Hirata *et al. J Wood Sci (2020) 66:36*
https://doi.org/10.1186/s10086-020-01883-2
Journal of Wood Science

NOTE

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Color measurements according to three sections of wood

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Abstract

The purpose of this study was to measure each color of three sections of wood with instruments, and to examine whether there were differences between each color of three sections. The total number of tree species measured was 60, with the same number of conifers and broadleaf trees. A test piece, which was a cube with one side of 34 mm, was prepared for each tree species. End grain, edge grain, bark side and pith side of each test piece were flattened by a hand planer. Then, lightness L^* and hue/saturation (a^*, b^*) in the $L^*a^*b^*$ color space were measured with a spectrophotometer. The results showed that the end grain had a lower L^* compared to the other planes. The end grain was reddish and yellowish because it had a large a^* and small b^*. When chroma C^* and hue angle h in the L^*C^*h color space were calculated from a^* and b^*, the end grain had a small dullness with less vividness because C^* was smaller than the other planes. L^*, a^*, b^*, C^* and h on the other planes excluding the end grain were almost equal for each plane. Furthermore, it was found that the plane whose lightness L^* had the strongest correlation with the density of the test piece was the end grain. Therefore, the correlation diagrams between the density, average of annual ring width, and $L^*$of the end grain of each test piece were shown.

Keywords: Three sections of wood, Glossiness, Color measurement, $L^*a^*b^*$ color space, L^*C^*h color space, Density, Average of annual ring width

Introduction

There are many examples in measuring the color of wood with instruments for tree type, heartwood/sapwood, early wood/late wood, and knots [1–16]. However, in most of these measurement examples, it is unclear which side of the three cross-sections—end grain, edge grain, or flat grain—was measured. Even in clear cases, measurement is limited to the measurement of one plane.

For example, regarding the hardness of wood, it is stipulated in the Japanese Industrial Standard [17] that measurement be made for each of the three sections of wood. The relationship of surface hardness for three cross-sections has been clarified. In the average hardness of all tree species, the relationship of "End grain hardness > Flat grain hardness ≧ Edge grain hardness" [18] has been clarified. We have experienced those situations, when looking at the sawed boards and square timbers, in which the color of end grain is slightly darker than the other planes. However, in past measurement examples of wood color by instruments, it is unclear whether there are any differences between the three sections.

Therefore, in this study, we measured the color of each of the three sections of test pieces of almost the same size as the test piece [17] of which the hardness of wood was measured in the Japanese Industrial Standard [17]. The number of tree species measured was 60 in total, with the same number of conifers and broadleaf trees.

Materials and methods

Test pieces

To measure the color of wood in three sections, we prepared a test piece in the air-dried state of a cube with one side 34 mm with three clear sections as shown in Fig. 1. As shown in Table 1, a total of 60 tree species, with 30 species each of conifers and broadleaf trees, were

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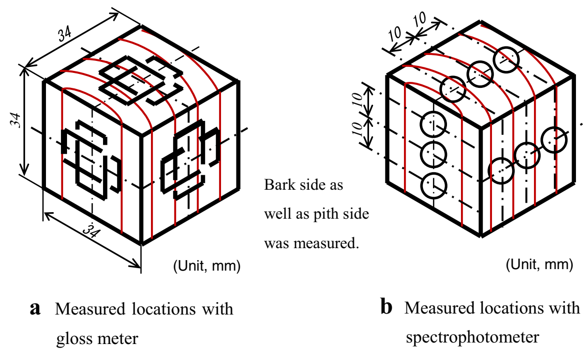

Fig. 1 Measured planes of test piece

prepared. Table 1 also shows the production area, density, and average of annual ring width—hereafter, it is abbreviated as "AARW"—of each test piece. Both production areas of conifers and broadleaf trees were halved from Japan and foreign countries. Some test pieces shown in Table 1 had clear early and late woods. There were four test pieces (Serial numbers: 3, 9, 30, and 31) whose entire surface of the bark side and the pith side were sapwood and heartwood, respectively.

Table 2 shows averages of density and AARW of conifers, broadleaf trees, or all trees in Table 1. As shown in Table 2, an unpaired *t* test was conducted to examine the significant differences in the averages of density/AARW between conifers and broadleaf trees. It can be said that both the density and AARW of broadleaf trees are higher than those of conifers with significant differences of 5%.

For each test piece, finally, using a changeable blade-type hand planer (Shimizu Seisakusho Kanna-mini J50) with a thickness of 0.04 mm, one end grain, one edge grain, bark side and pith side of flat grain were planed. That is, each measurement plane was flattened by the same method. On the bark and pith sides of the test piece, we cut with grain.

The changeable blade was replaced each time when approximately three test pieces were planed, and the sharpness was good and constant.

Glossiness and color measurement

As shown in Fig. 1a, glossiness was measured at the center of each measurement surface with a gloss meter (NIPPON DENSHOKU PG-IIM, measurement angle 60°, measurement size 10.0 × 20.0 mm). Tangential direction and radial direction of the annual rings were measured on the end grain, and directions parallel and perpendicular to the fiber were measured on the edge grain and flat grain.

After glossiness of each plane was measured, three locations in the center and 10 mm away from it were measured with a spectrophotometer (NIPPON DENSHOKU NF333, measuring diameter 8 mm, illumination light source), as shown in Fig. 1b. At present, the $L^*a^*b^*$ color space (JIS Z 8781-4 [19], ISO 11664-4 [20]) is the most popular color system [21] used in all fields to represent object colors. Therefore, in this study, we measured spectral reflectance, lightness L^*, and a^*, b^* indicating hue and saturation in the $L^*a^*b^*$ color space.

The average of three locations on each plane measured with a spectrophotometer was used as the value for each measured plane. Then, we intended to find the average color of each of the end grain, the edge grain, the bark side, and the pith side of the target test pieces.

Results and discussion

Glossiness

Figure 2 shows the averages of the glossiness of each measured plane. To support the measurement results for all trees, conifers and broadleaf trees are also shown. (Similarly, the following measurement results are shown for all trees, conifers and broadleaf trees.)

For all trees shown in Fig. 2, the value of glossiness is small on the end grain, and is almost equally large on edge grain, bark side and pith side. There is not a large difference in gloss level between the tangential direction and the radial direction on end grain, but glossiness is naturally large in the fiber direction and small in the direction perpendicular to the fiber on the other planes [22].

For conifers and broadleaf trees, it can be said that all trees are the same for both genera.

Spectral reflectance

Figure 3 shows the measured spectral reflectance as an average value. For all trees, the spectral reflectance of each plane is similar to the previously measured timber example [3, 23]. Spectral reflectance is small on the end grain and is almost equally large on the other planes.

For conifers and broadleaf trees, it can be said that all trees are the same for both genera.

Lightness L^* and hue/saturation (a^*, b^*) in $L^*a^*b^*$ color space

Table 3 shows the measured values of lightness L^*, and hue/saturation (a^*, b^*) of measured plane of each test piece in Table 1.

Lightness L^*

Figure 4 shows the averages of the measured lightness L^* of each plane in Table 3. For all trees, L^* of the end grain is smaller than that of the edge grain, the bark side and pith side. L^* of the edge grain, the bark side and the pith side are almost equal. For conifers and broadleaf trees, it can be said that all trees are the same for both genera.

Table 1 Tree name, density, and AARW of each test piece

Serial numbers		Tree name	Scientific name	Production area	Density (g/cm^3)	AARW (mm)	Correlation coefficient between density and AARW
1	Conifers	Akamatsu	*Pinus densiflora*	Japan	0.49	0.80	-0.0462
2		Kaya	*Torreya nucifera*	Japan	0.46	5.09	
3		Ichou*	*Ginkgo biloba*	Japan	0.48	3.05	
4		Sawara	*Chamaecyparis pisifera*	Japan	0.34	3.11	
5		Momi	*Abies firma*	Japan	0.41	4.41	
6		Togasawara	*Pseudotsuga japonica*	Japan	0.46	3.27	
7		Karamatsu	*Larix kaempferi*	Japan	0.50	2.10	
8		Hinoki	*Chamaecyparis obtusa*	Japan	0.51	1.08	
9		Sugi	*Cryptomeria japonica*	Japan	0.46	3.32	
10		Ezomatsu	*Picea jezoensis*	Japan	0.43	0.80	
11		Todomatsu	*Abies sachalinensis*	Japan	0.49	4.18	
12		Mizuki	*Cornus controversa*	Japan	0.61	3.43	
13		Yakusugi	*Cryptomeria japonica*	Japan	0.40	0.39	
14		Aomori hiba	*Thujopsis dolabrata*	Japan	0.50	0.71	
15		Himekomatsu	*Pinus parviflora*	Japan	0.39	2.72	
16		Noto hiba	*Thujopsis dolabrata*	Japan	0.45	3.27	
17		Agathis	*Agathis* sp.	Southeast Asia	0.47	1.81	
18		Western redceder	*Thuja plicata*	North America	0.35	1.21	
19		Douglas fir	*Pseudotsuga menziesii*	North America	0.57	0.50	
20		Taiwan cypress	*Chamaecyparis taiwanensis*	Taiwan	0.54	1.02	
21		Spruce	*Picea sitchensis*	North America	0.51	0.58	
22		Southern yellow pine	*Pinus* sp.	North America	0.60	4.65	
23		Western hemlock	*Tsuga heterophylla*	North America	0.47	0.42	
24		Merkus pine	*Pinus merkusii*	Laos	0.75	3.33	
25		Hard cypress	*Callitris columellaris*	Australia	0.69	0.56	
26		Yellow cedar	*Chamaecyparis nootkatensis*	North America	0.45	0.95	
27		Sequoia	*Sequoia sempervirens*	California	0.44	4.42	
28		Sosna	*Pinus sylvestris*	Europe	0.49	1.32	
29		Korean pine	*Pinus koraiensis*	Russia	0.44	2.22	
30		Fujian cypress	*Fokienia hodginsii*	Laos	0.54	0.62	
31	Broadleaf trees	Udaikanmba	*Betula maximowicziana*	Japan	0.78	0.75	− 0.657**
32		Katsura	*Cercidiphyllum japonicum*	Japan	0.46	3.82	
33		Kiri	*Paulownia tomentosa*	Japan	0.27	7.11	
34		Sen	*Kalopanax pictus*	Japan	0.65	1.63	
35		Buna	*Fagus crenata*	Japan	0.74	2.42	
36		Doronoki	*Populus maximowiczii*	Japan	0.42	9.66	
37		Shirakaba	*Betula platyphylla*	Japan	0.56	1.73	
38		Shirakashi	*Quercus myrsinaefolia*	Japan	0.92	2.98	
39		Yachidamo	*Fraxinus mandshurica*	Japan	0.64	1.70	
40		Kuri	*Castanea crenata*	Japan	0.60	2.29	
41		Hoonoki	*Magnolia obovate*	Japan	0.51	1.89	
42		Keyaki	*Zelkova serrata*	Japan	0.55	1.64	
43		Onigurumi	*Juglans mandshurica*	Japan	0.44	1.72	

Table 1 (continued)

Serial numbers	Tree name	Scientific name	Production area	Density (g/cm^3)	AARW (mm)	Correlation coefficient between density and AARW
44	Kusunoki	*Cinnamomum camphora*	Japan	0.52	4.30	
45	Popura	*Populus nigra*	Japan	0.41	4.68	
46	Balsa	*Ochroma lagopus*	Latin America	0.14	11.68	
47	White ash	*Fraxinus americana*	North America	0.77	1.84	
48	Teak	*Tectona grandis*	Myanmar	0.72	1.35	
49	Aspen	*Populus tremuloides*	North America	0.46	4.51	
50	Alder	*Alnus rubra*	North America	0.52	4.68	
51	White oak	*Quercus alba*	North America	0.73	1.30	
52	Jelutong	*Dyera costulata*	Southeast Asia	0.44	1.65	
53	Hard maple	*Acer saccharum*	North America	0.77	3.41	
54	Assamela	*Pericopsis elata*	Africa	0.71	3.83	
55	Soft maple	*Acer rubrum*	China	0.48	2.33	
56	Hackberry	*Celtis Occidentalis*	North America	0.64	2.40	
57	Surian	*Toona sureni*	Southeast Asia	0.35	5.24	
58	Coffee tree	*Coffea arabica*	North America	0.69	3.07	
59	Mersawa	*Anisoptera* sp.	Southeast Asia	0.60	2.67	
60	Black cherry	*Prunus serotina*	North America	0.75	3.48	
Correlation coefficient between density and AARW in all trees				− 0.376**		

AARW average of annual ring width

A comment on Tree name * "Ichou" is not a conifer, but is listed here for convenience

Significance test results of correlation coefficient ***p* < 0.01

Table 2 Average values of density and AARW in Table 1

	Density (g/cm^3)		AARW (mm)	
	Average	S.D.	Average	S.D.
Conifers	0.490 *	0.088	2.178 *	1.479
Broadleaf trees	0.575 *	0.168	3.391 *	2.410
All trees	0.532	0.141	2.784	2.088

Unpaired *t* test results of differences between conifers and broadleaf trees

* $p < 0.05$

Table 4 shows the results of paired mean difference tests between each measured L^* of each plane in Fig. 4. From Table 4, there are significant differences of 1% between the L^* of the end grain and that of the other planes for all trees, both conifers and broadleaf trees.

The reason for the low spectral reflectance and the low lightness L^* of end grain in Figs. 3 and 4 seems to be related to the low glossiness of the end grain in Fig. 2.

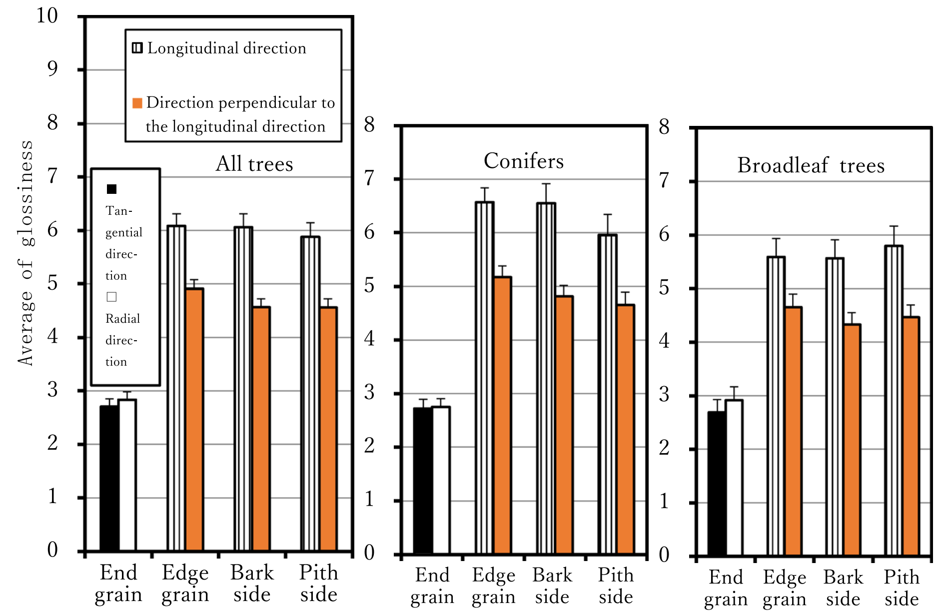

Fig. 2 Glossiness of measured planes in test pieces. Only standard errors for the plus side are shown at the end of each bar

Hue/saturation (a*, b*)

Figure 5 shows the relationship between a^* and b^* representing the hue and saturation of each measured plane in Table 3. For all trees, end grain has larger a^* and smaller b^* than those of other planes. This means that the end grain is more reddish and less yellowish than the other planes. This is true for both conifers and broadleaf trees.

For each of a^* and b^* shown in Fig. 5, the paired *t* tests of average differences between each plane were tested, and the results are shown in Table 5. For all trees, significant differences of 1% level are recognized between the end grain and each of the other planes for both a^* and b^*.

On a^* for conifers, significant differences are recognized between the end grain and both edge grain, bark side. But there is no significant difference between the end grain and the pith side. On b^* for conifers, significant differences of 1% level are recognized between the end grain and each of the other planes.

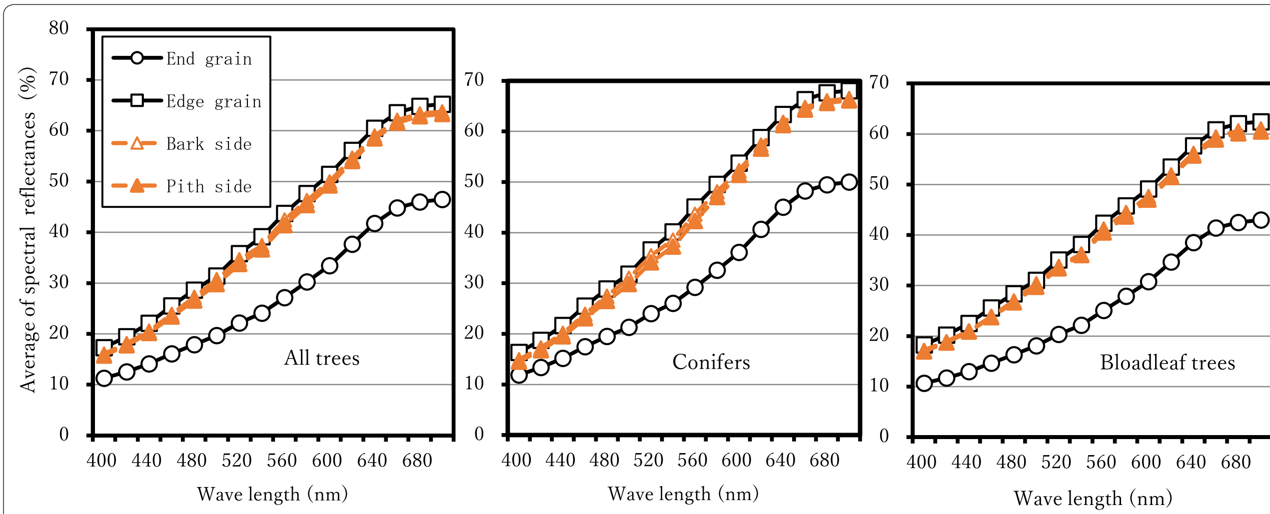

Fig. 3 Spectral references of measured planes in test pieces

Table 3 Measured lightness *L and hue/saturation (*a**, *b**) in *L** *a** *b** color space**

Serial numbers		End grain			Edge grain			Bark side			Pith side		
		*L**	*a**	*b**	*L**	*a**	*b**	*L**	*a**	*b**	*L**	*a**	*b**
1	Conifers	56.70	10.21	23.39	68.17	9.33	31.44	67.06	10.20	35.60	65.07	12.02	32.12
2		76.95	5.50	30.22	80.62	3.96	34.90	80.12	4.36	34.90	79.49	4.65	35.31
3		64.76	6.89	23.98	71.54	6.85	32.12	75.32	3.27	28.18	67.95	7.84	32.65
4		64.26	8.06	23.91	74.08	6.97	29.67	73.12	7.35	30.78	75.30	6.88	27.92
5		71.30	6.62	22.84	78.77	3.92	23.36	72.17	6.60	25.02	74.28	5.71	28.47
6		56.75	13.33	26.61	71.40	9.07	26.28	64.43	13.22	28.67	69.37	9.79	28.84
7		66.05	7.30	20.86	73.68	8.12	28.49	69.41	9.69	30.88	70.82	10.08	28.84
8		66.32	5.55	19.90	77.68	3.99	25.36	78.63	2.95	25.06	77.46	3.67	26.96
9		58.70	9.46	25.52	72.63	6.13	26.11	74.49	3.48	25.14	60.41	14.47	23.78
10		69.90	7.81	27.24	81.21	3.06	26.48	83.75	2.07	26.99	76.44	5.38	28.54
11		65.86	7.69	25.12	78.68	2.98	26.02	77.05	3.27	28.80	75.80	3.36	28.40
12		71.10	4.33	23.83	82.11	1.64	22.32	77.25	2.45	22.25	76.33	3.20	24.08
13		49.98	8.89	17.40	60.96	11.27	25.83	57.98	13.19	27.88	62.09	10.48	26.17
14		57.14	4.46	18.65	69.17	5.32	32.58	71.07	4.75	31.04	72.16	5.53	29.17
15		73.60	6.12	23.85	80.73	4.20	30.26	78.29	4.12	32.65	81.72	2.39	31.00
16		67.09	5.52	21.40	81.09	2.11	26.13	78.62	1.77	29.76	75.04	5.42	27.79
17		49.56	6.12	17.66	59.42	8.85	28.61	63.96	8.81	28.35	63.58	8.23	28.01
18		48.45	5.42	19.18	50.77	7.04	22.48	45.71	7.53	21.31	44.78	7.57	21.09
19		55.51	11.72	23.39	69.71	10.99	29.56	72.77	8.98	28.42	72.26	8.97	30.95
20		57.42	9.40	23.23	72.68	8.48	34.17	70.14	7.95	34.69	70.15	9.43	34.64
21		50.14	12.90	22.48	68.73	9.09	30.16	69.54	8.87	28.59	69.06	8.23	26.43
22		57.50	10.82	24.72	75.18	4.16	32.20	78.78	3.05	31.35	72.45	4.95	31.67
23		63.28	6.58	20.38	71.70	6.85	25.63	73.83	6.06	27.54	70.86	7.15	28.81
24		48.37	8.09	17.78	60.12	13.28	27.76	55.41	12.00	23.80	65.31	11.38	28.15
25		47.02	9.01	18.43	56.97	12.00	26.72	60.45	10.80	28.82	54.20	10.61	27.11
26		67.26	9.78	30.44	78.62	5.18	32.46	76.63	5.46	33.51	77.62	5.84	34.06
27		53.43	12.72	18.54	67.14	12.38	22.09	65.65	12.74	26.41	65.28	12.73	24.63
28		65.22	10.41	25.35	79.70	3.85	24.63	78.90	3.62	27.82	78.28	3.98	29.43
29		61.42	11.68	24.18	77.11	6.56	25.97	71.77	8.20	30.24	77.65	6.50	27.36
30		50.05	6.13	14.71	66.66	7.62	27.96	64.85	6.70	28.87	64.59	7.20	27.96
31	Broadleaf trees	47.77	11.88	22.44	62.02	9.37	28.33	71.47	5.38	26.23	66.71	9.80	27.72
32		55.13	9.24	23.54	61.91	9.29	25.47	59.11	11.24	26.69	62.76	8.73	25.39
33		64.24	3.90	17.12	74.62	2.30	20.71	70.56	3.88	19.80	74.09	3.05	20.50
34		49.16	8.27	19.48	68.05	5.35	20.51	65.97	6.55	22.84	68.80	5.46	21.20
35		58.42	11.90	26.07	70.99	7.98	25.55	68.14	9.42	27.39	68.19	9.50	27.35
36		78.39	3.72	20.49	89.72	-1.43	19.87	83.65	-0.52	23.35	86.67	-1.32	22.04
37		61.08	7.39	18.88	76.99	3.59	22.58	81.79	2.34	22.89	78.93	3.89	21.73
38		54.75	6.52	21.15	63.19	5.57	25.11	67.65	4.86	24.46	62.13	5.65	26.24
39		49.97	9.72	22.27	67.47	7.22	25.02	62.69	8.48	25.32	65.83	7.33	26.14
40		61.72	4.94	20.59	74.67	3.24	23.43	74.58	2.94	23.92	75.24	2.60	23.61
41		42.63	2.32	14.79	56.87	3.26	21.48	53.93	4.07	20.35	49.35	3.45	21.36
42		50.41	10.13	26.19	69.41	6.37	27.42	63.14	7.60	28.04	69.03	6.68	26.40
43		49.67	7.37	16.41	66.42	7.59	20.91	61.83	8.46	24.95	64.36	7.23	25.02
44		59.41	7.81	23.23	71.32	6.74	28.24	69.03	5.45	25.40	71.60	5.17	27.56
45		67.08	5.72	20.85	76.12	3.69	21.88	74.52	4.11	24.31	78.31	2.43	24.00
46		73.45	3.38	24.09	83.49	1.37	18.18	83.05	0.33	17.55	81.46	1.06	18.43
47		56.39	8.39	24.08	74.74	4.31	24.63	78.92	2.59	28.49	72.09	4.67	25.12
48		39.41	5.47	16.48	47.10	6.96	22.47	48.97	6.49	24.06	45.67	7.21	22.71

Table 3 (continued)

Serial numbers	End grain			Edge grain			Bark side			Pith side		
	*L**	*a**	*b**	*L**	*a**	*b**	*L**	*a**	*b**	*L**	*a**	*b**
49	72.34	7.55	31.02	84.24	-0.82	21.37	81.83	0.50	28.01	87.24	-1.21	23.91
50	55.77	8.44	20.28	65.27	8.12	26.39	67.63	8.12	24.57	65.74	8.10	23.87
51	50.67	7.12	20.21	62.89	6.50	26.01	65.40	6.34	24.44	61.79	6.92	25.26
52	62.25	9.40	26.80	70.54	7.28	31.45	72.09	5.37	30.71	72.59	5.25	32.20
53	59.67	11.00	26.09	76.34	4.92	23.30	77.72	4.99	25.60	76.62	5.57	24.64
54	42.45	6.37	16.21	58.77	8.99	27.91	53.85	9.18	26.22	53.22	8.30	23.28
55	55.66	10.11	19.92	73.51	8.37	22.48	74.72	5.69	17.38	70.46	9.32	25.53
56	62.50	8.88	27.27	79.75	3.50	25.10	75.27	3.47	27.73	73.70	3.95	26.37
57	40.30	12.56	20.94	52.97	15.06	25.15	49.40	15.11	27.65	47.54	15.38	26.53
58	49.15	13.76	22.90	77.89	6.53	23.93	74.32	8.40	27.08	69.35	8.36	29.68
59	63.22	7.23	25.81	72.34	6.52	31.37	72.20	6.53	31.63	65.64	8.21	28.19
60	47.62	11.85	19.46	60.86	13.86	28.53	56.17	14.81	29.72	59.55	14.31	27.09

The serial numbers are the same as in Table 1

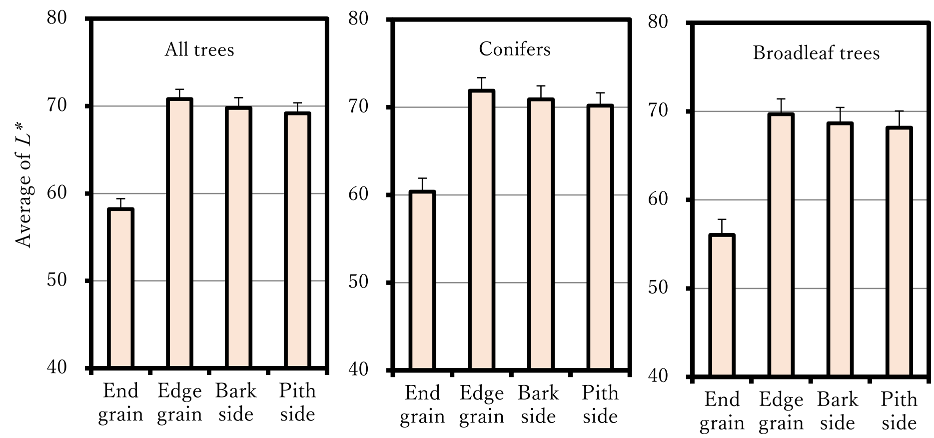

Fig. 4 Lightness L^* of measured planes of test pieces. Only standard errors for the plus side are shown at the end of each bar

For broadleaf trees, there are significant differences of 1% between the end grain and each of the other planes for both a^* and b^*.

Calculation of chroma C^* and hue angle h in L^*C^*h color space

From the measured values a^* and b^* in $L^*a^*b^*$ color space of each test piece shown in Table 3, the chroma C^* and the hue angle h in L^*C^*h color space were calculated by the following two equations [7, 16, 21].

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{1}$$

$$h = \tan^{-1}\left(\frac{a^*}{b^*}\right)(^\circ) \tag{2}$$

Figure 6 shows the averages of the calculated C^* and h. Table 6 shows the results of the paired t test of the differences between the average values of each measurement plane for each C^* and h shown in Fig. 6.

According to Fig. 6 and Table 6, for all trees, both C^* and h are the smallest on the end grain, and are almost the same values on the other planes. For both C^* and h, there are significant differences between the end grain and each of the other planes. Therefore, it can be said that the end grain is a dull color with less vividness and a strong reddish color compared to other planes.

Focusing on both conifers and broadleaf trees, significant differences are recognized in C^* and h between

Table 4 Paired *t* test results of differences between each measuring plane average on *L in Fig. 4**

	Edge grain	Bark side	Pith side
All trees			
End grain	**	**	**
Edge grain	–	*	**
Bark side	–	–	*n.s.*
Conifers			
End grain	**	**	**
Edge grain	–	*n.s.*	*
Bark side	–	–	*n.s.*
Broadleaf trees			
End grain	**	**	**
Edge grain	–	*n.s.*	*
Bark side	–	–	*n.s.*

n.s. not significant

Significance level * $p < 0.05$, ** $p < 0.01$

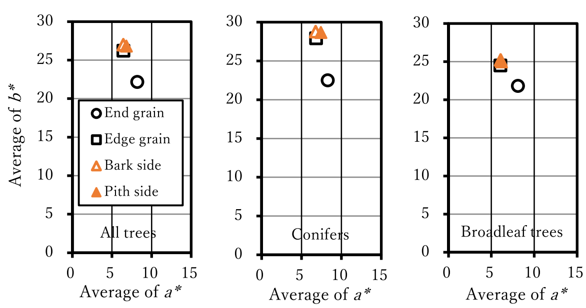

Fig. 5 Correlation diagrams between *a** and *b**

Table 5 Paired *t* test results of differences between each measuring plane on *a and *b** in Fig. 5**

	Edge grain	Bark side	Pith side
All trees			
On *a**			
End grain	**	**	**
Edge grain	–	*n.s.*	*n.s.*
Bark side	–	–	*n.s.*
On *b**			
End grain	**	**	**
Edge grain	–	*	*
Bark side	–	–	*n.s.*
Conifers			
On *a**			
End grain	*	*	*n.s.*
Edge grain	–	*n.s.*	*n.s.*
Bark side	–	–	*n.s.*
On *b**			
End grain	**	**	**
Edge grain	–	*	*n.s.*
Bark side	–	–	*n.s.*
Broadleaf trees			
On *a**			
End grain	**	**	**
Edge grain	–	*n.s.*	*n.s.*
Bark side	–	–	*n.s.*
On *b**			
End grain	**	**	**
Edge grain	–	*	*n.s.*
Bark side	–	–	*n.s.*

n.s. not significant

Significance level * $p < 0.05$, ** $p < 0.01$

the end grain and the other planes. Then, in L^*C^*h color space, all that was mentioned for all trees can be said for both conifers and broadleaf trees.

Relationships between density of test piece and lightness L^*, hue/saturation (a^*, b^*), chroma C^*, and hue angle *h* of each plane

One text on wood colors states that "the higher the density, the lower the lightness, and the lower the density, the higher the lightness" [8]. This text does not describe which of the three planes it is referring to. In this study, we investigated the relationship between density and lightness L^* of each measured plane of each test piece. In addition, the relationships between density and hue/saturation (a^*, b^*), chroma C^*, and hue angle h were also examined.

Figure 7 shows the correlation coefficients between test piece density and L^*, a^*, b^*, C^*, and h of each measurement plane. For all trees, the strongest correlation with density is recognized with L^* of the end grain, indicating a significance level of 1%.

For broadleaf trees, there was the strongest correlation between density and L^* of the end grain with a significance level of 5%. For conifers, there was also the strongest but not significant.

From Fig. 7, the density seems to have the strongest correlation with the lightness L^*, but it is the lightness L^* of the end grain.

Since the relationships between density and L^* of the end grain were found to be strong, Fig. 8 shows the

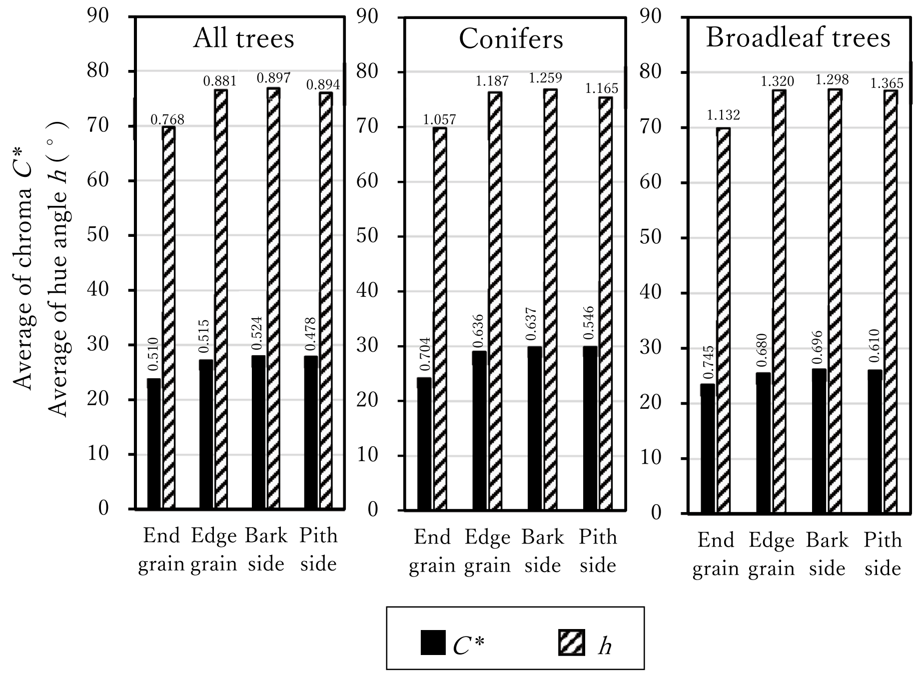

Fig. 6 Calculated Chroma C^* and Hue angle h in L^* C^* h color space. Standard error values are shown near the tip of each bar

correlation diagrams between the density of each test piece and L^* of the end grain. Figure 8 also shows the regression equations that estimate the L^* of the end grain by density for all trees and broadleaf trees for which the correlation coefficients between the density and the L^* of the end grain are significant in Fig. 7.

Relationships between AARW of each test piece and lightness L^*, hue/saturation (a^*, b^*), chroma C^*, and hue angle h of each plane

In Figs. 7 and 8, there was no significant correlation between density and lightness L^* of the end grain for conifers. Therefore, we investigated into the relationship between AARW instead of density and L^* of each measured plane of each test piece. In addition, the relationships between AARW and hue/saturation (a^*, b^*), chroma C^*, and hue angle h were also examined.

Figure 9 shows the correlations between test pieces AARW and L^*, a^*, b^*, C^*, and h of each measured plane. For all trees, conifers and broadleaf trees, the strongest correlations with AARW are recognized with L^* of the end grain, indicating significance levels. Then, Fig. 10 shows the correlation diagrams between the AARW and L^* of the end grain of each test piece. Figure 10 also shows the regression equations that estimate the L^* of the end grain by AARW.

From Figs. 7, 8, 9 and 10, $L^*$of end grain seems to be affected not only by density but also by AARW.

In Figs. 8 and 10, there were some test pieces that deviated considerably from the equations for estimating L^* by density or AARW. We could find recent papers [24–26] of the differences in reflectance depending on the fiber direction of wood. So the elucidation of the factor of lightness L^* value of wood surface will be for further study.

Conclusion

To examine whether there are differences in color depending on the three sections of wood, 60 test pieces of a cube with one side of 34 mm were prepared for 30 conifers and 30 broadleaf trees. After the end grain, edge gain, bark side and pith side of each test piece were flattened by a same method of hand plane; lightness L^* and hue/saturation (a^*, b^*) in the L^* a^* b^* color space were measured with a spectrophotometer. Each plane was compared to each other.

When the target of consideration was all trees used in this experiment, the following results were obtained.

Table 6 Paired *t* test results of differences between each measuring plane on *C, *h* in Fig. 6**

	Edge grain	Bark side	Pith side
All trees			
On *C**			
End grain	**	**	**
Edge grain	–	*	**
Bark side	–	–	*n.s.*
On *h*			
End grain	**	**	**
Edge grain	–	*n.s.*	*n.s.*
Bark side	–	–	*n.s.*
Conifers			
On *C**			
End grain	**	**	**
Edge grain	–	*n.s.*	*
Bark side	–	–	*n.s.*
On *h*			
End grain	**	**	**
Edge grain	–	*n.s.*	*n.s.*
Bark side	–	–	*n.s.*
Broadleaf trees			
On *C**			
End grain	*	**	**
Edge grain	–	*n.s.*	*n.s.*
Bark side	–	–	*n.s.*
On *h*			
End grain	**	**	**
Edge grain	–	*n.s.*	*n.s.*
Bark side	–	–	*n.s.*

n.s. not significant

Significance level $*p < 0.05$, $**p < 0.01$

(1) The end grain had a lower lightness L^* than those of the other planes. In addition, the end grain was reddish and yellowish because it had a larger a^* and a smaller b^* compared to the other planes.
(2) From a^* and b^* measured, chroma C^* and hue angle h in the L^* C^* h color space were calculated. As a result, it could be seen that the end grain was dull with less vividness because C^* was smaller than the other planes. In addition, since h on the end grain was small, it was confirmed that redness was strong on it, as was also found in L^* a^* b^* color space.
(3) Lightness L^*, hue/saturation (a^*, b^*), chroma C^*, and hue angle h on the other planes excluding the end grain were almost equal for each plane.
(4) The plane whose lightness L^* had the strongest correlation with the density of the test piece was the end grain.
(5) The correlation diagrams between the density, average of annual ring width, and $L^*$of the end grain of each test piece were shown.

And, when the targets of consideration were focused on conifers and broadleaf trees, most of the above be similarly applied for both tree genera.

From the above, it has been clarified that the color of the end grain has characteristics contrasting with other planes. To elucidate the cause, it may be necessary to examine the differences in color depending on the angle at which the cell is cut, but this is the future task.

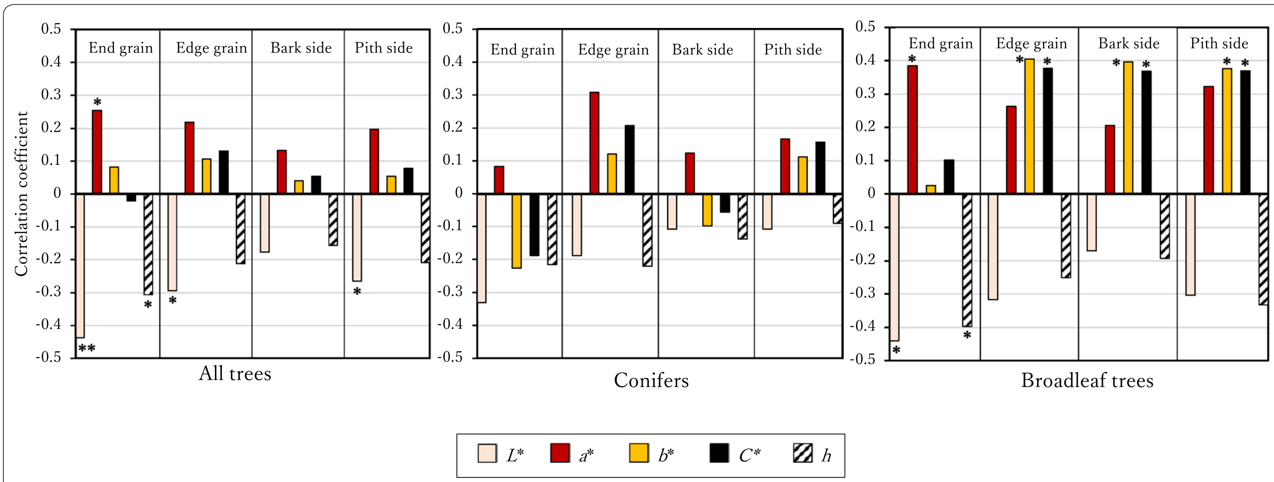

Fig. 7 Correlations between density and L^*, a^*, b^*, C^*, h of each measured plane. Significance level $*p < 0.05$, $**p < 0.01$

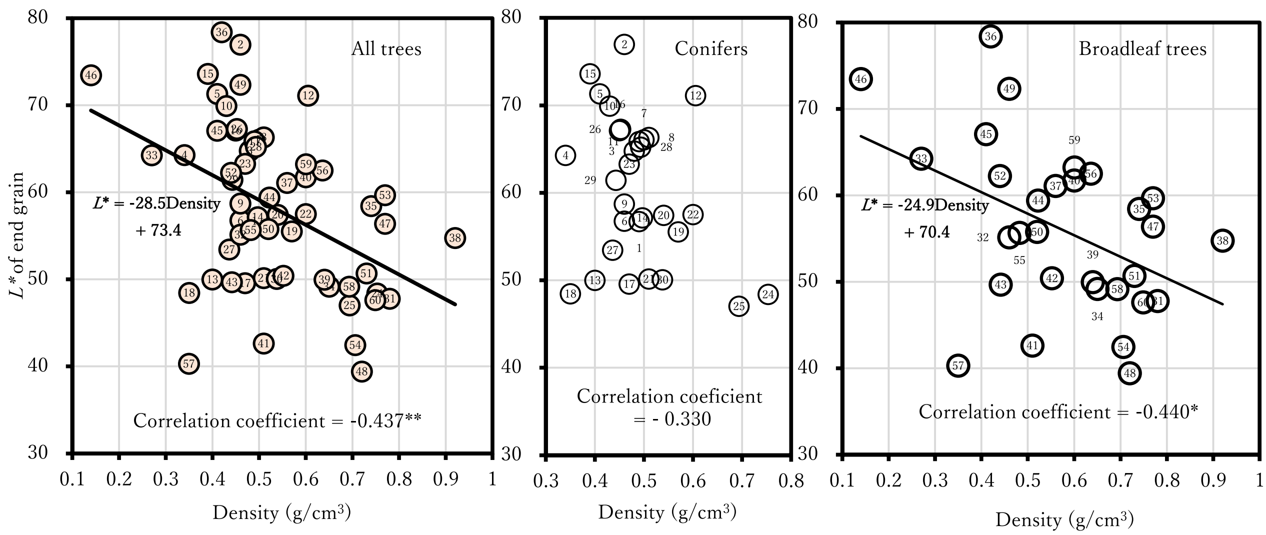

Fig. 8 Correlation diagrams between density and L^* of end grain of each test piece. Each test piece number is shown as in Tables 1 and 3

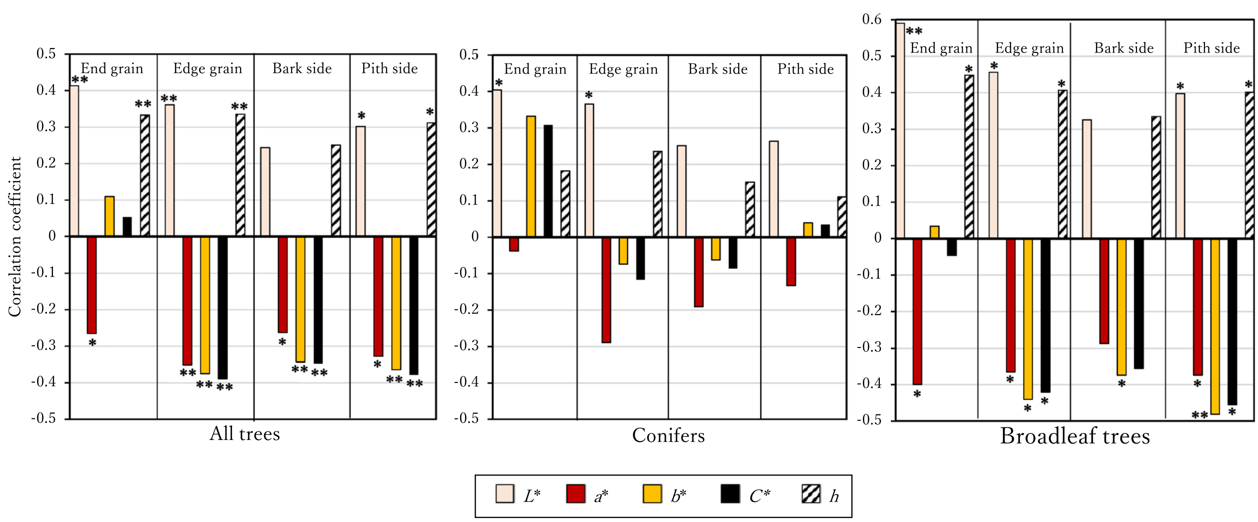

Fig. 9 Correlations between AARW and L^*, a^*, b^*, C^*, h of each measured plane. Significance level $^*p < 0.05$, $^{**}p < 0.01$

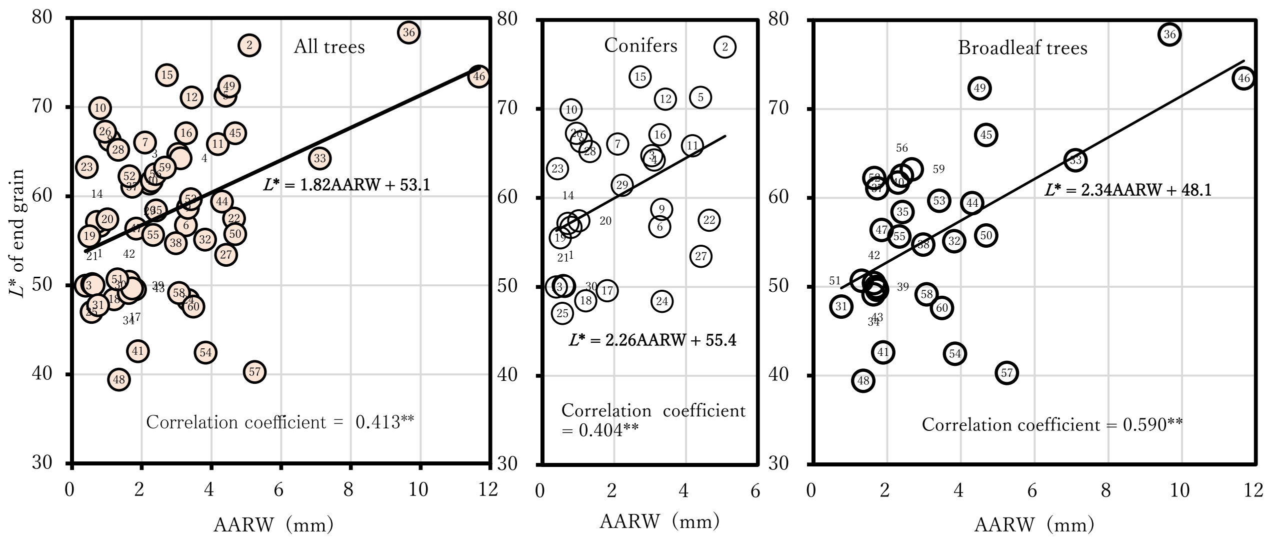

Fig. 10 Correlation diagrams between AARW and L^* of end grain of each test piece. Each test piece number is shown as in Tables 1 and 3. Significance test results of correlation coefficient $^{**}p < 0.01$

Abbreviation

AARW: Average of annual ring width.

Acknowledgements

Not applicable.

Part of this article was presented at the 67th Annual Meeting of Japan Wood Research Society in Fukuoka, March 2017.

Authors' contributions

SHi and SHa designed this study and prepared test pieces. Both measured the glossiness and color of the test pieces and analyzed the measurement results. MO considered the analysis results. SHi then wrote the manuscript. All authors read and approved the final manuscript.

Funding

No specific grant was received.

Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 9 January 2020 Accepted: 1 May 2020
Published online: 18 May 2020

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