Variation in density and shrinkage of six eucalyptus species and interspecific hybrid combinations at three sites in Northern New South Wales

T Listyanto1*, J D Nichols2, K Glencross2, and L Schoer3

1Faculty of Forestry, Gadjah Mada University, Yogyakarta.
2Sustainable Forestry Program, School of Environmental Science and Management, 3Southern Cross University, Lismore, NSW Australia 2480, Lesley Schoer & Associates Pty Limited, PO Box 477 Coffs Harbour, NSW 2450 Australia

*Email: tomy.listyanto@gadjahmada.edu

Abstract. The study aimed to investigate the variation of density and shrinkage at radial and axial directions of nine eucalypt taxa at three different sites (Muller, Convery, and Ironbolt). The data used in this research was collected from six years old trials of nine Eucalyptus taxa at those three sites. Density and shrinkage were collected from 145 selected trees based on British Standard (BS 373 1957). A two-way analysis of variance and Tukey HSD were used to analysis density and shrinkage parameters. The effect of site, taxa, and interaction between sites and taxa on oven-dry density and shrinkage were statistically significant different (p<0.05). In terms of density, Corymbia variegata provenance Wodum had the highest oven-dry density at 781 kg/m^3 (CV=11.7%). There was a significant variation in oven-dry density at the radial and axial directions. The oven-dry density at Diameter at Breast Height (DBH) of all taxa, except E. cloeziana and the hybrid E. grandis x E. camaldulensis, tended to be lower than at the top point of measurement (TMS). In terms of variation in the radial direction, there were three types of trends of oven-dry density from pith outward. In terms of shrinkage, C. variegata provenance Richmond and Wodum, and E. saligna had the lowest radial shrinkage, tangential shrinkage and T/R ratio, while E. dunnii and E. pilularis showed the highest one. Another important finding is that the hybrid between E. grandis x E. camaldulensis and E. urophylla x E. grandis showed higher radial and tangential shrinkage than their parent species (E. grandis).

1. Introduction
Several species of Eucalyptus are in great demand for planting because of its fast growth, adaptability and potential purposes. There are several groups suitable for future genotype selection, including E. dunnii, E. grandis, E. cloeziana, E. pilularis, and Corymbia variegata, for breeding, improved seed production, and clone development [1]. Arnold [2] explains that E. grandis is an important parent for breeding inter-specific eucalypt hybrids (with E. saligna, E. camaldulensis or other species). On the other hand, E. camaldulensis is one of the hardwood species which has been shown to be well-adapted to low water availability, shows good stem-straightness, and is often without bifurcations [2]. Meanwhile C. variegata has desirable timber properties for appearance-grade products, good stem form, drought tolerance and adaptability [3]. Therefore, it is remained important to investigate the suitable eucalyptus species that have good growth performance and wood quality.
Species and environment are important factors in developing prescriptions for plantation forests. Different growth conditions significantly affect wood density and shrinkage of selected young poplar hybrid crosses [4]. Survival, growth, stem form and resistance to stem-boring insect larvae were significantly different between sites and between taxa [5]. The Convery site that had Red Ferrosol soil and the highest mean annual rainfall, 1400 mm showed the highest growth of all taxa [5]. It is necessary also to evaluate their wood quality for a range of species and hybrids in different soil types and annual rainfall.

Wood quality can be defined as the characteristics of wood that in turn affect the properties of the manufactured product [6]. Wood density and shrinkage are often used as general indicators of the suitability of wood for many purposes, including manufacture products [7, 8]. This is because the density of wood is a main determinant of strength; consequently, density and strength are directly related to each other [6,9,10]. Wood density also has an influence on wood processing, including on cutting, gluing, finishing, rate of drying and paper making [7], while shrinkage is important in terms of the stability of wood during and after drying [6,11,12].

In eucalyptus species (diffuse porous hardwood), wood density and shrinkage generally are controlled by a combination of environmental factors and silvicultural practice [7]. Understanding the wood density of a particular species allows the wood industry and the consumer to decide the appropriateness of wood uses. The variation of wood density between and within trees is caused by a combination of factors: growth rate, climate, silviculture and breeding [6,13]. Therefore, considering environmental factors and species is an important step in establishing plantations for commercial purposes with higher wood quality. Consideration of environmental conditions will help to produce a short list of candidate species [14]. Accordingly, different species or hybrids may give different responses for different sites. This research assesses wood quality of nine selected species of eucalyptus in three different sites in northern New South Wales. This study examined whether there were differences in oven-dry density and shrinkage among nine selected species of Eucalyptus at three different sites namely Muller, Convery, and Ironbolt.

2. Materials and Methods
The data used in this research was collected from six-year-old trials of nine Eucalyptus taxa at three different sites (Muller, Convery, and Ironbolt). The nine taxa trials are seven Eucalypt species and two inter hybrid combinations. The six eucalyptus species were Eucalyptus cloeziana (CLO), E. grandis (GRA-5), E. dunnii (DUN-Y), E. saligna (SAL-56), E. pilularis (PIL-W), Corymbia variegata provenance Richmond (VAR-R), and Corymbia variegata provenance Wodum (VAR-W). Three inter hybrid combination are E. grandis x E. camaldulensis (GxC-11), E. urophylla x E. grandis (UxG-57). Codes indicate geographical origins of seed is presented in Table 1. Detail planting patterns are explained in Listyanto et al. [5].

| Codes   | Taxon                        | Seedlot/Provenance/ Clone no                  |
|---------|------------------------------|-----------------------------------------------|
| Clo     | Eucalyptus cloeziana         | Natural provenance (identity was not known)   |
| Dun-Y   | Eucalyptus dunnii            | Safcol clonal seed orchard, South Africa      |
| Gra5    | Eucalyptus grandis           | Clone 5150                                    |
| SAL-56  | Eucalyptus saligna           | Clone 5156                                    |
| PIL-W   | Eucalyptus pilularis         | Whian Whian elite, NSW                        |
| VAR-R   | Corymbia citriodora subsp. variegata | Provenance Richmond Range, NSW          |
| VAR-W   | Corymbia citriodora subsp. variegata | Provenance Woondum, Queensland        |
| GxC-11  | E. grandis x E. camaldulensis| Clone 11                                      |
| UxG-57  | E. urophylla x E. grandis    | Clone 5157                                    |
2.1. Site locations and description.
The detail of site location and description can be found in Listyanto et al. [5]. In general, the Muller site has annual rainfall of approximately 1200 mm and an elevation of 220 m above sea level. The soil is Brown Dermosol, which has good water holding capacity, organic matter levels and nutrient status. The Convery site has rainfall of approximately 1400 mm and an elevation of 450-500 m above sea level. The soils (Red Ferrosols) has a good water holding capacity and is well drained, with relatively high organic matter content and nutrient status. The Ironbolt site has annual rainfall of approximately 1100 mm and an elevation of 200 m. The soils in Ironbolt are also Brown Dermosols.

2.2. Data collection
Oven-dry density and shrinkage were measured as a preliminary indication of wood quality. Samples of wood quality and shrinkage were taken by cutting down 145 trees or 5 trees each species. Straight stems were considered to minimize the probability of the presence of compression wood [15]. Cross sections, 14 cm thick, at DBH and at the top of the merchantable stem (TMS) or at diameter 10 cm of each log (approximately 70% of total height) were removed from the trees. Then the disks were cut into 20 x 20 x 20 mm³ blocks for wood oven-dry density assessment [15,16]. A total of 120 samples for each species per site were collected. The method of determining oven-dry density and shrinkage were based on the British Standard [17]. Wood density and shrinkage of the wood sample were determined in the radial, tangential directions and T/R ratio was also recorded. Radial sections were measured along the rays or radius of the log, at right angles to the annual rings while tangential sections were measured perpendicular to the rays and tangential to the annual rings and face of the log.

2.3. Statistical analysis
Two-way ANOVA was used to test whether there was a difference in the wood oven-dry density and shrinkage of nine taxa of eucalyptus between three different sites then continued by Tukey Honest Significant Different (HSD) as a post hoc test with using level of significance of 5%. These analyses were conducted using the Statistical Program for Social Science (SPSS) version 16.

3. Results and Discussion
3.1. Oven-dry density
Variance analyses indicated that the mean values of oven-dry densities of different taxa were significantly different among the three sites. Details of oven-dry density of all taxa in three sites can be seen in Figure 1. The lower density was found significantly in the Convery compared to Ironbolt and Muller. The significance difference might be due to the distinction of the site quality among three sites was extensive [18]. One of important results is that there is a tendency for good sites to produce wood of lower density, among the taxa tested. It is possible that production within the tree of larger vessels with relatively thin fibers at a good site might produce lower oven-dry density of species [18-20]. The results also showed that the mean of oven-dry density decreased with increasing annual rainfall and the decreasing of elevation. For instance, the Convery site, which has annual rainfall higher than other sites (approximately 1400 mm) and has an elevation lower than other sites (220 masl), produced six-year old trees with the lowest mean oven-dry density. These results are also coincident with the summary of Blakmore [21] who worked with four low rainfall eucalypt species and concluded that low rainfall eucalypt species have much higher oven-dry density.

Interactions between species and site for oven-dry density were shown for nine species at three different sites. Corymbia variegata provenance Wodum had the highest oven-dry density at 808 kg/m³ at Ironbolt, while the highest oven-dry densities at Convery and Muller were shown by E. cloeziana (665 kg/m³) and C. variegata provenance Richmond (766 kg/m³), respectively. In general, C. variegata provenances Wodum and Richmond, E. cloeziana, and E. dunnii behaved consistently as a higher group in oven-dry density. The significance of interaction between species and site was also in agreement with the summary of Lima [22] and Zobel and Buitjtenen [18]. Hybrids of E. grandis with E. camaldulensis or E. urophylla had higher densities than pure E. grandis as a parent species. The hybrid E. grandis x
E. camaldulensis showed oven-dry density at 679 kg/m³ and E. urophylla x E. grandis showed oven-dry density at 613 kg/m³, while E. grandis was only 554 kg/m³. Subsequently, hybrids between E. grandis with E. camaldulensis or E. urophylla succeeded in increasing their oven-dry density. It is often found that important characteristics of eucalypt hybrids tends to be intermediate between their parent species [2].

![Figure 1. Wood oven-dry density of nine taxa at the Convery, Ironbolt and Muller sites, northern NSW.](image)

Variations of oven-dry density in the radial and axial directions were also found. The oven-dry density at DBH of all taxa, except E. cloeziana and hybrid E. grandis x E. camaldulensis, tend to have a lower oven-dry density than at top of the stem (TMS). It appears that this type of variation of axial position may be due to the proportion of early wood at DBH, which is lower than in at the higher point (TMS) [19].

In terms of variation in the radial direction, there are three types of trends for oven-dry density from pith outward (the figure is not shown). In the first type, wood near the pith tends to have a lower oven-dry density than near bark. This occurs in E. cloeziana, E. dunnii, E. grandis, E. saligna, E. urophylla x E. grandis, and C. variegata provenance Richmond. In the second type, wood near the pith tends to have a higher oven-dry density than near bark and occurs in E. grandis x E. camaldulensis. In the third type, wood near the pith tends to have lower oven-dry density than near bark at DBH but have higher than near bark at top (TMS), which occur in E. pilularis. The opposite condition occurs in C. variegata provenance Wodum where wood near the pith tends to have higher oven-dry density than near bark at DBH but have lower than near bark at top (TMS). Hillis [7] also noted that the oven-dry density of eucalypts varies with the distance from pith outward. In the first type it appears that the lower oven-dry density of wood near the pith occurs because of the appearance of juvenile wood near the pith that tends to be have thinner cell walls than wood formed in later years [18]. In addition, the proportion of juvenile wood near the pith is slightly higher than near the bark creating the difference in oven-dry density between near pith and near bark in top (TMS) of E. dunnii, and E. grandis. E. saligna, E. urophylla x E. grandis tended to have lower density at DBH.

Variations in radial shrinkage, tangential shrinkage and T/R ratio were found among the three different sites, species and within individual trees. Details of radial shrinkage, tangential shrinkage and T/R ratio of all taxa in three sites can be seen in Figures 2-4. Interestingly, variance analysis indicated that radial shrinkage, tangential shrinkage and T/R ratio showed a trend in relation to the site quality. According to the results, radial and tangential shrinkage tend to have a higher percentage at good sites where oven-dry density showed a lower value. This result corresponds with the findings of Yang et al. [23] who worked with E. globulus Labil and concluded that shrinkage properties of E. globulus Labill were affected significantly by site. It has been noted that density may affect shrinkage behavior [6,19].
Variation in radial shrinkage, tangential shrinkage and T/R ratio are also shown between species (the figure is not shown). According to the results, *C. variegata* provenance Richmond and Wodum, and *E. saligna* had the lowest radial shrinkage, tangential shrinkage and T/R ratio, while *E. dunnii* and *E. pilularis* showed the highest. It has been noted that the shrinkage behavior can vary by individual tree [24]. Overall, mean values of radial and tangential shrinkage of *E. pilularis*, *E. urophylla* x *E. grandis*, and *E. dunnii* were higher than recorded by Spear and Walker [25] for medium density woods. These results are consistent with the report of McComb *et al.* [26] that tangential shrinkage of a young hybrid between *E. camaldulensis* x *E. globulus* was greater than in a mature *E. camaldulensis* x *E. globulus*. This might be due to the presence of juvenile wood which is usually found in early growth. A lower proportion of latewood and a thin cell wall in juvenile wood tend to increase the mean value of shrinkage of hardwoods [18]. Another important result was that hybrids between *E. grandis* x *E. camaldulensis* and *E. urophylla* x *E. grandis* showed higher radial and tangential shrinkage than did their parent species (*E. grandis*). These results were consistent with the report of McComb *et al.* [26] that young hybrid *E. camaldulensis* x *E. globulus* had higher levels of shrinkage than their parent species. Thus, in this case, hybrid species showed higher value of shrinkage compared with one of their parent species.

Variations of radial and tangential shrinkage were also found within tree, especially in the radial and axial direction (the figure is not shown). In terms of radial direction, tangential shrinkage generally decreased from pith to bark, except for *E. grandis* and *E. pilularis*. This result was not consistent with the report of Kang and Lee [24] who worked on Korean larch and found that shrinkage generally increased from pith to bark. The change from juvenile to mature wood has been proposed to explain the variation of shrinkage from pith to the bark. The thinner and shorter fibers near the pith possibly explain the higher shrinkage at near pith than near bark [18]. In the axial direction, radial and tangential shrinkage varied at different heights in tree. For radial shrinkage, there were two patterns of variation. The first pattern was decreasing radial shrinkage from DBH to the top (TMS) such as in *E. dunnii*, *E. grandis* x *E. camaldulensis*, *E. pilularis*, *E. saligna*, and *E. urophylla* x *E. grandis*. The second pattern was that there was no significant difference between radial shrinkage at DBH and at top (TMS), such as in *E. cloeziana*, *E. grandis*, and *C. variegata* provenance Richmond and Wodum. For tangential shrinkage, there was only one pattern. The pattern is decreasing tangential shrinkage from DBH to the top point measured (TMS). A full understanding of wood shrinkage with height in tree can be achieved by studying the trend of juvenile and mature wood along the length of the stem [18].

Variation in radial shrinkage and tangential shrinkage of nine taxa eucalypts due to the anisotropic structure was also shown in this study. The ratio of tangential to radial shrinkage (T/R ratio) of all species was more than 1.6 (the figure is not shown). This result might be due to the hygro-expansion coefficient of tangential shrinkage which is usually greater than twice coefficient of radial shrinkage [27,28]. This may be a function of fibril arrangement, especially the thickness of the S2 layer [29]. Less shrinkage in the radial direction shrinkage also has been proposed to be due to the greater microfibril angle in radial walls than in tangential and a high proportion of latewood, which forces weak earlywood to shrink more tangentially than independently of the latewood [25,28]. Furthermore, the T/R ratio of several species, such as *E. dunnii* planted at the Convery and the Ironbolt sites, and *E. pilularis* planted at the Convery site, were more than 2.5. This is higher than the typical findings of Spear and Walker [25] who reported that the range of T/R ratio of normal shrinkage is 1.5-2.5:1. A high proportion of juvenile wood might be the possible reason for these results.
Figure 2. Radial shrinkage of nine taxa at the Convery, Ironbolt and Muller sites, northern NSW

Figure 3. Tangential shrinkage of nine taxa at the Convery, Ironbolt and Muller sites, northern NSW

Figure 4. Tangential and radial ratio of nine taxa at the Convery, Ironbolt and Muller sites, northern NSW
4. Conclusions

Oven-dry density, tangential shrinkage, radial shrinkage and T/R ratio were significantly affected (p<0.05) by site, taxa and interaction between site and taxa on. In terms of sites, the plantation at Convery, where there is high soil quality, annual rainfall higher (approximately 1400 mm) than the other sites and an elevation lower than other sites (220 masl), showed the lowest oven-dry density and the highest radial shrinkage, tangential shrinkage and T/R ratio.

*C. variegata* provenance Wodum had the highest oven-dry density at 781 kg/m³. Variations in oven-dry density in the radial and axial directions were also found. The oven-dry density at DBH of all taxa, except *E. cloeziana* and the hybrid *E. grandis* x *E. camaldulensis*, tended to be lower than at the top point of measurement (TMS). In terms of variation in the radial direction, there are three types of trends of oven-dry density from pith to outward.

In terms of shrinkage, *C. variegata* provenance Richmond and Wodum, and *E. saligna* had the lowest radial shrinkage, tangential shrinkage and T/R ratio, while *E. dunnii* and *E. pilularis* showed the highest. Another important finding is that hybrid between *E. grandis* x *E. camaldulensis* and *E. urophylla* x *E. grandis* showed higher radial and tangential shrinkage than their parent species (*E. grandis*). Another important result is that the oven-dry density of sampled species decreased in the better growth condition.

References

[1] Eldridge K, Davidson J, Hardwood C, and van Wyk G 1993 *Eucalypt Domestication and Breeding* (Clarendon: Oxford)

[2] Arnold R, Bush D, and Stackpole D 2005 *Genetic variation and tree improvement* (New Forests: Wood production and environmental services) Ed. Nambiar S and Ferguson I (CSIRO: Victoria) pp. 25-50

[3] FAO 1979 *Eucalypts for planting* (Rome: FAO Forestry and Forest Product Studies)

[4] Pliura A, Yu Q, Zhang SY, MacKay J, Perinet P, and Bosquet J 2005 Variation in wood density and shrinkage and their relationship to growth of selected young poplar hybrid crosses *For. Sci.* 51 472-82

[5] Listyanto T, Glencross K, Nichols J, Schoer L, and Harwood C 2010 Performance of eight eucalypt species and interspecific hybrid combinations at three sites in northern New South Wales, Australia *Aust. For.* 73 47-52

[6] Bowyer JL, Shmuls ky R, and Haygreen JG 2007 *Forest Products and Wood Science: An Introduction* (New Jersey: Wiley-Blackwell)

[7] Hillis WH 1978 *Wood Quality and Utilization (Eucalypts for Wood Production)* Ed. Hillis WH and Brown AG (Canberra: CSIRO)

[8] Listyanto T 2018 Wood quality of *paraserianthes falcataria* l. Nielsen syn wood from three years rotation of harvesting for construction application *Wood Res. Slovakia* 63(3) 497-504

[9] Bendsten BA 1978 Properties of wood from improved and intensively managed forest *For. Prod. J.* 28 61-72

[10] Bootle KR 1983 *Wood in Australia* (New South Wales: McGraw-Hill Book Company Australia)

[11] Listyanto T, Ando K, Yamauchi H, and Hattori N 2013 Microwave and steam injection drying of CO2 laser incised Sugi lumber *J. Wood Sci.* 59(4) 282-9

[12] Listyanto T, Ando K, Yamauchi H, and Hattori N 2016 CO2 Laser-Incised Teak and Mahogany Lumber Dried by Microwave and Steam Injection *For. Prod. J.* 66(7-8) 461-6

[13] Repola J 2006. Models for vertical wood density of Scots Pine, Norway Spruce and Birch Stems, and their application to determine average wood density *Silva Fenn.* 40 673-85

[14] Booth T 2005 *Environment, species selection and productivity prediction* (New Forests: wood production and environmental services) Ed. Nambiar S and Ferguson XI (Victoria: CSIRO) pp. 5-24

[15] Olivia AG, Merino VB, Seco JIF-G, Garcia MC, and Prieto EH 2006 Effect of growth conditions on wood density of Spanish *Pinus nigra* *Wood Sci. Technol.* 40 190-204
[16] Molteberg D 2004 Methods for the determination of wood properties, kraft pulp yield and wood fibre dimensions on small wood sample *Wood Sci. and Technol.*. 37 395-410  

[17] BS 373 1957 *Methods of Testing Small Clear Specimens of Timber* (London: British Standards Institution)  

[18] Zobel BJ and Buitjten JPV 1989 *Wood Variation: Its Causes and Control* (Berlin: Springer-Verlag) pp. 418  

[19] Panshin AJ and de Zeeuw C 1980 *Textbook of Wood Technology* (New York: McGraw-Hill Book Company)  

[20] Raiskila S, Saranpää P, Fagerstedt K, Laakso T, Löija M, Mahlberg R, Paajanen L, and Ritschkoff AC 2006 Growth rate and wood properties of Norway spruce cutting clones on different sites *Silva Fenn.*. 40 247-56  

[21] Blakemore P 2004 Density and shrinkage of four low-rainfall plantation-grown eucalypts *Aust. For.*. 67 152-5  

[22] Lima JT, Breese MC, and Cahalan CM 2000 Genotype-environment interaction in wood basic density of eucalyptus clones *Wood Sci. and Technol.*. 34 197-206  

[23] Yang JL, Fife D, Ilic J, and Blackwell P 2002 Between-site and between-provenance differences in shrinkage properties of 10 years old *Eucalyptus globulus* Labill *Aust. For.*. 65 220-226  

[24] Kang W and Lee NH 2004 Relationship between radial variation in shrinkage and drying defects of tree disk *Journal of Wood Science* 50 209-16  

[25] Spear M and Walker J 2006 *Dimensional Instability in Timber* (Primary Wood Processing: Principles and Practice) Ed. Walker JCF (Netherlands: Springer)  

[26] McComb JA, Meddings RA, Siemon G, and Davis S 2006 Wood density and shrinkage of five years old *Eucalyptus camaldulensis* x *E. globulus* hybrids: preliminary assessment *Australian Forestry* 67 236-9  

[27] Schulgasser K and Witztum A 2015 How the relationship between density and shrinkage of wood depends on its microstructure *Wood Sci. and Technol.*. 49 389-401  

[28] Skaar C 1988 *Wood Water Relations* (Berlin, Heidelberg: Springer-Verlag) pp. 279  

[29] Gu H, Zink-Sharp A, and Sell J 2001 Hypothesis on the role of cell wall structure in differential transverse shrinkage of wood *Holz Roh Werkst.*. 59 436-42

**Acknowledgements**

We thank to Forest Enterprises Australia for providing access to the trials and details of their establishment and management. John Grant provided information on soils at the three sites, and David Kleining provided taxa details.