RELATIONSHIP OF BLACK WALNUT WOOD COLOR TO SOIL PROPERTIES AND SITE[1]

Neil D. Nelson,[2] *Robert R. Maeglin,* and *Harold E. Wahlgren*
Forest Products Laboratory,[3] Forest Service, U. S. Department of Agriculture, Madison, Wisconsin 53705

ABSTRACT

This investigation is the first to provide information for any species on the magnitude of quantitative wood color differences between individual trees and between groups of trees at specified locations. It is also the first to report on the effects of specific environmental factors on wood color. Larger differences were found between black walnut (*Juglans nigra* L.) trees in heartwood luminance (lightness) than in dominant wavelength (hue) or purity (percentage of principal hue). Indiana-grown walnut heartwood had higher luminance than Missouri-grown. The relationship of heartwood color to soil properties was greater than it was either to tree age or to diameter-growth rate (rings per inch).

For decorative hardwoods, the most important wood characteristics are the esthetic. This applies especially to the most valuable of the important hardwoods of the United States, black walnut (*Juglans nigra* L.). Of the esthetic characteristics of this species, the color of the heartwood is of greatest importance.

Log buyers have developed a general classification of the natural color range of black walnut, and arbitrarily designate some areas as "good" and others as "poor." They pay prices for walnut trees partially according to this classification.

Prior to this investigation, there was little or no information on the magnitude of heartwood color differences between individual trees or between groups of trees growing at specified locations or on the effects of specific environmental factors on wood color. In related work, Sullivan (1967) found significant within-species differences in the color properties of yellow-poplar (*Liriodendron tulipifera* L.) and black cherry (*Prunus serotina* Ehrh.) that showed relationships to the geographic areas in which the trees were grown. He suggested that the cause of the within-species differences by geographical area was a smaller concentration of color precursors in trees of some areas and that this was caused by differences in physiological processes. Moslemi (1967) has demonstrated that differences in walnut wood color can be determined by spectrophotometric analysis.

Although the physiological explanation for the production of color in the heartwood of trees is not too clear, the general theory has been that polyphenols and other organic extractives or their precursors are produced in leaves, needles, or cambium and are transported by phloem and rays to the heartwood. In the heartwood, these compounds supposedly undergo chemical change to produce heartwood color (Frey-

[1] Research for this work was conducted in cooperation with the North Central Forest Experiment Station, St. Paul, Minn. The paper is based on work by the senior author for an M.S. degree at the University of Wisconsin, Madison.

[2] Acknowledgment is made to W. H. Carmean and C. Losche, North Central Forest Experiment Station, for helpful suggestions on soil sampling and analysis; to F. B. Clark, R. D. Williams, N. F. Rogers, all of the North Central Forest Experiment Station, to C. L. Norton, Fulton, Mo., U. S. Forest Service—Cedar Creek Land Use Area, D. O. Holmes, Jr., and B. Moyer, Holmes Lumber Company, Inc., Columbia City, Ind., and to the Theising Veneer Company, Indianapolis, Ind., for selection and donation of sample trees; to D. Farmer, Huntington, Ind., and R. M. Sturm, Lafayette, Ind., U. S. Soil Conservation Service, and to J. Millett, North Central Forest Experiment Station, for classification of soils; and to E. A. Okkonen and J. F. Heinrichs, U. S. Forest Products Laboratory, for assistance with sampling and laboratory work.

[3] Maintained in cooperation with the University of Wisconsin.

TABLE 1. *Design for sampling black walnut trees*

Site quality	Growth rate	Number of trees	
		Indiana	Missouri
Good	Fast	4	4
	Slow	4	4
Poor	Fast	4	4
	Slow	4	4

Wyssling and Bosshard 1959). A current theory, gaining in acceptance, is that the heartwood extractives are formed *in situ* in sapwood cells, thus changing them to heartwood (Hillis 1962).

From these previous studies, it is believed that environment substantially influences wood color by its effects on tree physiology in general and on extractive and other wood-component production in particular.

The problem, then, is to determine the environmental factors that may most affect the physiology of the tree.

The trifold objective of this work was to determine the following: the degree to which individual black walnut trees vary in heartwood color; whether groups of trees in specified areas on sites of different quality and with different growth rates vary in heartwood color; and the relationships that may exist between heartwood color of black walnut trees and properties of the soil on which the trees were grown.

STUDY METHODS

Trees were selected from Missouri and from Indiana because the quality of walnut wood is supposed to differ between them. The sample trees, 16 from each state, were to be distributed equally within each state by site quality and by growth rate in a 2 × 2 × 2 factorial design as shown in Table 1.

The trees were selected arbitrarily for site quality and growth rate by foresters familiar with walnut growth in the areas; selection was based on external appearances only. Site quality was evaluated on tree characteristics and not soil properties. A log was cut from the 8- to 13-foot aboveground portion of each tree for the sample unit to represent the tree. The logs were at least 11 inches in diameter inside bark (d.i.b.) at the small end. It should be emphasized that all mean tree-color values discussed here are values for the 8- to 13-foot aboveground portion of the tree; color values for other parts of a black walnut tree may be different from those of the section tested. The color values found, however, are assumed to be closely related to color values of the section of greatest commercial importance, the butt log.

For each sample tree, a composite sample of the 6-inch surface soil layer was taken with a calibrated sampling tube. Each composite consisted of eight subsamples taken systematically within a 20-foot radius of each tree. In addition, a pit was excavated, and the soil profile described and classified. Depth to mottling or impervious layer was obtained from the soil profile description; depths of more than 60 inches were assigned a value of 60 inches.

Wood Sample Preparation

Each 5-foot sample bolt was broken down in the laboratory by the following procedures:

1) Two-inch-thick disks were cut from each bolt end to determine average age of the tree (bolt) and average diameter-growth rate of the tree (bolt). ("Tree" age and "tree" diameter-growth rate subsequently mentioned are actually values for the 8- to 13-foot bolts. Values were determined from the averages of ring counts and diameter measurements on both small-end and large-end disks.)

2) At least eight 1- × 4-inch boards were flat sawed from each log. Eight boards were then randomly selected and planed.

3) One 6-inch-long piece was randomly selected from each board for color samples.

4) Each 6-inch piece was dried to approximately 12% moisture content in a room controlled at 65% relative humidity and 80 F to equalize moisture content.

5) Each conditioned piece was sanded with 100 grit 2/0 sandpaper to standardize surface roughness.

6) One 1- × 3/4- × 3/16-inch piece of heartwood was then randomly selected as a

color sample from each face of the 6-inch piece. Substitutions were made for pieces containing knots or other defects.

7) All color samples were stored in the room controlled at 65% relative humidity and 80 F until color was analyzed.

This procedure resulted in 16 color samples from each tree; the samples were used to compute an average color value for a tree.

Soil Analysis

Soil samples were analyzed by the following methods: pH with a pH meter by thin paste method (Chapman, Axley, and Curtis 1941); organic matter by ferrous sulfate ($FeSO_4$) titration (Walkley and Black 1934); available phosphorus (P) by sodium bicarbonate extraction ($NaHCO_3$), ammonium molybdate method with use of a spectrophotometer (Black et al. 1965); exchangeable potassium (K), calcium (Ca) and magnesium (Mg) by 1N, neutral sodium acetate (NaOAc) extraction, and the use of a flame spectrophotometer; total nitrogen (N) by macro-Kjeldahl digestion (Bremner and Shaw 1958); soil texture by Bouyoucos hydrometer method using mechanical shaking for dispersion, with temperature correction (Black et al. 1965; Wilde, Voigt, and Iyer 1964); cation exchange capacity by 1N, neutral magnesium acetate ($Mg(OAc)_2$) saturation, 1N sodium chloride (NaCl) displacement, and ethylenediamine tetraacetate (EDTA) titration (Corey 1964).

The extraction method for available P was used because the majority of the soils were of a calcareous nature. Normally an acid extraction is used, and most values given for available P are thus derived. An acid extraction on calcareous soils would give availability values for P that would not be realistic. The values for the two methods are not directly comparable. Values of more than 10 ppm are considered high for this extraction.

Wood Color Analysis

Color was analyzed according to the International Commission on Illumination (I.C.I.) color system (1931). This system requires a spectrophotometric curve of diffuse reflectance plotted against wavelength over the visible range of the spectrum for each sample of material to be measured. From a weighted integration of this curve, the three following color properties are obtained for the sample: 1) per cent luminance, lightness or brightness of the color; 2) dominant wavelength (millimicron), directly related to the hue of the color; and 3) per cent purity, per cent of the principal hue, or richness of hue in the color.

A Beckman model B spectrophotometer with reflectance accessory and beam-expanding lens (1954) was used for the reflectance measurements, utilizing standard light source A to simulate incandescent lighting (International Commission on Illumination 1931), and a magnesium carbonate ($MgCO_3$) reflectance standard. Per cent reflectance was recorded at 10-millimicron (mμ) intervals over the visible spectrum (400 to 700 mμ) for each sample. To ensure constant moisture conditions while making readings, all reflectance readings were taken in the controlled room, used for conditioning and storage. The air drying conditions used in this study will result in different color values than those where the wood is exposed to high temperatures and variable humidity as in kiln drying (Brauner and Loos 1968).

Tristimulus values, trichromatic coefficients, and the three color properties (per cent luminance, dominant wavelength, per cent purity) were calculated from the reflectance data for each sample according to the I.C.I. system. To calculate the color properties from reflectance data, distribution coefficients (in Wright (1964), Table 8, and in Judd (1933), Table 6) were utilized. Table 8 in Wright was slightly revised to allow the same distribution sums listed, for only the visible spectrum (400 to 700 mμ). All reflectance data were adjusted by a factor of 0.98 because the diffuse-reflectance of the $MgCO_3$ standard approximates 98% of total diffuse reflectance (Benford, Lloyd, and Schwarz 1948).

All conversions from reflectance data to final color properties were calculated by a computer program incorporating the con-

TABLE 2. *Means and between-tree variation for color properties*

Item	Luminance, %	Dominant wavelength, mμ	Purity, %
Overall tree mean	25.3	594.9	31.0
Range of tree means	22.5–29.6	592.7–596.5	27.5–34.0
Differences in extremes	7.1	3.8	6.5
Standard deviation among trees	1.7	1.0	1.4
Coefficient of variation among trees, %	6.76	.17	4.39

stants and the values in the tables of Wright and Judd.

RESULTS AND DISCUSSION

Color Variation between Individual Trees

Means and between tree variation for color properties are shown in Table 2.

In the following tabulation, based on visual observation of the samples, minimum color differences which are distinguishable to the unaided eye are shown.

Color property	Minimum visual difference
Luminance, %	3.5
Dominant wavelength, mμ	4
Purity, %	5

Data in Table 2 indicate that there are greater differences between trees in luminance than in either dominant wavelength or purity. The coefficients of variation show that dominant wavelength varies only a minute amount compared to the other color properties. The data also indicate that there are differences visible to the eye between individual trees in luminance and purity but not in dominant wavelength.

These results would seem to indicate that luminance and purity are the most important properties in evaluating differences in color between individual black walnut trees. This is in partial agreement with the conclusion reached by Moslemi (1967) from a more limited study on the color of black walnut veneer, in which he found only luminance as an important factor, and Sullivan (1967), who found all three color properties differing significantly in black cherry and yellow-poplar.

Color Variation between Factorial Groupings

Differences in color properties between states, sites, and growth rates were tested by analysis of variance. The results (Table 3) indicate that geographical areas differed significantly in luminance but not in the other properties. The heartwood of Indiana trees had higher luminance than the heartwood of Missouri trees. This difference, although not visibly distinguishable, is

TABLE 3. *Means and differences in color of black walnut heartwood*

Classification	Luminance, %	Dominant wavelength, mμ	Purity, %
Indiana	25.999	595.07	30.55
Missouri	24.573	594.70	31.39
Difference	1.426*	0.37	0.84
Good site	25.797	594.89	31.10
Poor site	24.775	594.88	30.84
Difference	1.022	0.01	0.26
Fast grown	25.539	505.04	30.93
Slow grown	25.033	594.72	31.01
Difference	0.506	0.32	0.08

* Difference significant at 0.05 level, other differences not significant.

TABLE 4. *Averages for the three color properties by site quality and by growth rate*

Factor	Luminance, %	Dominant wavelength, mμ	Purity, %
Site quality			
Good:			
Indiana	26.682458	594.93020	30.976665
Missouri	25.190599	594.87541	31.071719
Poor:			
Indiana	24.804330	595.52859	30.093672
Missouri	23.895000	595.60478	31.325531
Growth rate			
Fast:			
Indiana	26.450078	595.47859	30.430234
Missouri	24.633687	594.60703	31.426328
Slow:			
Indiana	25.548375	594.65508	30.670547
Missouri	24.518437	594.78836	31.353281

pertinent because it may indicate a trend toward easily distinguishable luminance differences in wood color in walnut from widely separated climates and races.

There were no significant differences between sites or growth rates. A possible reason for the lack of significant differences in site or growth rate may be the manner of selection; the trees were selected before cutting without the tree age or growth rate being known. Because of the value of the trees, this was necessary; they could not be bored to check their age or growth rate. Any further research should be predicated on absolute and substantial site and growth rate differences. Such would be possible if plantations of known age were used.

Although the results of the analysis of variance do not reflect a significant difference between wood from sites of different quality, resulting values (Table 4) show that poor quality sites have, on the average, wood that is lower in luminance and higher in dominant wavelength. No consistent relationships were evident in purity. Neither were there consistent relationships evident for any color property to growth rates.

Color Relationships

Relationships of the mean color values to 10 soil properties, to tree age, and to diameter-growth rate were explored by regression analysis. The "best" regressions, or those explaining the largest amount of variation, were subsequently selected through significant improvement tests. The "best" regression is established as the combination of variables giving the highest coefficient of determination (R^2) and the lowest standard deviation from regression. Each added variable must reduce the residual sum of squares significantly.

Tree age was included as a factor not influenced by soil properties that may logically be expected to affect the color of black walnut heartwood. Tree age varied from 40 to 78 years, except for one tree of 122 years. Diameter-growth rate was included as a check to determine whether any effect of soil properties on wood color properties was caused by the effects of soil properties on growth. The growth rate varied from 5.16 to 12.55 rings per inch except for the 122-year-old tree which had 21.18 rings per inch.

Table 5 gives the range of soil property values of the walnut sites examined in Indiana and Missouri. Soil property values ran from moderate to very high; a few soils had low values for available P, silt plus clay, and organic matter.

Tables 6 and 7 list coefficients of determination, r^2 (simple) and R^2 (multiple),

TABLE 5. *Ranges of soil properties[1] for black walnut sites of Indiana and Missouri*

	Ranges
pH	5.8–7.5
Organic matter, %	2.38–20.02
Available P, ppm	0.05–27.72
Exchangeable K, ppm	126.3–625.4
Exchangeable Ca, ppm	2,153.0–7,898.0
Exchangeable Mg, ppm	30.1–1,112.7
Total N, %	0.180–0.804
Silt and clay, %	23.9–88.2
Cation exchange capacity, meq/100g	12.9–59.5
Depth to mottling or impervious layer, in.	5–60

[1] For surface 6 inches of soil.

for all simple regressions and the two variable combinations having the largest R^2 values.

Although significantly correlated with luminance and dominant wavelength, pH is not associated with very much of the variation in these properties (23% for luminance and 15% for dominant wavelength). Arnon and Johnson (1942) show that within the range of pH found in this study, no direct effect from pH can be expected. The relationship of pH in the simple regressions is believed to reflect the effect of pH on other soil properties that may directly affect wood color.

In no case does a two-variable regression with the highest R^2 include pH. Instead, various combinations of available and exchangeable nutrients are found. Available P and exchangeable Mg associate with 30% of the variation in luminance. Exchangeable K and Ca associate with 31% of the variation in dominant wavelength. None of the one or two variable regressions were significant for purity.

To carry the analysis one step further, the "best" regressions for combinations of

TABLE 6. *Coefficients of determination for independent variables with luminance, dominant wavelength, and purity as dependent variables*

Independent variables†	r^2, simple coefficient of determination††		
	Luminance, §	Dominant wavelength, §	Purity, §
pH	0.2316**, – §	0.1535*, +	0.1026, +
Organic matter, %	.0080 , –	.0688 , +	.0040, –
Available P, ppm	.1520* , –	.0245 , +	.0745, –
Exchangeable K, ppm	.0017 , –	.0054 , –	.0881, +
Exchangeable Ca, ppm	.0141 , –	.0515 , +	.0499, –
Exchangeable Mg, ppm	.0254 , –	.0016 , +	.0396, +
Total N, %	.0086 , –	.0422 , +	.0163, –
Silt and clay, %	.0755 , +	.0831 , –	.0008, +
Cation exchange capacity, meq/100g	.0001 , –	.0342 , +	.0132, –
Depth to mottling or impervious layer, in.	.1080 , –	.0496 , +	.0138, –
Average tree age, yr.	.0443 , –	.0004 , –	.0161, +
Average diameter-growth rate, rings/in.	.0095 , –	.0366 , –	.0003, +

† Soil properties are for surface 6 inches, except depth to mottling or impervious layer.
†† Only footnoted values are significant.
** Significant at 0.01 level of probability.
* Significant at 0.05 level of probability.
§ Sign of correlation coefficient.

TABLE 7. *Coefficients of determination for combinations of two independent variables with luminance, dominant wavelength, and purity as dependent variables*

Independent variables	Multiple coefficients of determination, R^2† Luminance	Dominant wavelength	Purity
Available P (ppm) and exchangeable Mg (ppm)	0.3014**	——	——
Exchangeable K (ppm) and exchangeable Ca (ppm)	——	0.3131**	——
Organic matter (%) and exchangeable Mg (ppm)	——	——	0.1303

† Only footnoted values are significant.
** Significant at 0.01 level of probability.

factors related to wood color were selected using significant improvement tests (Table 8).

With combinations of three and four variables, all three color properties have significant regressions. The "best" regression for luminance includes available P, exchangeable Ca and Mg, and depth to mottling or impervious layer. The regression is associated with about 53% of the variation in luminance. The "best" regression for dominant wavelength is associated with about 44% of the variability and involves pH, exchangeable K, and total N. The "best" regression for purity is associated with somewhat less of the variability, about 30%.

By using the observed range of each variable times its respective regression coefficient in the "best" equations shown in Table 8, it is possible to assess the maximum effect of the variable on each of the three color properties. For example, the observed values of P varied from 0.05 to 27.72 ppm, a range of 27.67 ppm. In the equation for luminance, the coefficient of P is 0.237. Hence, the "maximum effect" of P is $0.237 \times 27.67 = 6.5578$. The maximum effects for all significant variables are shown in Table 9. In the case of luminance, three of four soil properties, P, Ca, and Mg, result in a color change that is well beyond the minimum value discernible to the unaided eye. For dominant wavelength, only the range in values for K results in a color change that is visible to the eye. Of the four soil properties associated with the purity regression equation only the range in Ca values result in a color change visible to the eye.

It should be pointed out, however, that although this type of analysis is useful for assessing the individual contribution of a particular soil property to a wood color characteristic, it does not consider the interrelationships and resulting effects that must occur among the soil properties. For example, alteration of the N level will not guarantee the predicted change in dominant wavelength according to the regression equation shown in Table 8. This is because N also affects the pH of the soil which could negate any change in the

TABLE 8. *"Best" equations for predicting the three color properties of black walnut*

Regression equation	Multiple coefficient of determination (R^2)	Standard deviation from regression
Luminance = 263.94 − 0.237 available P + 0.001 exchangeable Ca − 0.006 exchangeable Mg − 0.033 depth to mottling or impervious layer	0.5301**	± 1.276 (%)
Dominant wavelength − 587.39 + 1.16 pH − 0.01 exchangeable K + 4.63 total N	.4364**	± 0.75 (mμ)
Purity = 30.279 + 0.140 available P − 0.001 exchangeable Ca + 0.004 exchangeable Mg + 0.025 silt plus clay	.2960**	± 1.22 (%)

** Significant at the 0.01 per cent level of probability.

TABLE 9. *Color* changes over the range of variables for "best" equations*

Variable	Coefficient	Variable range (Δ)	Coefficient × Δ
		Luminance	
Depth	−0.237	27.67	6.5578†
P	.001	5,745	5.745†
Ca	− .006	1,082.6	6.4956†
Mg	− .033	54	1.782
		Dominant Wavelength	
pH	1.16	1.7	1.972
K	− .01	499.1	4.991†
N	4.63	.624	2.8891
		Purity	
P	.140	27.67	3.8738
Ca	− .001	5,745	5.745†
Mg	.004	1,082.6	4.3304
Silt and clay	.025	64.3	1.6075

* Luminance and purity are by per cent; dominant wavelength by millimicron.
† Soil properties resulting in color changes that could be visible to the unaided eye.

dominant wavelength. Such relationships between soil properties are not considered in the preceding analysis.

The importance of these data is the potential for estimating the color of walnut heartwood from a few relatively simple soil tests. If the techniques and the resulting data can be improved, perhaps by including minor elements such as Fe, Mg, Cu, and others, it may become feasible by manipulating soil properties to grow wood of a desired color.

SUMMARY

This study was concerned with the influence of soil and other physical and environmental conditions on the heartwood color of black walnut (*Juglans nigra* L.). This influence was studied within a 2 × 2 × 2 factorial design in which the factors were geographical location (Indiana and Missouri), site quality (good and poor), and diameter-growth rate (fast and slow). Thirty-two trees were selected, four trees for each factorial grouping. Soil properties examined included pH, organic matter content, texture, cation exchange capacity, major nutrients, and depth to mottling or impervious layer. Wood color properties studied were per cent luminance, dominant wavelength, and per cent purity, according to I.C.I. standards.

Greater differences between trees were found in luminance than in dominant wavelength and purity. Visually detectable differences were found between trees in luminance and purity, but not in dominant wavelength.

Mean tree luminance was significantly higher for the Indiana-grown trees than for the Missouri-grown, but the difference was not visually detectable. Color did not differ significantly between any other factorial groupings for any of the three color properties.

Regression analyses indicated that mean tree luminance was most highly related to available P, exchangeable Ca, exchangeable Mg, and depth to mottling or impervious layer; mean tree dominant wavelength, to pH, exchangeable K, exchangeable Ca, and total N; and mean tree purity, to available P, exchangeable Ca, exchangeable Mg, and silt plus clay content or texture. The results suggest that soil properties are associated with wood color independently of their effect on diameter-growth rate, and independently of tree age.

The findings of this study allow for the possibility of one day controlling wood color by manipulating soil properties.

REFERENCES

ARNON, D. I., AND C. M. JOHNSON. 1942. Influence of hydrogen ion concentration on the growth of higher plants under controlled conditions. Plant Physiol., **17**: 525–539.

BECKMAN INSTRUMENTS, INC. 1954. Instruction manual for Beckman Model B spectrophotometer and accessories. Fullerton, Calif.

BENFORD, L., G. P. LLOYD, AND S. SCHWARZ. 1948. Coefficients of reflection of magnesium oxide and magnesium carbonate. J. Opt. Soc. Amer., **38**: 445–447.

BLACK, C. A. et al. [eds.]. 1965. Methods of soil analysis. American Society of Agronomy, Madison.

BRAUNER, A. B., AND W. E. LOOS. 1968. Color changes in black walnut as a function of temperature, time, and two moisture conditions. Forest Prod. J. **18**: 29–34.

BREMNER, J. M., AND K. SHAW. 1958. Denitrification in soil: I. methods of investigation. J. Agr. Sci., **51**: 22–39.

CHAPMAN, H. D., J. H. AXLEY, AND D. S. CURTIS. 1941. The determination of pH at soil moisture contents approximating field conditions. Soil Sci. Soc. Amer. Proc., **5**: 191–200.

COREY, R. B. 1964. Cation exchange capacity. Lab. Inst. Soils 621, Soils Dep., Univ. Wis., Madison.

FREY-WYSSLING, A., AND H. H. BOSSHARD. 1959. Cytology of the ray cells in sapwood and heartwood. Holzforschung, **13**: 129–136.

HILLIS, W. E. [ed.]. 1962. Wood extractives, and their significance to the pulp and paper industries. Acad. Press, Inc., New York. 513 p.

INTERNATIONAL COMMISSION ON ILLUMINATION. 1931. Proc. of the 8th Sess., Cambridge, England.

JUDD, D. B. 1933. The 1931 I.C.I. standard observer and coordinate system for colorimetry. J. Opt. Soc. Amer., **23**: 359–374.

MOSLEMI, A. A. 1967. Quantitative color measurement for black walnut wood. U.S.D.A. Forest Serv. N. Cent. Forest Exp. Sta., Res. Paper NC-17.

SULLIVAN, J. D. 1967. Color characterization of wood: color parameters of individual species. Forest Prod. J., **17**: 25–29.

WALKLEY, A., AND J. A. BLACK. 1934. An examination of the Degtjareff method for determining soil organic matter and proposed modification of the chromic acid titration method. Soil Sci., **37**: 29–38.

WILDE, S. A., G. K. VOIGT, AND J. G. IYER. 1964. Soil and plant analysis of tree culture, 3rd ed. Oxford Publ. House, New Delhi.

WRIGHT, W. D. 1964. The measurement of color, 3rd ed. D. Van Nostrand Co., Princeton.