.D. (2013). Species-site matching in mixed species plantations of native trees in tropical Australia. *Agroforestry Systems* 87:233-250.

Maree, B. and Malan, F.S. Growing for solid hardwood products – a South African experience and perspective. The Future of Eucalypts for Wood

Products, In *proceedings of IUFRO Conference*, Launceston, Tasmania, Australia, 19-24 March, 2000.

Marko, M. (1999). Wood treatment process to prevent splitting and checking during drying. CA Patent No. CA2238353.

Matos, J.L.M., Iwakiri, S., Rocha, M.P. and Andrade, L.O. (2003). Reduction of growth stress effects in the logs of *Eucalyptus dunnii. Scientia Forestalis* 64: 128-135.

McGavin, R.L., Bailleres, H., Lane, F., Fehrmann, J. and Ozarska, B. (2014). Veneer grade analysis of early to mid-rotation plantation *Eucalyptus* species in Australia. *BioResources* 9: 6562-6581.

Meder, R. *Summary of solid wood assessment of E. pellita at four sites in East Malaysia.* Report to the members of the Borneo Forestry Cooperative. Boden and Associates, Cooroy, Australia 2016.

Meder, R. *Summary of the findings of the BFC Solid Wood Project during 2016: Report to members of the Borneo Forestry Cooperative*. Boden and Associates, Cooroy, Australia 2017.

Murphy, T.N., Henson, M. and Vanclay, J.K. (2005). Growth stress in *Eucalyptus dunnii*. *Australian Forestry* 68: 144-149.

Nambiar, E.K.S, Harwood, C.E. and Mendham, D.S. (2018). Path to sustainable wood supply to the pulp and paper industry in Indonesia after diseases have forced a change of species from acacia to eucalypts. *Australian Forestry* 81: 1-14.

Nascimento, T.M., Monteiro, T.C., Barauna, E.E.P., Moulin, J.C. and Azewedo, A.M. (2019). Drying influence on the development of cracks in *Eucalyptus* logs. *BioResources* 14: 220-233.

Paridah, M.T., Zaiton, S., Hazandy, A.H., Raja Abdul, A.R.A. *Potential of eucalyptus plantation in Malaysia.* Malaysian Timber Industry Board. Ministry of Plantation Industries and Commodities: Kuala Lumpur. 2017.

Pelletier, M.C., Henson, M., Boyton, S., Thomas, D. and Vanclay, J. (2008). Genetic variation in shrinkage of *Eucalyptus pilularis* (Smith) assessed using increment cores: Preliminary results. *New Zealand Journal of Forestry Science* 38: 194-210.

Peng, Y., Washusen, R., Xiang, D., Lan, J., Chen, S. and Arnold, R. (2014). Grade and value variation in *Eucalyptus urophylla* x *E. grandis* veneer due to variation in initial plantation spacings. *Australian Forestry* 77: 39–50.

Prasetyo, A., Aiso, H., Ishiguri, F., Wahyudi, I., Wijaya, I.P.G., Ohshima, J. and Yokota, S. (2017). Variations on growth characteristics and wood properties of three Eucalyptus species planted for pulpwood in Indonesia. *Tropics* 26: 59-69.

Rice, R.W. (1995). Transport coefficients for six log and lumber end coatings. *Forest Products Journal* 45: 64-68.

Santos, P.E.T., Geraldi, I.O. and Garcia, J.N. (2003). Estimates of genetic parameters for physical and mechanical properties of wood in *Eucalyptus grandis*. *Scientia Forestalis.* 63: 54-64.

Sharma, M., Walker, J.C.F. and Chauhan, S. (2017). Eliminating growth-stresses in eucalyptus: A scoping study with *E. bosistoana* and *E. nitens*. In *Wood is Good*; ed. K.K. Panday, V. Ramakantha and S.S. Chauhan, pp. 47-54, Singapore: Springer.

S- hook information from Max Amrhein GmbH. N.d. Retrieved 25 August 2020 from https://m.-amrhein.de

S- hook information from Sahabat Usaha SDN BHD. N.d. Retrieved 25 August 2020 from https://ecommerce.unifi.com.my

Silva, J.C.D., Carvalho, A.M.M.L. and Faria, B.F.H.D. (2017). Methods for alleviation and reduction of the effects of growth stresses in *Eucalyptus urophylla*. *Revista Arvore* 41: 1-8.

Szeles, P., Koman, S. and Feher, S. (2015). Mitigation of end shakes on oak saw timber as a result of storage by applying environment-friendly methods. *Wood Research* 60: 823-832.

Tarigan, M., Van W.M., Roux, J., Tjahjono, B. and Wingfield, M.J. (2010). Three new *Ceratocystis* spp. in the *Ceratocystis moniliformis* complex from wounds on *Acacia mangium* and *A. crassicarpa. Mycoscience* 51: 53-67.

Tran, D.H., 2014. *NIR for combined selection in hardwoods for both growth and wood properties,* PhD Thesis, University of Queensland, Australia.

USDA Soil Texturing Field Flow Chart. N.d. Retrieved 14 October 2020 from envoglobal.com/catalog/soil/soil-classification/soil-texture/usda-soil-texturing-field-flow-chart

Vega, M., Hamilton, M.G., Blackburn, D.P., McGavin, R.L., Baileres, H. and Potts, B.M. (2016). Influence of site, storage and steaming of *Eucalyptus nitens* log-end slitting. *Annals of Forest Science* 73: 257-266.

Wu, H.X., Ivkovich, M., Gapare, W.J., Matheson, A.C., Baltunis, B.S., Powell, M.B. and McRae, T.A. (2008). Breeding for wood quality and profit in *radiata* pine: A review of genetic parameters and implication for breeding and deployment. *New Zealand Journal of Forestry Science* 38: 56-87

Yahya, A.Z. (2020). Planting of Eucalyptus in Malaysia. *Acta Scientific Agriculture* 4: 139-140.

Yamane, T. (1967). Sampling Distribution. In *Statistics: An Introductory Analysis*, pp. 129-133. New York: Harper and Row.

Yang, D.Q. and Beauregard, R. (2001). Check development on jack pine logs in Eastern Canada. *Forest Products Journal* 51: 63-65.

Yang, D.Q. and Normand, D. (2012). *Best practices to avoid hardwood checking, part I. hardwood checking – the causes and prevention*. FP Innovations, Pointe-Claire, Canada 2012.

Yang, D.Q. and Normand, D. *End coating to prevent checks on hardwood.* FP Innovations-Forintek report No. 5366. Eastern Region, Quebec, Canada. 2008.

Yang, D.Q. *Prevention of hardwood fungal stain through proper sawmill operations.* FP Innovations-Forintek report No. 3258. Eastern Region, Quebec, Canada. 2004.

Yang, J.L., Fife, D., Waugh, D. and Blackwell, P. (2002). The effect of growth strain and other defects on the sawn timber quality of 10-year-old *Eucalyptus globulus* Labill. *Australian Forestry* 65: 31-37.

Yang, J.L. and Pongracic, S. *The impact of growth stresses on sawn distortion and log end-splitting of 32-year-old plantation Blue Gum.* Forest & Wood Products Research and Development Corporation, Australia. 2004.

Yang, J.L. (2005). The impact of log-end splits and spring on sawn recovery of 32-year-old plantation *Eucalyptus globulus* Labill. *Holz als Roh- und Werkstoff* 63: 442-448.

Yang, J.L. and Waugh, G. (2001). Growth stress, its measurement and effects. *Australian Forestry* 64: 127-135.

Zeltins, P., Katrevics, J., Gailis, A., Maaten, T., Baders, E. and Jansons, A. (2018. Effect of Stem Diameter, Genetics, and Wood Properties on Stem Cracking in Norway Spruce. *Forests* 9: 546