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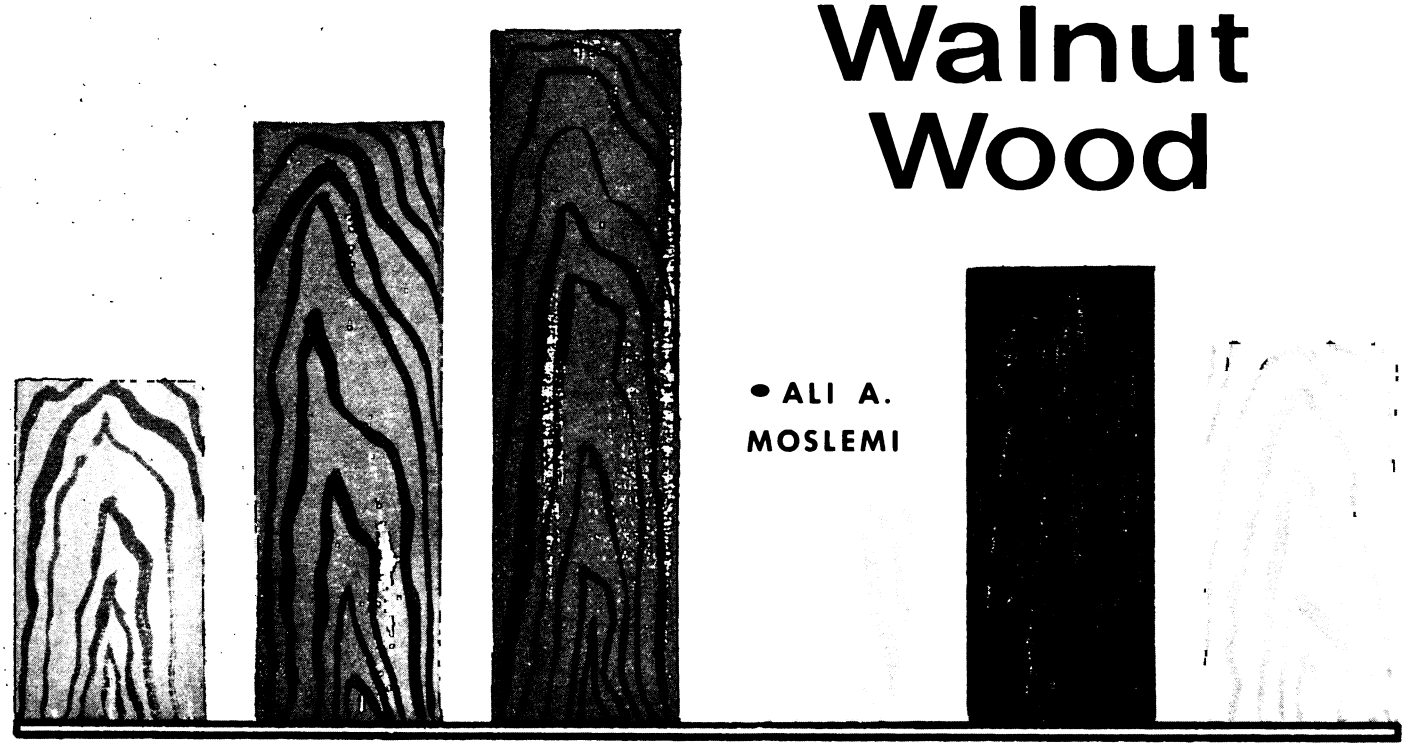
Quantitative Color Measurement for Black Walnut Wood



• ALI A. MOSLEMI

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NOTE: The author is Assistant Professor, Department of Forestry, School of Agriculture, Southern Illinois University, Carbondale, Illinois. Financial support by the Division of Timber Management of the North Central Forest Experiment Station, Forest Service, U.S. Department of Agriculture, made this study possible. The author is grateful to Mr. F. Bryan Clark for obtaining veneer specimens, Dr. Willard H. Carmean for his informal advice on the project, and Mr. Robert W. Merz for his comprehensive review and criticism of the manuscript.

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Quantitative Color Measurement for Black Walnut Wood

by
Ali A. Moslemi

Black walnut (*Juglans nigra* L.) wood is well known for its beautiful, warm color. The current demand for black walnut is strong both in the United States and abroad. Top grade logs are much sought after, making individual trees of good quality worth several thousand dollars. The great demand coupled with a shrinking supply has stimulated research to find out how to produce high-quality logs in a shorter period of time. To do this, genetic, site, and cultural factors affecting the growth of walnut must be scrutinized and their influence upon the quality of wood determined.

One factor that affects the quality of walnut wood is its color. To specify the influence of various factors on color, a quantitative means of color measurement is essential. But customary visual color evaluations are inconsistent and inaccurate. So there is no reliable means of comparing walnut wood color among trees grown on different sites, nor of evaluating the effect of fertilization on color of black walnut. Neither is there a quantitative means of measuring color changes that might result from finishing, machining, weathering, and steaming walnut which would be useful to the walnut-using industry.

Several walnut-using firms that were queried on the subject agreed that color influences quality of veneer and lumber; however, no consistent answers were received concerning what was needed.

Apparently, then, there is a need for a walnut wood color evaluating technique for both research purposes and industry. Therefore, a study was made to determine whether existing quantitative color measurement methods could be utilized. The initial study, reported here, showed that walnut wood color can be evaluated by the international CIE (Commission Internationale de Eclairage) method. It was further shown that these walnut wood color data can be expressed in terms of the Munsell color notation. The study also pointed out that the natural hue differences in black walnut wood do not vary greatly but luminosity does. It was, therefore, concluded that luminosity can be used to discriminate color in walnut wood.

The Study

A review of pertinent literature and of color evaluating methods and equipment revealed that information on wood colorimetry in general is limited (Moon and Spencer 1945, Nakamura and Tackachio 1960, Resch and Dost 1965, Sandermann and Schlumbom 1962, Shibamoto *et al.* 1960) and that a nonvisual color evaluating technique would have to be used with walnut (Gray 1961, Loos and Coppock 1964). Twenty randomly selected 5- by 5-inch walnut veneer specimens were sent to a commercial laboratory for spectrophotometric analysis. Reflectance data were obtained for each veneer sample over the visual wavelength spectrum ranging from 400 to 700 millimicrons (400-700 mu).

In some types of color analyses, one may be interested only in color differences between a standard and one or more samples. So one of a second set of four 5- by 5-inch walnut veneer samples was arbitrarily chosen as a standard with which the color of three other veneer samples was compared. These comparisons were made at a second commercial laboratory with a Hunterlab color and color-difference meter.

Methods Used in the Study

Color Analysis

One of the systems used for evaluating color is the CIE system, sometimes referred to as the ICI (International Commission on Illumination) system. To use this system, spectrophotometric color data must be transformed to so-called tristimulus values.[1] These values represent the amounts of the three primary lights or primary colors required in combination to match the color being analyzed. Tristimulus values are usually symbolized by letters X, Y, and Z.

To obtain X, Y, and Z, assume H is the amount of light from the visible spectrum (400-700 mu)

[1] *Because the specialized terminology used in this paper may not be familiar to many of the readers, a glossary of technical terms appears on inside back cover.*

striking a unit area of the object; then within the small wavelength interval $\Delta\lambda$ the amount of light striking the object per unit area will be equal to $H\Delta\lambda$. The reflected light entering the observer's eye from an opaque object (such as wood) would be $RH\Delta\lambda$ in which R represents the relative spectral reflectance of the material. The tristimulus values of the reflected light entering the eye are computed by $RH\bar{x}\Delta\lambda$ for all wavelengths in which $\bar{x}$ (or $\bar{y}$ or $\bar{z}$) is a weighting function. By adding these computed values for all of the visual spectrum, the tristimulus values are obtained. These can be written as follows:

$$X = C \sum_{\lambda=400}^{700} RH\bar{x}\Delta\lambda \qquad (1)$$

$$Y = C \sum_{\lambda=400}^{700} RH\bar{y}\Delta\lambda \qquad (2)$$

$$Z = C \sum_{\lambda=400}^{700} RH\bar{z}\Delta\lambda \qquad (3)$$

in which

$$C = 100 / \sum_{\lambda=400}^{700} H\bar{y}\Delta\lambda \qquad (4)$$

This method of computing tristimulus values is called the weighted-ordinate method because each ordinate of the reflectance curve ($RH\Delta\lambda$) is weighted by $\bar{x}$, $\bar{y}$, and $\bar{z}$ for a given wavelength (fig. 1).

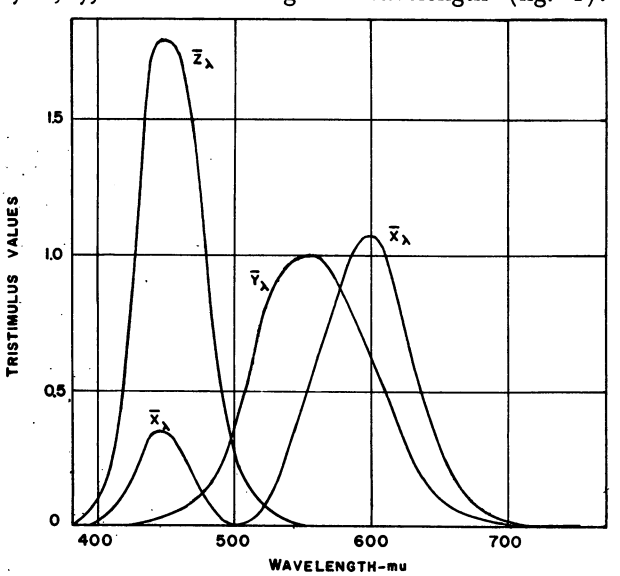


Figure 1.—The weighting functions for the standard observer over the visible wavelengths as recommended by the International Commission on Illumination in 1931. Note that $\bar{x}$ has two maxima.

Published tables (Judd and Wyszecki 1963) of $\bar{x}$, $\bar{y}$, and $\bar{z}$ values are available for various standard illumination sources.

When the values of X, Y, and Z are obtained, they can be converted to specify the x and y chromaticity coordinates which locate the wood hue being analyzed on the CIE color chart:

$$x = \frac{X}{X+Y+Z} \qquad (5)$$

$$y = \frac{Y}{X+Y+Z} \qquad (6)$$

With the values of these coordinates, the color can be plotted and specified.

Color Difference Analysis

The color difference analysis requires that both chromaticness and luminosity be combined for a given sample. This is advantageous for analyzing walnut wood color because, as noted later in this report, walnut does not vary much in chromaticness but exhibits significant variations in luminosity. Color differences among samples can be calculated from the spectrophotometric data. Scofield (1943) specifies the following equation for calculating color differences:

$$\Delta E = \sqrt{(L_s - L_g)^2 + (a_s - a_g)^2 + (b_s - b_g)^2}^{1/2} \qquad (7)$$

in which

$$L_s = 10Y_s^{1/2} \qquad (8)$$

$$a_s = 7L_s\alpha_s \qquad (9)$$

$$b_s = 7L_s\beta_s \qquad (10)$$

are parameters for a standard color sample and

$$L_g = 10Y_g^{1/2} \qquad (11)$$

$$a_g = 7L_g\alpha_g \qquad (12)$$

$$b_g = 7L_g\beta_g \qquad (13)$$

are corresponding parameters for a sample to be compared with the standard. In the above equations Y is a tristimulus value given by Equation 2; α and β are computed as follows:

$$\alpha = \frac{2.4266x - 1.3631y - 0.3214}{x + 2.2633y + 1.1054}$$

and

$$\beta = \frac{0.5710x + 1.2447y - 0.5708}{x + 2.2633y + 1.1054}$$

In these equations, x and y are the chromaticity coordinates as given by Equations 5 and 6. The constants used above are given by Hunter (1941).

Conversion to Munsell System

The spectrophotometric color data can be converted to Munsell color notation in terms of hue, value, and chroma. In the Munsell system (Anon. n.d.), the value parameter specifies the degree of brightness (or darkness) of a color as compared to a neutral gray. Theoretically, value can range from pure black (designated as 0/) to pure white (designated as 10/). Therefore, light colors have a value greater than 5/ while dark colors have values less than 5/. The walnut veneer samples, as noted later in this report, had values ranging approximately from 4/ to 6/.

The chroma parameter specifies the strength of a particular hue. In other words, a chroma value shows how far a given hue departs from neutral gray with the value remaining constant. Numbers assigned to various chromas range from zero to 14 or more (usually designated as /0, /14, etc.). The complete notation for a given color in the Munsell system is written in the following order and manner:

Hue, Value/Chroma.

Thus, a color with a Munsell notation of 2.5YR 6/10 denotes the exact location of a yellowish-red color in the three-dimensional Munsell color space (fig. 2).

Tables and charts for color data conversion from CIE to Munsell, or vice versa, have been prepared (Glenn and Killian 1940, Kelly *et al.* 1943, Kramer 1950, Nickerson 1946, Richmond and Harrison 1959). Using these sources, walnut wood color can be expressed in either CIE or Munsell notation.

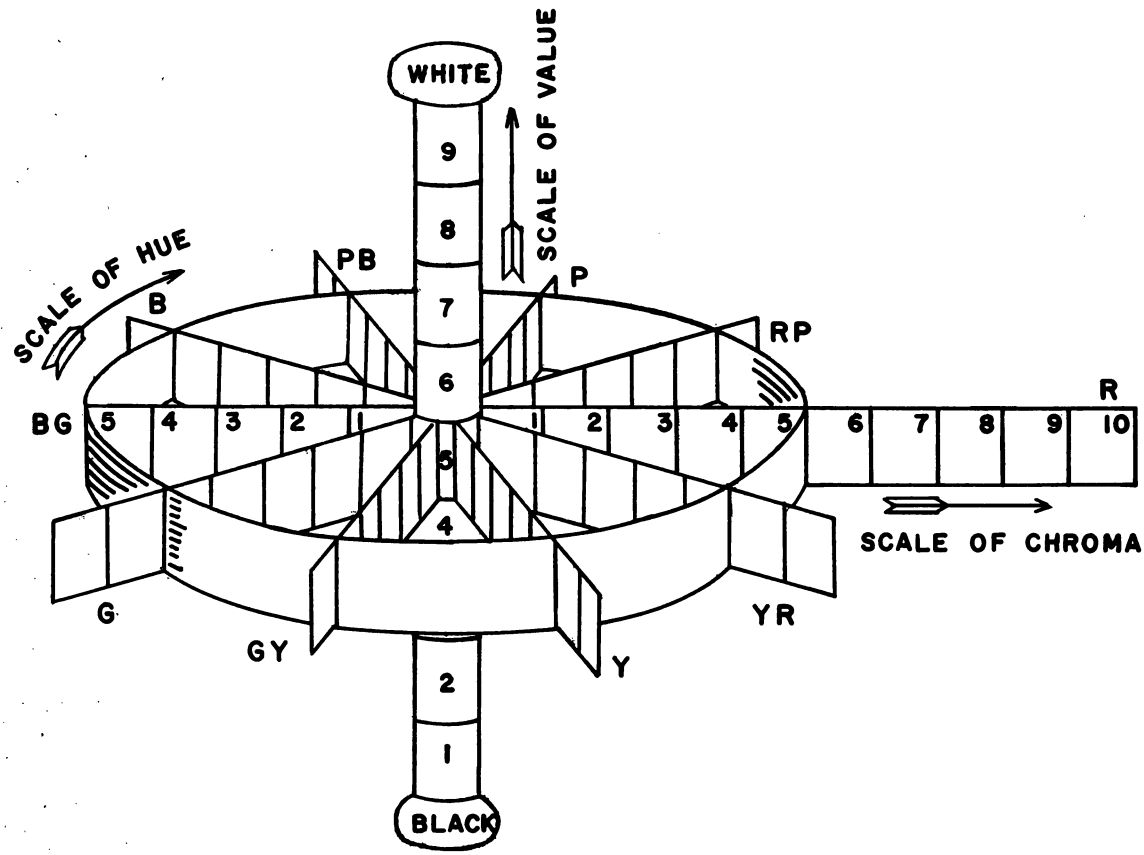


Figure 2.—The Munsell color space showing the three dimensional nature of color specification. The walnut veneer samples ranged in value from approximately 4/ to 6/ on the central axis of this figure. All values in the vertical axis can be expanded in terms of hue and chroma as illustrated for the value of 5/ in the figure.

Results and Discussion

Walnut wood best reflects longer wavelengths in the visible spectrum (orange, red). Other studies (Loos and Coppock 1964, Moon and Spencer 1948) conducted on reflectance characteristics of walnut demonstrated similar results.

The CIE Analysis

Using the data shown in figure 3 and utilizing Equations 1 through 4, the tristimulus values for 20 walnut veneer samples were calculated. The reflectance values of the samples were obtained from the spectrophotograms (fig. 3) and $H\bar{x}\lambda$, $H\bar{y}\lambda$, and $H\bar{z}\lambda$ were obtained from published tables from several sources (Judd 1952, Judd and Wyszecki 1963, Wright 1958). An illustration of how the calculations were made to obtain the tristimulus values (X, Y, Z) for one specimen when the light source is equivalent to average daylight (standard source C) is outlined in table 1. The chromaticity coordinates (x, y) for the walnut veneer specimens were calculated (Equations 5 and 6) as shown at the bottom of table 1. These calculations can be made automatically by some instruments equipped with computers (Loos and Coppock 1964).

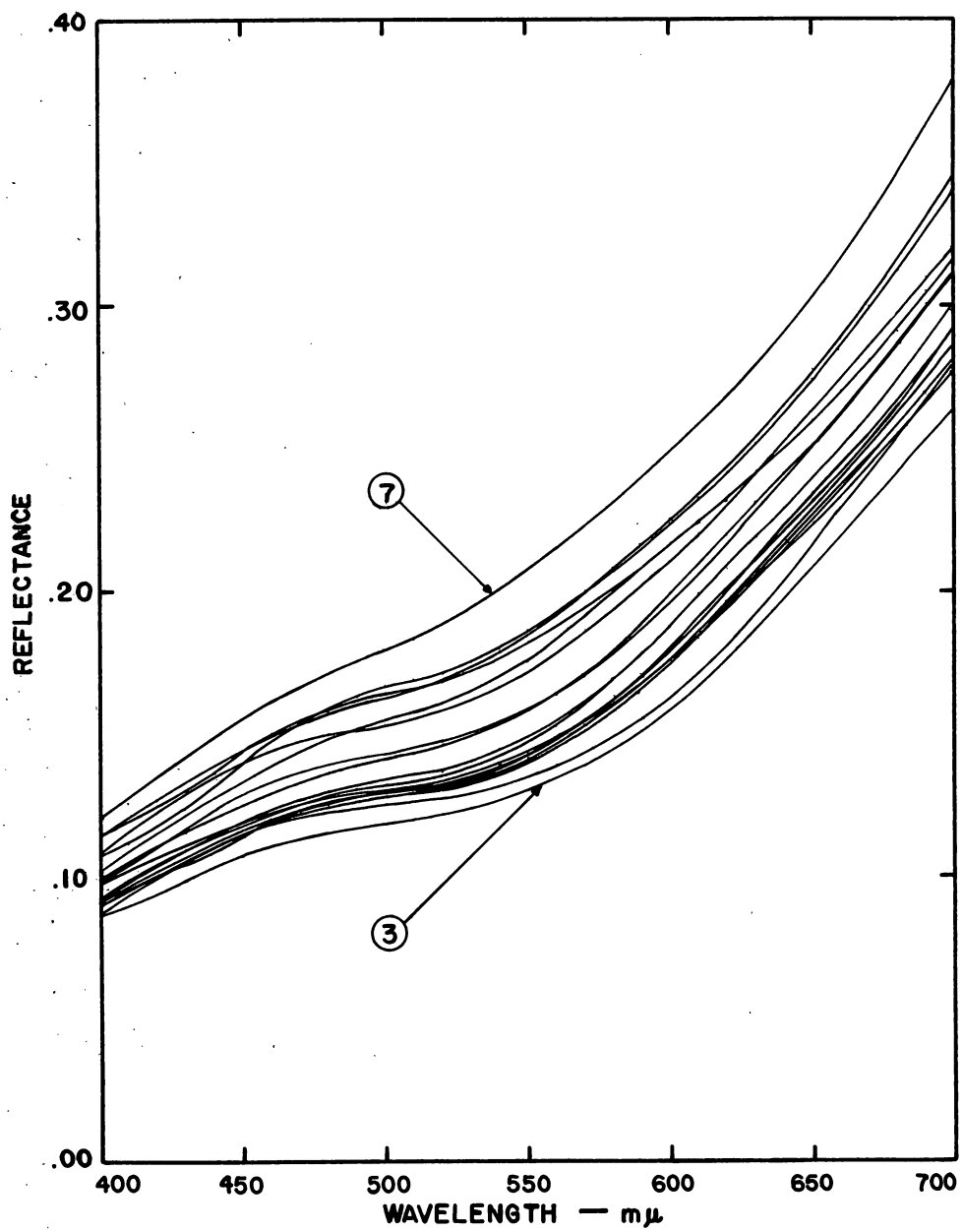


Figure 3.—The reflectance data obtained from 20 walnut veneer specimens. The specimen numbers with the highest and lowest reflectance characteristics are indicated. Note that walnut wood generally best reflects lights of long wavelengths.

Table 1.—*Sample calculation for determining the tristimulus values and chromaticity coordinates for walnut veneer specimen No. 1 using illumination source C*

Wavelength mu	R	$\bar{x}H\lambda$	$R\bar{x}H\lambda$	$\bar{y}H\lambda$	$R\bar{y}H\lambda$	$\bar{z}H\lambda$	$R\bar{z}H\lambda$
400	.088	.085	.075	.002	.000	.404	.036
410	.096	.329	.032	.009	.001	1.570	.151
420	.099	1.238	.123	.037	.004	5.949	.589
430	.105	2.997	.315	.122	.013	14.628	1.536
440	.110	3.975	.437	.262	.029	19.938	2.193
450	.116	3.915	.454	.443	.051	20.638	2.394
460	.119	3.363	.400	.694	.083	19.299	2.297
470	.121	2.272	.275	1.058	.128	14.972	1.812
480	.123	1.112	.137	1.618	.199	9.461	1.164
490	.124	.362	.045	2.358	.292	5.274	.654
500	.125	.052	.007	3.401	.425	2.864	.358
510	.126	.089	.011	4.833	.609	1.520	.192
520	.127	.576	.073	6.462	.821	.712	.090
530	.128	1.523	.195	7.934	1.016	.388	.050
540	.131	2.785	.365	9.149	1.199	.195	.026
550	.133	4.282	.570	9.832	1.308	.086	.011
560	.139	5.880	.817	9.841	1.368	.039	.005
570	.142	7.322	.104	9.147	1.299	.020	.003
580	.149	8.417	1.254	7.992	1.191	.016	.002
590	.156	8.984	1.402	6.627	1.034	.010	.002
600	.162	8.949	1.450	5.316	.861	.007	.001
610	.172	8.325	1.432	4.176	.718	.002	.000
620	.180	7.070	1.273	3.153	.568	.002	.000
630	.192	5.309	1.019	2.190	.420	.000	.000
640	.206	4.693	.761	1.443	.297	.000	.000
650	.220	2.349	.517	.886	.195	.000	.000
660	.230	1.361	.313	.504	.116	.000	.000
670	.242	.708	.171	.259	.063	.000	.000
680	.255	.369	.094	.134	.034	.000	.000
690	.269	.171	.046	.062	.017	.000	.000
700	.278	.082	.023	.029	.008	.000	.000
			X=14.190		Y=14.367		Z=13.566

$$x = \frac{14.190}{14.190 + 14.367 + 13.566} = 0.337$$

$$y = \frac{14.367}{14.190 + 14.367 + 13.566} = 0.341$$

$$z = \frac{13.566}{14.190 + 14.367 + 13.566} = 0.322$$

The tristimulus values do, of course, depend on the source of illumination used. In the CIE system, three standard illuminant sources designated as A, B, and C are used. Source A is representative of a gas-filled incandescent lamp that operates at a temperature of 2,848 degrees Kelvin (2,575°C). Source B is equivalent to noon sunlight at about 4,800°K, and source C simulates average daylight at about 6,700°K. (fig. 4). The same color will look somewhat different under these three standard sources (fig. 5). Source C is often used in colorimetric studies. Sources A and B are also used in colorimetry because under some circumstances source C may not be the best source to use. For example, source A, representing incandescent lamps, shows how walnut color appears under artificial lighting such as at night in a living room. The same applies to source B if one is interested in finding out how walnut color appears under noon sunlight. If a researcher wants to compare the color of a given piece of wood in average daylight and at night under lights, then he needs data obtained by using sources A and C.

The tristimulus values and chromaticity coordinates for the 20 walnut veneer specimens as examined

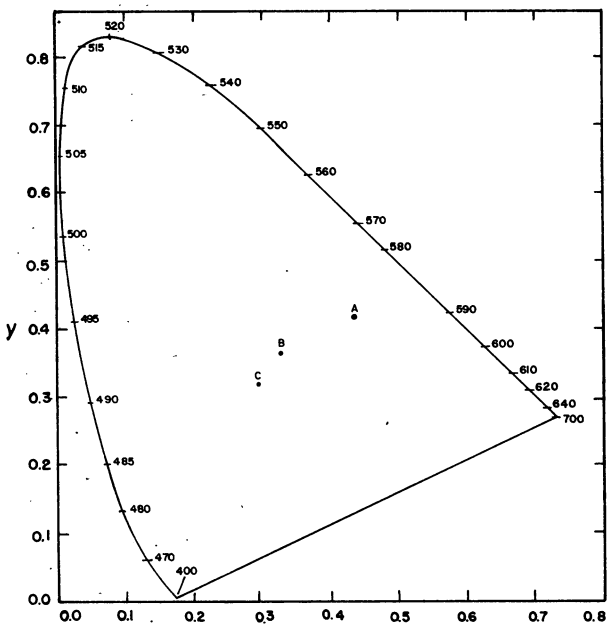


Figure. 4—The CIE color chart showing the location of the standard illumination sources A, B, and C with respect to their accepted hues. Figures on the loop represent wavelength in millimicrons.

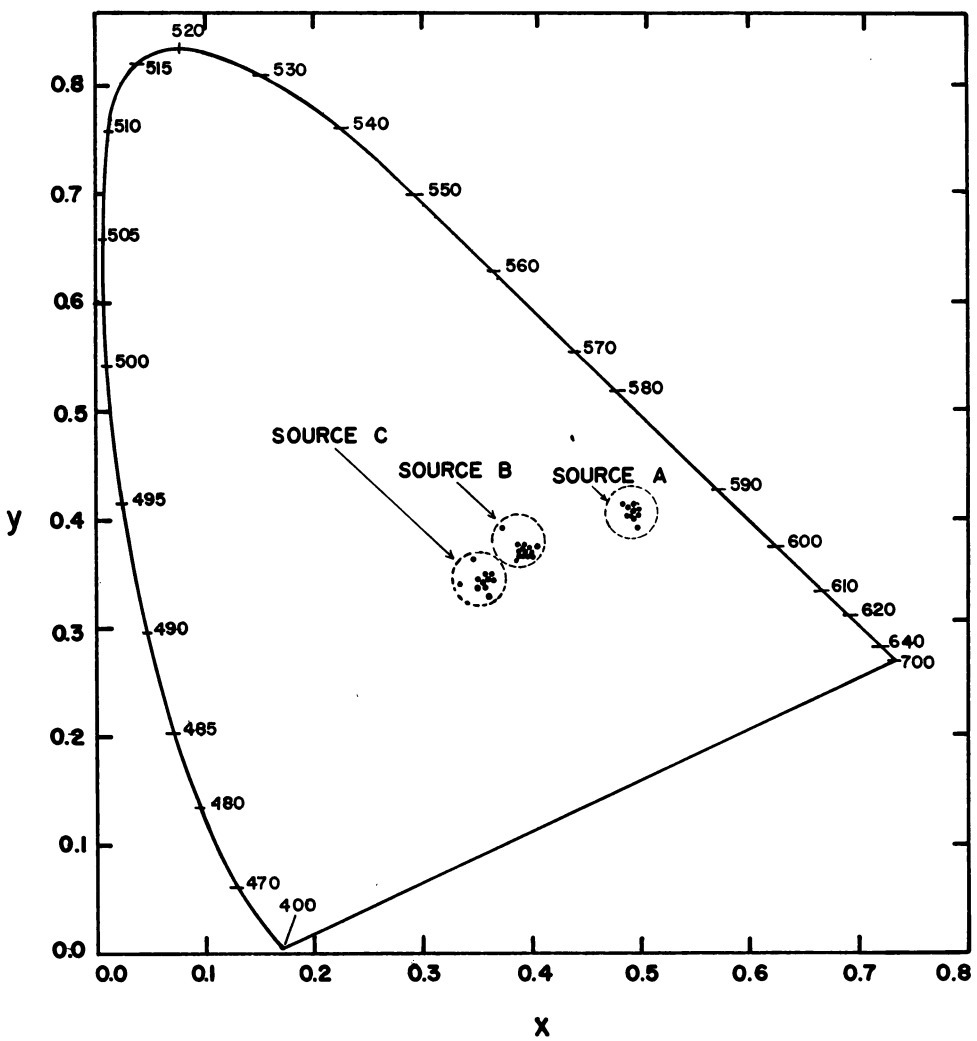


Figure 5.—The plot of walnut veneer hue on the CIE color chart for the test specimens using standard illumination sources A, B, and C. Note that the color of the same veneer specimens appears differently depending upon the source used.

under the three standard illumination sources (A, B, and C) show only small variations within any one of the chromaticity coordinates (see tables 2, 3, and 4). This indicates that hue changes among the veneer samples studied were small regardless of illumination source used. With light source C the color differences were brought out somewhat better than with light sources A or B (fig. 6). Because the hue

Table 2.—*Tristimulus values and chromaticity coordinates for 20 walnut veneer specimens using illumination source A*

Specimen No.	Tristimulus values			Chromaticity coordinates		
	X	Y	Z	x	y	z
1	18.365	15.108	4.154	.488	.402	.110
2	19.630	16.178	4.321	.489	.403	.108
3	17.914	14.754	3.876	.490	.404	.106
4	21.843	17.908	4.667	.492	.403	.105
5	19.689	16.133	4.179	.492	.403	.104
6	19.929	16.274	4.235	.493	.402	.105
7	27.442	22.898	5.754	.489	.408	.103
8	21.883	17.924	4.584	.493	.404	.103
9	19.410	15.919	4.210	.491	.403	.106
10	20.703	16.926	4.337	.493	.403	.103
11	19.926	16.271	4.192	.493	.403	.104
12	24.711	20.490	5.268	.490	.406	.104
13	23.244	18.282	5.080	.499	.392	.109
14	23.580	19.633	4.924	.490	.408	.102
15	23.732	19.955	5.272	.485	.408	.108
16	24.691	20.640	5.199	.489	.408	.103
17	20.740	16.923	4.308	.494	.403	.103
18	19.724	16.208	4.203	.491	.404	.105
19	21.910	18.169	4.615	.490	.407	.103
20	22.363	18.354	4.557	.494	.405	.101

Table 3.—*Tristimulus values and chromaticity coordinates for 20 walnut veneer specimens using illumination source B*

Specimen No.	Tristimulus values			Chromaticity coordinates		
	X	Y	Z	x	y	z
1	15.672	14.567	9.837	.391	.363	.245
2	16.740	15.578	10.229	.393	.366	.240
3	15.258	14.189	9.157	.395	.368	.237
4	18.565	17.205	11.024	.397	.368	.236
5	16.729	15.499	9.972	.396	.367	.236
6	16.899	15.612	10.000	.398	.367	.235
7	23.401	22.074	13.560	.396	.374	.230
8	18.578	16.993	10.821	.400	.365	.233
9	16.332	15.286	9.962	.393	.368	.240
10	17.567	16.237	10.242	.399	.369	.233
11	16.900	15.603	9.889	.399	.368	.233
12	21.077	19.725	12.435	.396	.371	.234
13	17.524	18.585	11.028	.372	.394	.234
14	20.095	18.914	11.587	.397	.374	.229
15	20.342	19.314	12.425	.391	.371	.239
16	21.039	19.925	12.190	.396	.375	.229
17	17.589	16.216	10.175	.400	.369	.231
18	16.771	15.581	9.922	.397	.369	.235
19	18.670	17.493	10.877	.397	.372	.231
20	18.977	17.597	10.753	.401	.372	.227

Table 4.—*Tristimulus values and chromaticity coordinates for 20 walnut veneer specimens using illumination source C*

Specimen No.	Tristimulus values			Chromaticity coordinates		
	X	Y	Z	x	y	z
1	14.190	14.367	13.566	.337	.341	.322
2	16.071	15.752	14.112	.350	.343	.307
3	14.624	13.225	12.622	.361	.327	.311
4	17.791	16.949	15.193	.356	.339	.304
5	16.017	15.270	13.608	.357	.340	.303
6	16.196	15.381	13.796	.357	.339	.304
7	22.421	21.768	18.669	.357	.346	.297
8	17.777	16.940	14.192	.363	.346	.290
9	15.836	15.078	13.736	.355	.338	.308
10	16.802	15.989	14.096	.358	.341	.301
11	16.178	16.831	13.631	.347	.361	.292
12	20.207	19.444	17.145	.356	.342	.302
13	19.003	18.203	16.591	.353	.338	.308
14	19.246	18.641	15.944	.358	.346	.296
15	19.555	19.080	17.123	.351	.342	.307
16	20.152	19.655	16.757	.356	.347	.296
17	16.759	15.960	14.021	.359	.341	.300
18	16.069	15.347	13.674	.356	.340	.303
19	17.886	17.241	14.982	.357	.344	.299
20	18.147	17.320	14.817	.361	.344	.295

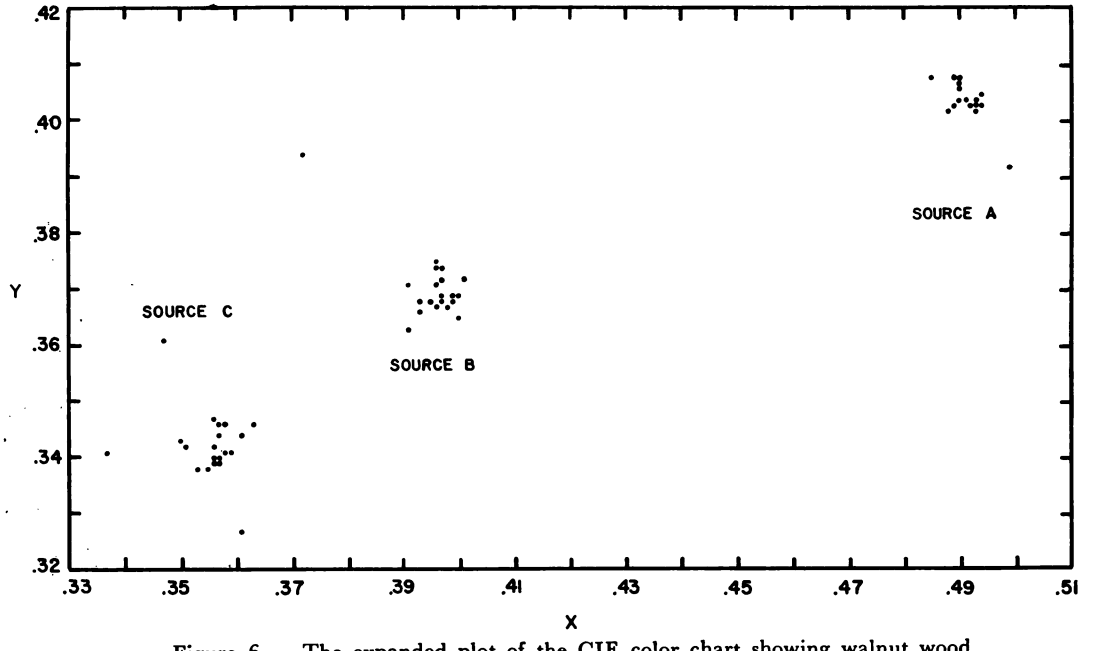
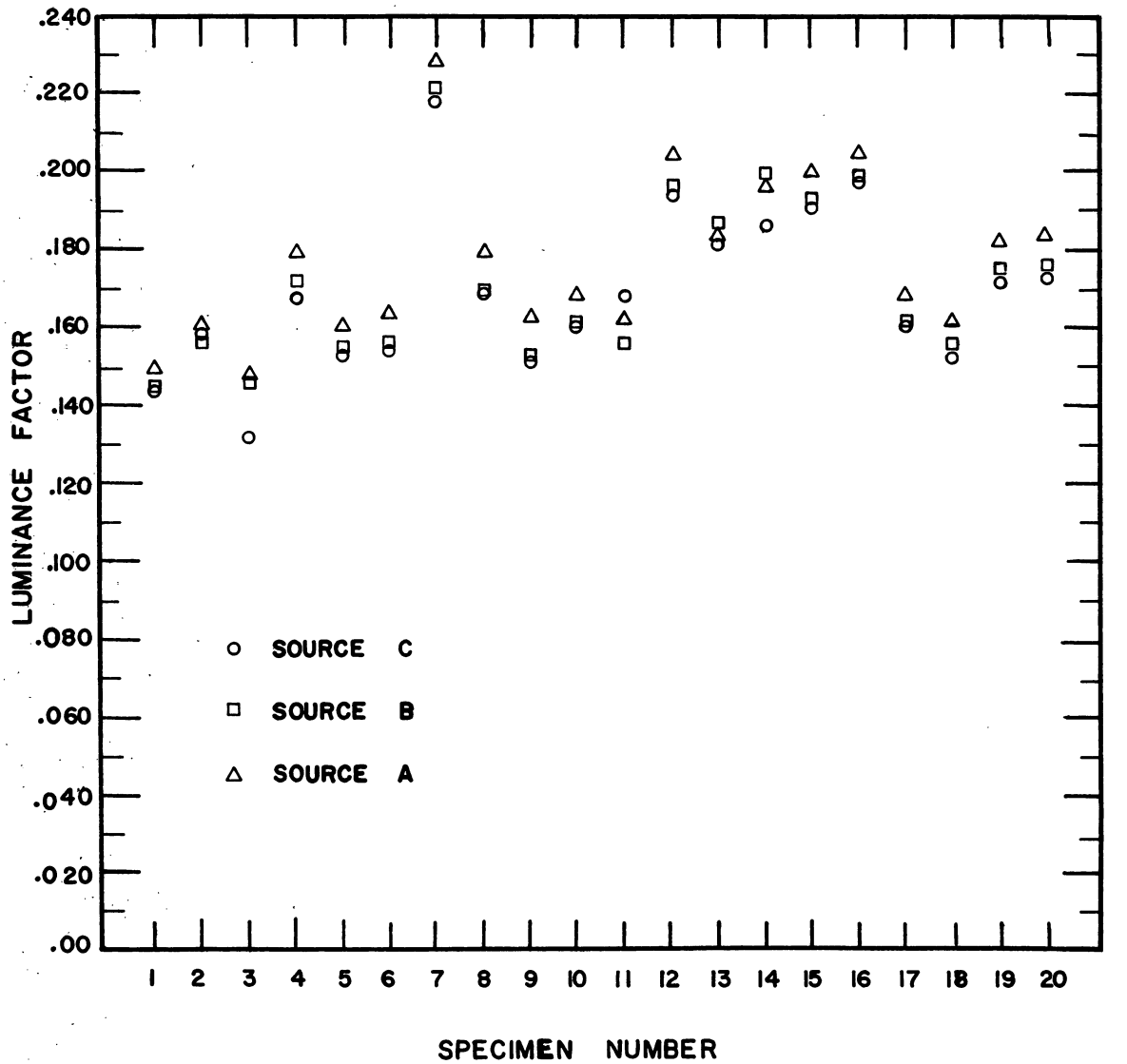


Figure 6. — The expanded plot of the CIE color chart showing walnut wood color points in detail for standard sources A, B, and C. Under source C the color data for walnut show more scatter, thus making this source more discriminating.

points were more widely scattered with light source C, this source appears to be best suited for evaluating hue differences.

Our study also indicated that the color luminance varied among the samples studied. Assuming the luminance of a perfectly reflecting surface as 1.0 then the luminance of study specimens is expressed as a fraction of 1.0. This value, termed the Luminance Factor (Wright 1958), is calculated by using Equation 2. The variations in luminance among the 20 specimens and within light sources were relatively large indicating that the Luminance Factor can be used in discriminating walnut wood color (fig. 7).

Figure 7.—Luminance Factor for walnut veneer specimen for standard illumination sources A, B, and C. This parameter shows significant scatter, thus appears to discriminate well for walnut wood color.



Walnut Color in Munsell System

As indicated earlier, the CIE color notation can be converted to the Munsell notation or vice versa. A series of charts for the various Munsell values have been prepared by a subcommittee of the Optical Society of America and are in wide use (Anon. 1943). A separate chart has been made for each value of the Munsell notation. These charts are composed of the CIE chromaticity chart on which Munsell hue and chroma have been plotted. The value for the Munsell notation can be obtained from data prepared by the Optical Society of America if the Y value in the CIE system is known.

The method of calculating the Munsell color notation for light source C is outlined below using the data for one veneer sample as an example.

1. The CIE data for specimen No. 1 are (table 4):
   Y=14.37 x=0.337 y=0.341
2. Using Y=14.37, the Munsell value is 4.34 (Nickerson 1946).
3. The value level indicates that conversion charts for value levels 4/ and 5/ are both needed. The hue for value 4/ is slightly over 2.5Y (fig. 8) and for value 5/ it is 2.5Y (fig. 9). In this case, 2.5Y is accepted as the hue notation.

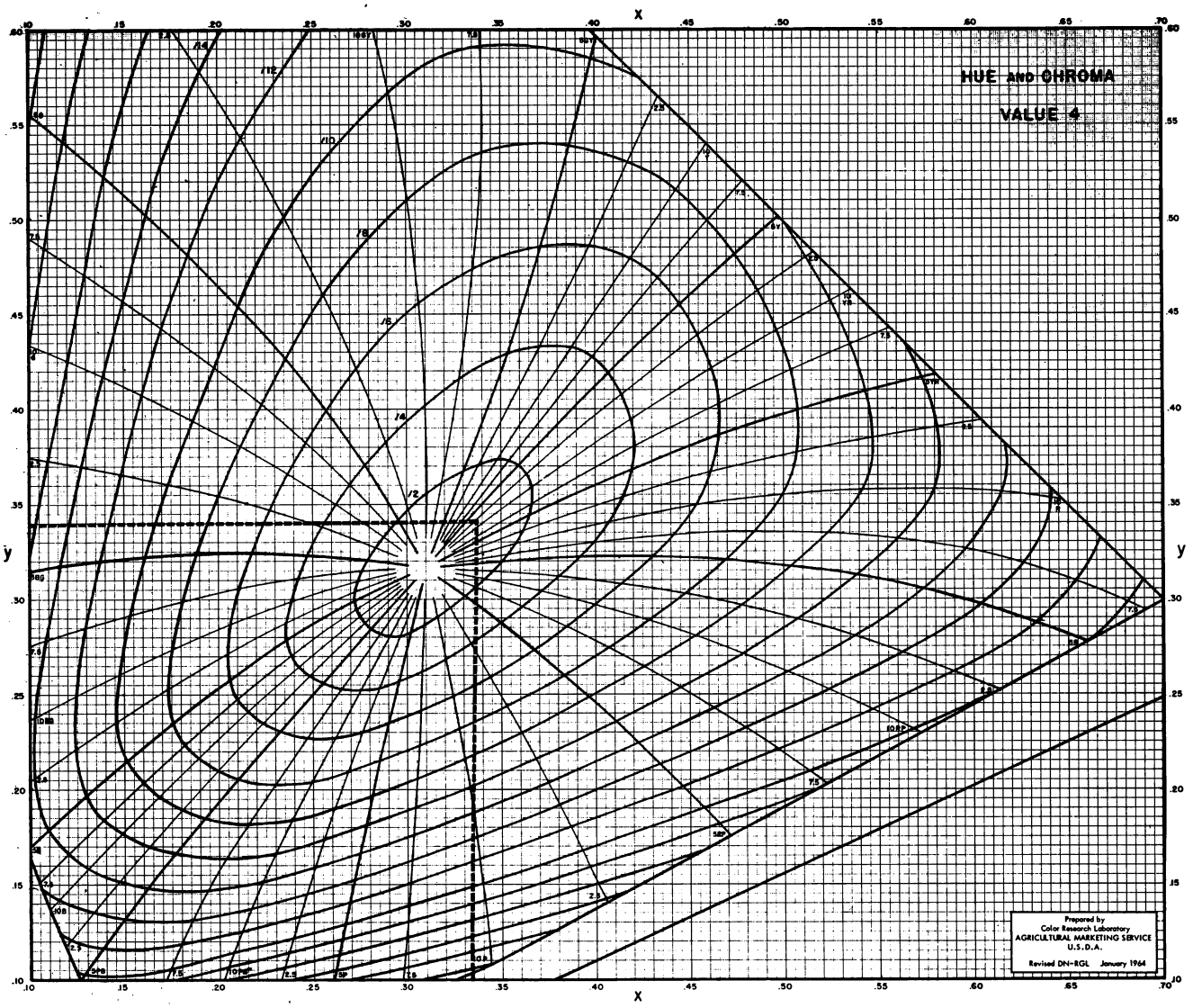


Figure 8.—Conversion chart from CIE to Munsell system for value 4/. This figure shows the loci of constant hue and constant chroma in CIE (x, y) coordinates. The conversion method for specimen No. 1 is shown (also see figure 9). (Reprinted with permission, Newhall, Nickerson, and Judd, J. Opt. Soc. Am. 33, 390, 391 (1943).)

4. The chroma (figs. 8 and 9) is less than /2. Reading the chroma is difficult on these small-scale charts but easy-to-read large-scale charts are available.

Table 5 lists the Munsell values and hues of the walnut veneer specimens as determined by using this method.

Color Difference Measurement

In some cases, one may be interested in determining what differences exist among the colors in a group of specimens when a standard is used. For example, a researcher may wish to determine the differences in color between the wood of a control tree with trees of the same species that have undergone a special treatment, such as fertilization or release. Other examples would be determining the effect of machining, finishing, weathering, or steaming on the color of wood by comparing the colors before and after such treatments. Equation 7 can be used to analyze color differences. This equation takes both luminance and chromaticness into account.

The Hunterlab color and color difference meter is one instrument that can be used to quantify color differences. The instrument specifies color differences in a three-dimensional space system (fig. 10). With

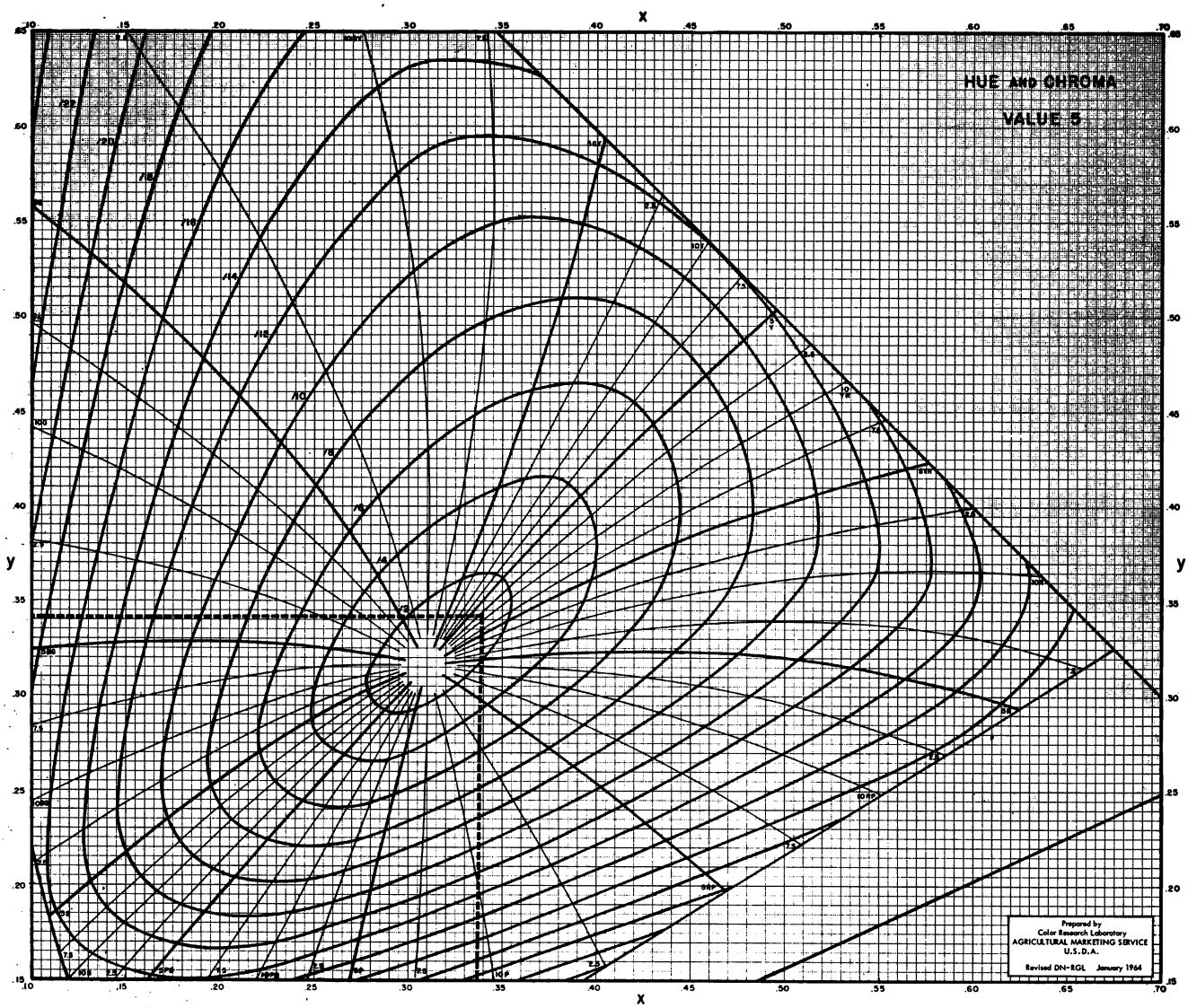


Figure 9.—Conversion chart from CIE to Munsell system for value 5/. The conversion method for specimen No. 1 is shown (also see figure 8). (Reprinted with permission, Newhall, Nickerson, and Judd, J. Opt. Soc. Am. 33, 390, 391 (1943).)

Table 5.—*Munsell color notation for 20 walnut veneer specimens as obtained from the CIE color data utilizing illumination source C*[1]

Specimen No.	CIE (Y)	Value	Hue[2/]
1	14.37	4.34	2.5YR[3/]
2	15.75	4.52	8.0YR
3	13.23	4.18	8.2R
4	16.95	4.67	5.0YR
5	16.02	4.56	5.0YR
6	15.38	4.48	5.0YR
7	21.77	5.22	7.2YR
8	16.94	4.67	5.5YR
9	15.08	4.44	3.5YR
10	15.99	4.55	5.0YR
11	16.83	4.67	6.0Y
12	19.44	4.96	5.2Y
13	18.20	4.82	5.0YR
14	18.64	4.87	7.5YR
15	19.08	4.92	7.5YR
16	19.66	4.99	7.5YR
17	15.96	4.55	5.6YR
18	15.35	4.47	5.5YR
19	17.24	4.71	6.8YR
20	17.32	4.72	6.2YR

1/ Data on chroma not presented due to gross inaccuracies that would have been caused had small conversion charts available in this study been used.

2/ Data approximate due to the small size of conversion charts used. Presented for illustrative purposes only.

3/ Y = yellow; R = Red.

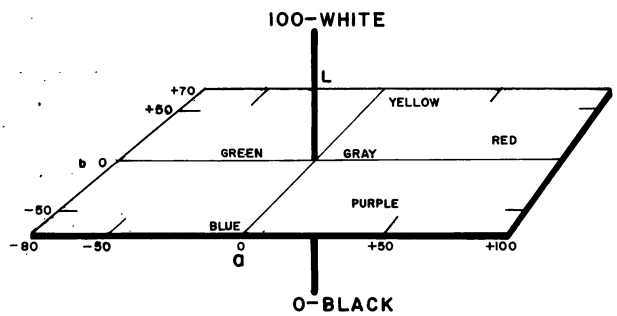


Figure 10.—Color space utilized in color difference specification. This color space was used for walnut veneers studied.

this color meter, using specimen No. 21 as a standard, it was found that the three specimens, as compared with No. 21, contained more blue and purple (fig. 11 and table 6). The results obtained would, of course, differ depending on the standard selected.

Color difference data were also determined mathematically for 20 walnut veneer specimens using CIE color data and Equation 7. Calculations were made using specimen No. 1 as a standard. Computations for specimens No. 1 and 2, as an example, are:

Specimen No. 1:

$$Y_1 = 14.4$$

$$L_1 = 10(14.4)^{1/2} = 38.0$$

$$\alpha_1 = \frac{2.4266(0.337) - 1.3631(0.341) - 0.3214}{(0.337) + 2.2633(.341) + 1.1054} = 0.0143$$

$$\beta_1 = \frac{0.5710(0.337) + 1.2447(0.341) - 0.5708}{(0.337) + 2.2633(0.341) + 1.1054} = 0.0208$$

$$a_1 = 7(38.0)(0.0143) = 3.804$$

$$b_1 = 7(38.0)(0.0208) = 5.533$$

Specimen No. 2:

$$Y_2 = 15.8$$

$$L_2 = 10(15.8)^{1/2} = 39.4$$

$$\alpha_2 = \frac{2.4266(0.350) - 1.363(0.343) - .3214}{(0.350) + 2.2633(0.343) + 1.1054} = 0.0271$$

$$\beta_2 = \frac{.5710(0.350) + 1.2447(0.343) - 0.5708}{(0.350) + 2.2633(0.343) + 1.1054} = 0.0251$$

$$a_2 = 7(39.4)(0.0271) = 7.474$$

$$b_2 = 7(39.4)(0.0251) = 6.923$$

$$\Delta E = [(38.0 - 36.5)^2 + (3.804 - 7.47)^2 + (5.533 - 6.92)^2]^{1/2} = 4.17$$

Table 7 lists the calculated color difference data for the 20 walnut veneer specimens (Specimen Nos. 1-20). In this table data obtained with the Hunterlab color and color difference meter are also included (Specimens Nos. 21-24) this time as compared with specimen No. 1 as a standard. With specimen No. 1 as a standard, most of the 23 remaining veneer specimens fell in the blue-green, green region of the color chart (fig. 12). Parameters *a* and *b* (see Equations 9 and 10) for the walnut specimens were also plotted

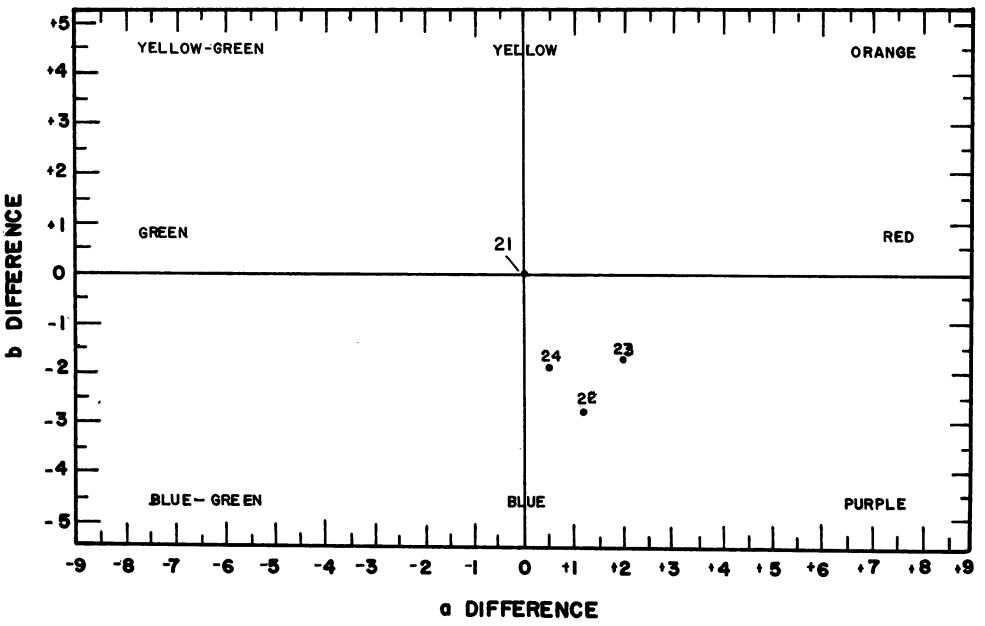


Figure 11.—Color difference graph for four walnut veneer specimens using specimen No. 21 as standard. Data for this graph were obtained by Hunterlab color and color difference meter. This graph indicates that the remaining specimens fell in blue, blue-purple area as compared with specimen No. 21. Specimen numbers are indicated for all points.

(fig. 13). The difference in parameter *a* between the standard and unknown specimens measures redness in relation to the standard when positive and greenness when negative. The difference in parameter *b* between the standard and unknown specimens measures yellowness when positive and blueness when negative. Our 23 walnut specimens as compared to specimen No. 1 appeared greenish and bluish with the exception of specimens 3 (difference in *b*'s positive) and 11 (difference in *a*'s positive). Finally the color difference values ΔE (see Equation 7), with specimen No. 1 as standard were graphed (fig. 14).

Table 6.—*Color difference parameters for 4 walnut veneer specimens as compared to specimen No. 21 and as obtained by Hunterlab color and color difference meter (Light Source C) (see figs. 10 and 11)*

Specimen No.	Color parameters			Parameter differences			Color difference
	L	a	b	L	a	b	ΔE
21	45.1	5.4	9.6	0	0	0	0
22	39.0	6.6	6.8	-6.1	+1.2	-2.8	6.8
23	39.0	7.4	7.9	-6.1	+2.0	-1.7	6.5
24	40.6	5.9	7.7	-4.5	+0.5	-1.9	5.0

Table 7.—*Calculated color difference parameters for 24 walnut veneer specimens as compared with specimen No. 1 utilizing illumination source C*

Specimen No.	Parameters			Differences			Color difference
	L	a	b	L	a	b	ΔE
1	38.0	3.80	5.53	0	0	0	0
2	39.4	7.47	6.92	-1.4	-3.67	-1.39	4.17
3	36.5	12.62	4.91	+1.5	-8.82	+0.62	8.96
4	41.2	10.38	6.92	-3.2	-6.58	-1.39	7.46
5	38.8	10.05	6.79	-0.8	-6.25	-1.29	6.44
6	39.2	10.15	6.86	-1.2	-6.35	-1.33	6.60
7	46.7	10.46	9.48	-8.7	-6.66	-3.95	11.65
8	41.2	11.25	8.08	-3.2	-7.45	-2.55	8.14
9	38.9	9.80	6.54	-0.9	-6.00	-1.01	6.15
10	40.0	10.36	7.28	-2.0	-6.56	-1.75	7.08
11	41.2	3.75	9.52	-3.2	+0.05	-3.99	5.12
12	44.3	10.54	8.06	-6.3	-6.74	-2.53	9.57
13	42.7	10.16	6.87	-4.7	-6.36	-1.34	8.04
14	43.4	10.33	8.51	-5.4	-6.53	-2.93	9.33
15	43.7	8.87	7.65	-5.7	-5.07	-2.12	7.92
16	44.5	9.66	8.72	-6.5	-5.86	-3.19	9.33
17	39.9	10.61	7.54	-1.9	-6.81	-2.01	7.37
18	39.2	9.88	6.86	-1.2	-6.08	-1.33	6.35
19	41.6	9.90	7.86	-3.6	-6.10	-2.33	7.46
20	41.6	11.07	8.15	-3.6	-7.27	-2.62	8.54
21	45.1	5.40	9.60	-7.1	-1.60	-4.07	8.36
22	39.0	6.60	6.80	-1.0	-2.80	-1.27	3.24
23	39.0	7.40	7.90	-1.0	-3.60	-2.37	4.43
24	40.6	5.90	7.70	-2.6	-2.10	-2.17	3.99

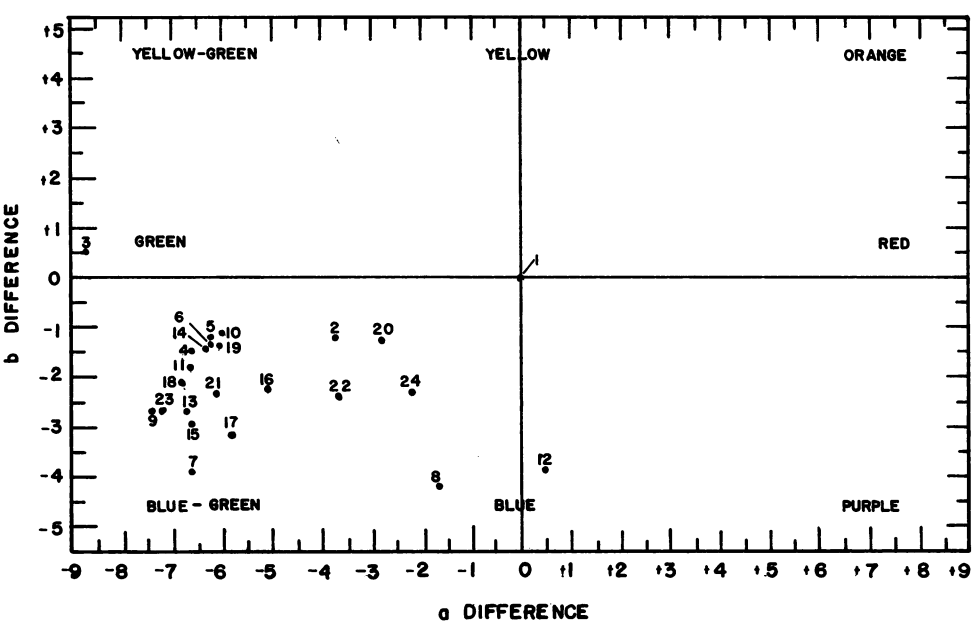


Figure 12.—Calculated color difference graph for 24 walnut veneer specimens as compared with specimen No. 1. Note that almost all remaining specimens fell in the blue-green area of the graph. Specimen numbers are indicated for all points.

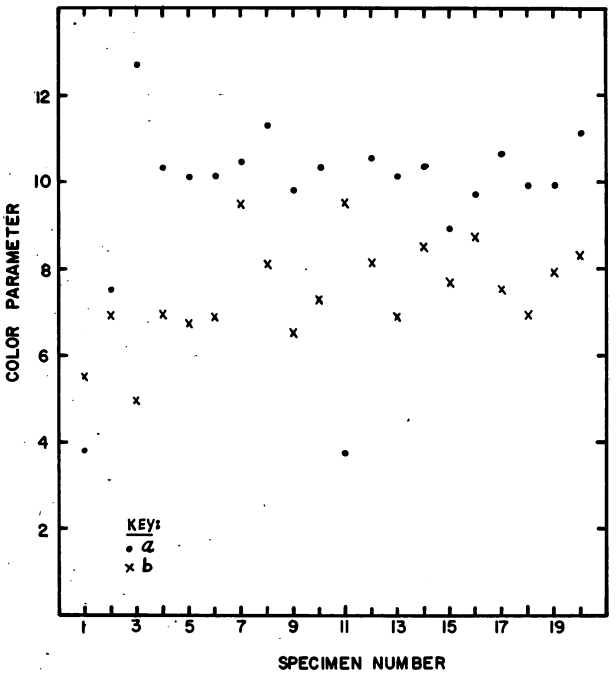


Figure 13.—Color difference parameters *a* and *b* for 20 walnut veneer specimens. The difference between the standard and the given specimen in parameter *a* measures redness when positive and greenness when negative. The difference in parameter *b* measures yellowness when positive and blueness when negative.

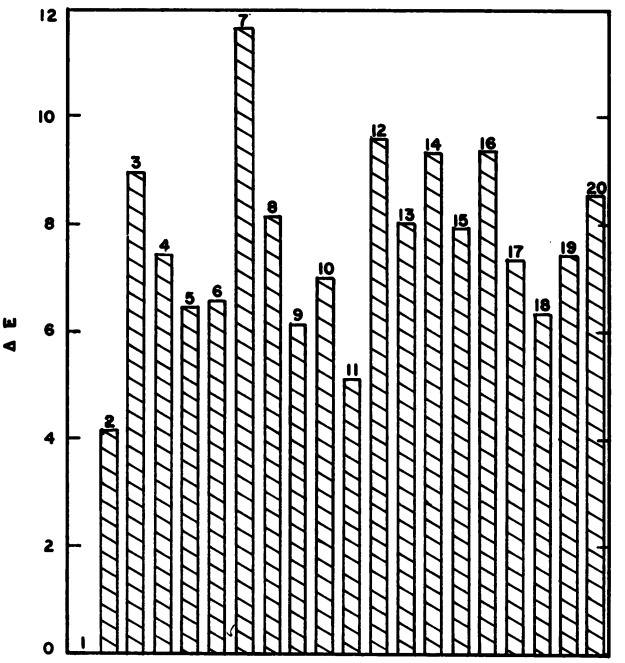


Figure 14.—Color difference values (ΔE) for 20 walnut veneer specimens as defined by Equation 7 in the text. Specimen numbers are indicated.

Conclusions

This study has demonstrated that walnut wood color can be determined quantitatively through spectrophotometric analysis. Although the chromaticity coordinates of walnut wood are not widely different due to little natural hue changes, the luminosity of this wood differs significantly and can be used in discriminating color.

Color notations obtained from the internationally adopted CIE method can be converted to the visual Munsell notation or vice versa which provides considerable freedom for expressing wood color. Also color differences taking into account both chromaticness and luminance can be calculated for walnut wood. These color difference calculations perhaps fulfill our needs best in dealing with wood since it combines both luminance and hue.

The methods for analyzing wood color reported here should generally prove useful in many research applications. These methods can become effective tools for soil scientists and tree geneticists in measuring the influence of environment and inheritance upon the color of wood. Furthermore, consistent color changes within a tree, if any, can be detected. The wood technologist can use the methods described in this report to study color changes due to fading, finishing, weathering, steaming, or bleaching.

Further research in perfecting the science of colorimetry for adaptation to wood is needed. The large color variations due to springwood and summerwood color differences in many species including walnut present a problem which perhaps can be resolved by averaging colors. Or color differences associated with growth rings within a piece of veneer or a board may be expressed in terms of maximum and minimum color values, thus providing a quantitative record for the wood figure. Quantitative color analysis also may prove to be a means of grading figured woods in industry.

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Glossary

Definitions of technical terms as referred to in this report are given below for convenience. Some definitions are based on those prepared by the Committee on Colorimetry of the Optical Society of America.

Combination of colors: Mixing or superimposing lights of different chromaticities.

Chroma: See Munsell chroma.

Chromaticity coordinates: Coordinates (ordinate and abscissa) of a given color to represent it in the chromaticity diagram.

Chromaticness: The quality of color in terms of hue and saturation.

CIE: The initials for Commission Internationale de Eclairage.

CIE chromaticity diagram: An x-y diagram on which chromaticity coordinates are plotted.

CIE coordinate system: The coordinate system used for plotting color using chromaticity coordinates.

Colorimeter: An instrument which is capable of measuring color.

Hue: Represents color as produced by various wavelengths within the visable range of the radiant energy spectrum.

ICI: Initials for International Commission on Illumination, the English language version of CIE.

Luminance factor: A fractional value representing the relative luminosity of colored surface.

Munsell chroma: Saturation as designated in the Munsell method of color measurement.

Munsell hue: That portion of Munsell notation which refers to the hue nature of the given color (see definition of hue above).

Munsell value: Lightness as referred to in the Munsell color notation.

Opaque: Impenetrable to light.

Primary colors: The basic colors whose additive mixtures produce an extensively large variety of colors.

Reflectance: The ratio of reflected light to incident light.

Spectrophotometer: The instrument which measures the spectral reflectance.

Standard observer: A hypothetical observer agreed upon by the CIE in 1931.

Standard Source A: A particular light source representative of artificial illumination recommended by CIE in 1931.

Standard Source B: A particular light source representative of direct sunlight at sea level recommended by CIE in 1931.

Standard Source C: Refers to a particular light source representative of average daylight recommended by CIE in 1931.

Trichromatic colorimetry: Color measurement in terms of mixtures of the three primary colors.

Tristimulus value: Amount of a component necessary in a three-color mixture to match a sample color.