J Wood Sci (2008) 54:431–435
DOI 10.1007/s10086-008-0977-1

© The Japan Wood Research Society 2008

ORIGINAL ARTICLE

Jerome K. Vanclay · Michael Henson · Graeme Palmer

Color variation and correlations in *Eucalyptus dunnii* sawnwood

Received: January 24, 2008 / Accepted: May 16, 2008 / Published online: August 15, 2008

Abstract A study of material thinned from a 9-year-old *Eucalyptus dunnii* progeny trial revealed that *E. dunnii* has light yellowish wood that is relatively uniform in color, and varies little within and between trees. The variation in color between half-sib families is small, but is statistically significant ($P = 0.008$). Most of the color variation relates to the yellowness (CIE b^*) of the wood, which in heartwood is moderately heritable ($h = 0.6$). The color of the endgrain, especially its lightness (CIE L^*) and whiteness index (E313), is correlated with basic density, hardness, and rates of shrinkage. The CIE rectangular opponent scale (L^*, a^*, b^*) appeared to be the most informative about wood color and properties, and no additional information was gleaned from an analysis of full spectral data in the range 400–700 nm.

Key words Dunn's white gum · Sawnwood · Timber · Hunterlab miniscan

Introduction

Eucalyptus dunnii Maiden (Dunn's white gum)[1] is a relatively new, but increasingly important plantation species in eastern Australia. Over 10 000 ha of *E. dunnii* plantation has been established in New South Wales (NSW), and it remains one of the favored species for planting, with some 40% of current plantings in north-east NSW and south-east Queensland using this species. Although it forms a crucial component of the long-term supply to the sawlog industry, this emerging resource remains relatively untried by industry. This is one of a series of studies[2,3] of wood quality in *E. dunnii*, and explores color variation and correlations with other wood properties in this emerging plantation resource.

Color is an important property in sawnwood, but is difficult to quantify.[4] The most widely used system of color measurement is the rectangular opponent scale (L^*, a^*, b^*) of the International Commission on Illumination.[5] This scale represents color as psychometric lightness (L^*, which varies from 0 = black to 100 = white), red–greenness (a^*, which measures red when positive, gray when zero, and green when negative), and yellow–blueness (b^*, which measures yellow when positive, gray when zero, and blue when negative). Other alternatives exist, and two of the more common are the tristimulus (X, Y, Z) scale, which records reflectance of each of the three primary colors, and the CIE polar (L^*, C^*, $h°$) scale, which represents lightness, chroma, and hue. A one-to-one mathematical relationship exists between these scales, so color measurements can be converted unambiguously from one scale to another. We used the CIE rectangular (L^*, a^*, b^*) scale because of the ease of interpretation and calculation of color differences.[5] This system has been used in several studies of wood color.[6–8] Dominant wavelength has also been used to characterize wood color.[9,10]

The color recorded by a colorimeter depends on the viewing conditions. We used the 10° standard observer (which represents the human retinal response viewing an object subtending an angle of 10°) under standard daylight (D65 with color temperature 6500 K), consistent with the work of Nishino et al.[11]

The color of wood may vary greatly within trees. Rink[12] recorded that heartwood color in black walnut may depend on the position in the tree (height, radius), and on the growth rate of the tree. Amusant et al.[8] recorded that heartwood color in *Dicorynia* became redder and darker as distance from the pith increased, and as distance from the stump decreased. Raymond and Bradley[7] also reported that redness (a^*) and yellowness (b^*) decreased with increasing height within *Eucalyptus nitens* trees, but they found that an estimate of yellowness (b^*) from a single core sample could provide a reliable indication of whole-tree color.

J.K. Vanclay (✉) · G. Palmer
Sustainable Forestry Program, Southern Cross University, PO Box 157, Lismore NSW 2480, Australia
Tel. +61-26-620-3147; Fax +61-26-621-2669
e-mail: jvanclay@scu.edu.au

M. Henson
Forests NSW, Coffs Harbour Jetty, NSW 2450, Australia

Mononen et al.[13] reported that wood became darker on drying, mainly due to a decrease in lightness (L^*). Sullivan[9] observed that during drying, brightness increased and chroma decreased, while dominant wavelength remained unchanged. These changes were prominent near the fiber saturation point. Sullivan[14] also observed that ultraviolet light tended to darken the surface of timber during the first 13 days of exposure after which continued exposure tended to cause bleaching.

Beckwith[10] found that radial and tangential sawnwood surfaces were indistinguishable in color, but that the transverse surface (endgrain) differed significantly in color from the longitudinal surfaces. Hannrup et al.[15] reported that wood color in *Picea abies* had low heritability ($h < 0.2$).

Materials and methods

Short boards (about 30 cm in length and 20 mm in thickness) were sawn from logs at a standard height of 3 m above ground level. These boards were sawn radially from pith to bark with a bandsaw, in a plane parallel to any end-splitting observed in the log. Sawing was completed within 1 week of felling, and logs were stored under sprinklers during the few days prior to sawing. Boards were air-dried for 2 weeks to about 25% moisture content under controlled conditions (in an air-conditioned laboratory), and were neither sanded nor planed. The colorimeter used to assess wood color was a HunterLab Miniscan XE, which sampled a 24-mm-diameter circle. The instrument was placed to record a sample representative of the board, midway along its length, wholly within the heartwood, but near the heart–sapwood boundary. The instrument recorded both tristimulus (X, Y, Z and L^*, a^*, b^*) and full spectral data (by 10-nm increments between 400 and 700 nm), as well as the dominant wavelength and whiteness index (E313 of the American Society of Testing and Materials).

Endgrain color was recorded from disks, 25 mm thick, cut from a height of about 2.5 m above the ground. The disks were air-dried for 2 weeks and fine-sanded with a belt sander. The same HunterLab Miniscan XE instrument was used to record the color attributes of the sapwood and heartwood. Endgrain surfaces tended to darken slightly during the first few hours after sanding, so all samples were left for 2 days between sanding and color measurement to minimize any possible impact of any small difference in the measurement interval. Sanded surfaces were wiped with a dry cloth to remove any loose dust.

Several other issues were also explored with the endgrain samples. Fine-sanding is a time-consuming process, so a color measurement was taken on an unsanded surface (rough-sawn with a chainsaw) to examine if any useful information could be gleaned from such a surface. This color measurement was taken on the opposite side (cf. upper versus lower surface) of the disk.

Wetting wood, especially endgrain, with water or oil causes the wood to darken and may highlight patterns in the wood. Thus, we took additional color measurements, from the same locations as the fine-sanded and rough-sawn samples, immediately after immersing the sample briefly in water. A final color measurement was taken 2 days later, after the wetted surface had dried.

Results and discussion

Boards

A study of a small sample of the boards confirmed that the tangential and radial faces were indistinguishable in color as previously reported,[10] so the radial-sawn face was used for comparison. Boards exhibited a mean dominant wavelength of 575.5 nm with a standard deviation of 0.6 nm and a range of 573–577 nm, implying that all the boards have a yellowish hue. Expressed in CIE polar coordinates, the typical board had lightness $L^* = 77.2$ (±2.5), chroma $C^* = 15.8$ (±1.4), and hue $h° = 76.3$ (±1.7). This means that the boards were quite light (L^* has a range 0–100 where 100 is bright white), pale (C^* has a range 0–100 indicating the proportion of reflected light at the dominant wavelength), and yellowish ($h°$ varies between 0° and 360° where 0° is red and 90° is yellow; Fig. 1). In CIE rectangular coordinates, $L^* = 77.2$ (±2.5), $a^* = 3.8$ (±0.6, a trace of red), and $b^* = 15.3$ (±1.4, some yellow). Although the boards were quite pale, they had a low whiteness index of –30 (±12; a perfect reflecting diffuser is +100) on the E313 scale of the American Society of Testing and Materials.

The CIE standard measure of color difference, ΔE ($= \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$), was used to assess how each board differed from the "typical" board. This difference averaged 8.4, and correlated most strongly with the yellowness (b^*) of the individual boards ($r = 0.23$). This correlation, plus the observation that single samples of yellowness (b^*) may be characteristic of whole-tree color,[7] indicate that b^* offers a good basis for comparing trees and families of *Eucalyptus dunnii*. Yellowness (b^*) was not significantly correlated with any easily observable tree characteristics (height, diameter, etc.), but was inversely related to density ($P = 0.05$; denser wood is less yellow) and exhibited a statistically significant relationship with family affinity ($P = 0.008$, after an inverse transformation to stabilize variance; Fig. 1). This implies that yellowness (b^*) is moderately heritable, and that tree-breeding efforts aimed at increasing wood density may also favor paler wood.

The sapwood–heartwood boundary was almost indistinguishable on most radially sawn boards, and was most clearly visible on the sanded endgrain. The color of the radial surface was rather similar to endgrain heartwood (color difference $\Delta E = 13 \pm 4$), and tended to be paler than the endgrain sapwood (color difference $\Delta E = 21 \pm 4$). The color difference between the radial and endgrain surfaces was mainly due to a change in lightness (L^*; Table 1).

Endgrain

The endgrain of samples tended to be somewhat darker than the radial-sawn face, and tended to accentuate the

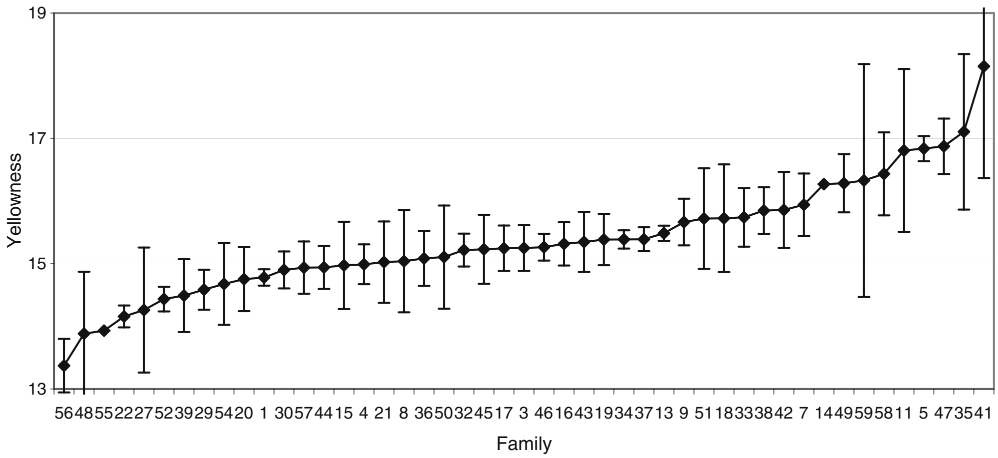

Fig. 1. Average yellowness (CIE b^*) of radial-sawn *Eucalyptus dunnii* boards, ranked by family, with error bars showing standard deviation

Table 1. Mean color data for boards and endgrain samples

Sample	Dominant wavelength	Lightness L^*	Red a^*	Yellow b^*	Chroma C^*	Hue $h°$	Whiteness index
Sawn boards	576	77	4	15	16	76	–30
Rough-sawn sapwood	578	53	7	22	23	70	–128
Sanded sapwood	578	57	6	15	16	70	–77
Wetted sapwood	579	47	9	22	24	68	–151
Dried sapwood	578	56	6	16	17	70	–87
Rough-sawn heartwood	578	52	8	23	24	71	–141
Sanded heartwood	578	65	6	15	17	70	–61
Wetted heartwood	580	53	11	26	28	67	–155
Dried heartwood	578	63	6	18	19	71	–76

Table 2. Correlations between color of dry fine-sanded endgrain and stem and wood properties

Property	Sapwood			Heartwood			Sap:heartwood ΔE
	L^*	b^*	WI	L^*	b^*	WI	
Tree size (DBH)	0.01	0.03	–0.02	–0.29*	–0.14	–0.10	–0.24*
Basic density	–0.20	0.27*	–0.35*	–0.16	0.18	–0.27*	0.02
Pilodyn hardness	0.25*	–0.25*	0.37*	0.10	–0.18	0.23	–0.08
Tangential shrinkage	–0.19	0.14	–0.25*	–0.26*	0.07	–0.27*	–0.07
Radial shrinkage	–0.27*	0.00	–0.20	0.10	0.12	–0.03	0.28*
Heritability	0.40	0.42	0.47*	0.35	0.64*	0.12	

WI, Whiteness index (E313); DBH, diameter at breast height; ΔE, $(= \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2})$ measures the overall color difference between sapwood and heartwood

* Significant correlations ($P < 0.05$)

difference between sapwood and heartwood (Table 1). The major difference between heartwood and sapwood was in lightness, which varied by 8 units, whereas the difference in dominant wavelength was imperceptible.

Heartwood color, especially its lightness (L^*), was correlated with tree size, with larger trees having darker heartwood, and less difference between sapwood and heartwood (Table 2). Sapwood, notably its whiteness (E313 index), was significantly correlated ($P < 0.01$) with basic density and hardness (Pilodyn), with denser wood having a more yellow appearance. There is some suggestion that large color differences between sapwood and heartwood may be correlated with high radial shrinkage (Table 2).

Sanding is time consuming, but appears necessary to obtain reliable measurements of color. Correlations between sanded and unsanded material were low (Table 3), and, unlike sanded material (Table 2), unsanded material does not appear to offer any useful insights into wood properties. Dominant wavelength of unsanded material appeared to be relatively unbiased (Table 1), but this property exhibited a poor correlation with the fine-sanded material (Table 3).

Texture in wood can often be highlighted by wetting the sample with water or oil, so we remeasured our samples after dipping them briefly in water. Wetting in this way tended to darken the wood (reduce L^*) and increase the chroma (C^*, see Table 1), but did not significantly change the dominant wavelength or hue. Wetting the wood in this way did not reveal any new insights into wood quality; correlations between color and wood properties were uni-

Table 3. Importance of sample preparation: correlations with dry fine-sanded endgrain samples

Sample (endgrain)	Sapwood					Heartwood				
	L^*	a^*	b^*	DW	WI	L^*	a^*	b^*	DW	WI
Rough sawn	0.16	–0.02	0.14	0.15	–0.00	0.61*	–0.01	0.33*	–0.19	–0.04
Wetted rough sawn	0.25*	0.12	0.14	0.22	–0.10	0.64*	0.30*	0.46*	–0.30*	–0.07
Wetted fine-sanded	0.70*	0.48*	0.58*	0.57*	0.24	0.84*	0.71*	0.68*	0.50*	0.40*
Sanded, rinsed, dried	0.85*	0.81*	0.78*	0.80*	0.76*	0.91*	0.92*	0.75*	0.90*	0.73*

DW, Dominant wavelength
*Significant correlations ($P < 0.05$)

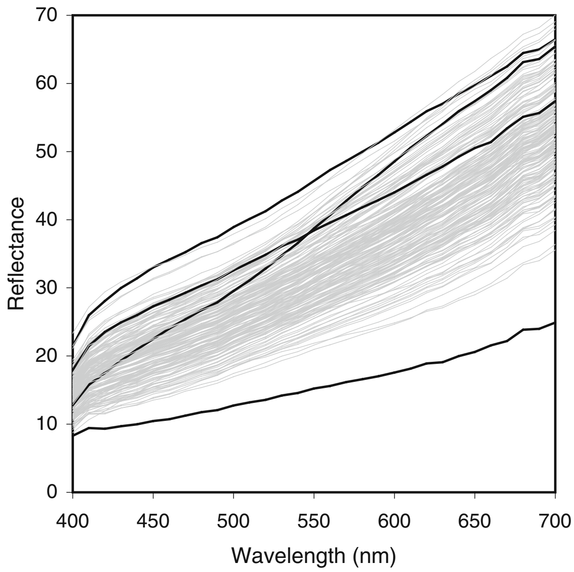

Fig. 2. Spectral signatures of 182 heartwood samples in 10-nm intervals between 400 (blue) and 700 nm (red). The diversity in trends is indicated by the four *dark lines* illustrating families 30, 13, 36 and 52 (top to bottom)

formly lower than those reported in Table 2, except for the correlation between heartwood and stem size (–0.33, –0.23, and –0.20 for L^*, b^*, and whiteness index, respectively, cf. Table 2).

It seems possible that sanding may cross-contaminate the endgrain of samples, and that the rinsing of samples may remove dust left behind by sanding. Thus, samples were reassessed for color after rinsing and drying. However, the results were disappointing, and yielded few insights not already offered by the original fresh-sanded samples. The only substantial improvement offered by this treatment was in the correlation between heartwood and stem size (–0.33 and –0.22 for L^* and whiteness index, respectively, cf Table 2).

Complete spectral responses in 10-nm intervals for the full visible spectrum 400–700 nm were also recorded. Spectra derived from sapwood observations tended to form a series of parallel lines, but the heartwood data exhibited a greater range of trends. Figure 2 illustrates the spectral data from 182 samples of heartwood. Four of the samples are highlighted with darker and heavier lines to emphasize the highest and lowest average values, and the greatest and least gradients. Many samples show a kink at 680 nm, with reflectance at this wavelength greater than the general trend, but there is no obvious explanation for this phenomenon, and the magnitude of the kink was not correlated with observable wood properties. The first derivative of the spectral signatures was also examined, but it appears that the 10-nm resolution of the Miniscan XE is insufficient for informative analyses. These detailed spectral data offered no new insights not already revealed by the lightness (L^*), yellowness (b^*), and whiteness indices reported in Table 2.

Conclusions

Eucalyptus dunnii has pale yellowish wood that is relatively uniform in color within trees and between families. The variation in color between families is small, but statistically significant ($P = 0.008$). Most of the color variation relates to the yellowness (CIE b^*) of the wood.

The color of the endgrain, especially its lightness (L^*) and whiteness index (E313), is correlated with basic density, hardness (Pilodyn), and with rates of shrinkage, but does not appear to be informative about other wood properties in *E. dunnii*. Sanding of endgrain material is necessary to obtain reliable insights of wood color and other properties, but there appeared to be no advantage in wetting samples to highlight colors and texture. Tristimulus data, especially the CIE rectangular (L^*, a^*, b^*) and polar (L^*, C^*, $h°$) opponent scales, appeared to be the most informative about wood colors and properties, and no additional information was gleaned from an analysis of full spectral data in the range 400–700 nm.

Acknowledgments This work was funded by State Forests of NSW and Southern Cross University through Collaborative Research Grant 50415-30535. Many students and staff from Southern Cross University were involved in this work, and thanks are due to Peter Bligh-Jones, Martin Davies, Alex Jay, and Tim Murphy for their assistance. Paul Fuller and Dr. Shakti Chauhan of the University of Canterbury also contributed to this work. Harvey Gough of Colour Technologies Australasia is thanked for loan of the HunterLab Miniscan XE colorimeter.

References

1. Benson JS, Hager TC (1993) The distribution, abundance and habitat of *Eucalyptus dunnii* (Myrtaceae) (Dunn's white gum) in New South Wales. Cunninghamia 3:123–145

2. Murphy TN, Henson M, Vanclay JK (2005) Growth stress in *Eucalyptus dunnii.* Aust Forest 68:144–149
3. Thinley C, Palmer G, Vanclay JK, Henson M (2005) Spiral and interlocking grain in *Eucalyptus dunnii*. Holz Roh Werkst 63:372–379
4. Jane FW (1970) The structure of wood, 2nd edn. Black, London, p 478
5. Commission Internationale de l'Eclairage (1986) Colorimetry, 2nd edn. Publication CIE 15.2-1986, p 83
6. Bond BH (1998) Characterization of wood features using color, shape, and density. PhD thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia
7. Raymond CA, Bradley AD (2002) Assessment of wood colour in *Eucalyptus nitens*. Appita J 55:118–122
8. Amusant N, Beauchene J, Fournier M, Janin G, Thevenon MF (2004) Decay resistance in *Dicorynia guianensis* Amsh.: analysis of inter-tree and intra-tree variability and relations with wood colour. Ann For Sci 61:373–380
9. Sullivan JD (1967) Color characterization of wood: color parameters of individual species. Forest Prod J 17:25–29
10. Beckwith JR (1979) Theory and practice of hardwood colour measurement. Wood Sci 11:169–175
11. Nishino Y, Janin G, Chanson B, Détienne P, Gril J, Thibaut B (1998) Colorimetry of wood specimens from French Guiana. J Wood Sci 44:3–8
12. Rink G (1987) Heartwood color and quantity variation in young black walnut progeny test. Wood Fiber Sci 19:93–100
13. Mononen K, Alvila L, Pakkanen TT (2002) CIE $L^*a^*b^*$ measurements to determine the role of felling season, log storage and kiln drying on coloration of silver birch wood. Scand J Forest Res 17:179–191
14. Sullivan JD (1966) Color characterization of wood: spectrophotometry and wood color. Forest Prod J 17:43–48
15. Hannrup B, Cahalan C, Chantre G, Grabner M, Karlsson B, le Bayon I, Jones GL, Müller U, Pereira H, Rodrigues JC, Rosner S, Rozenberg P, Wilhelmsson L, Wimmer R (2004) Genetic parameters of growth and wood quality traits in *Picea abies*. Scand J Forest Res 19:14–29