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## Laboratory Measurement of Soil Color: Theory and Practice

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### ABSTRACT

Determination of soil color is useful to characterize and differentiate soils. The color of soil materials can be measured in the laboratory by using diffuse reflectance spectrophotometers. The spectral reflectance data given by these apparatuses are easily converted to three figures ("tristimulus values") that define the color perceived by the human eye. In turn, tristimulus values can be converted to the Munsell notation or the parameters of other color systems. Modern, commercially available spectrophotometers not only allow a quick measurement of reflectance but usually provide color data in different systems. If care is taken in obtaining homogeneously granulated or powdered soil samples, and in preparing the white reflectance standards, high accuracy and precision are obtained. Small differences in soil color can then be used to identify and study differences in soil compositional properties. For this purpose, several "color indices" calculated from the color data can also be used.

Since color is one of the most useful attributes to characterize and differentiate soils, its adequate determination has importance in many soil studies. Routine determination of soil color in the field is usually accomplished by visually comparing a soil sample with the chips of standard color charts, of which the Munsell Soil Color Charts (Munsell Color Co., 1975) are the most familiar to pedologists. Owing to several psychophysical and physical factors, substantial errors are involved in this visual, subjective method. Consequently, in the last decades, soil scientists have made use of field and laboratory instruments that make more objective, precise, and accurate soil color determinations possible.

Instrumental characterization of the appearance of soils in the field has often been carried out by using remote sensors, such as those aboard satellites. Remote sensors provide information about properties at the soil surface. These are partly a function of the soil composition, but also reflect the microrelief, structure, and other properties of the "surface state" (Escadafal, 1989). In contrast, laboratory measurements of soil color have usual-

ly been made on small amounts of disturbed soil materials, In this case the color data reflect the soil composition, but not the in situ organization or anisotropy of the soil materials.

This chapter describes the basic principles and the experimental procedures involved in the laboratory measurement of the color of soil materials. It also deals with how spectrophotometric and color data can be handled and transformed to suit different purposes.

## SPECTRAL REFLECTANCE PROPERTIES OF SOILS

The manner in which light interacts with objects has been described by several workers (Hunter, 1975; Judd & Wyszecki, 1975; Wyszecki & Stiles, 1982). In the case of granulated or powdered soil materials, a small fraction of the incident light is reflected specularly (i.e., reflected as from a mirror). A major portion of the beam penetrates into the soil mass where it encounters many surfaces of mineral and organic particles. At these surfaces the beam undergoes multiple reflection and defraction. This process diffuses the light and returns part of it to the surface of the mass, where it leaves in all directions, giving rise to what is called *diffusely reflected light* (the process of diffusing the light is called *scattering* (Hunter, 1975)). The color of this light results from the ability of the different soil components to absorb more light in some wavelengths than others.

The diffuse reflectance properties of a soil can be described by spectrophotometric curves which show the *spectral reflectance*,  $\rho_\lambda$ , for each wavelength,  $\lambda$ . The spectral reflectance can be defined as the ratio of the spectral radiant flux reflected in a solid angle of  $2\pi$  (hemisphere above the test object) to the spectral radiant flux reflected by a perfectly reflecting diffuser that is identically illuminated. By definition, the perfectly reflecting diffuser reflects all the incident radiating flux in all directions (Judd & Wyszecki, 1975).

The primary instruments for obtaining spectral reflectance curves are spectrophotometers, which will be dealt with later. For the study of soil color *sensu stricto*, the spectral curve for the visible spectrum (from about 400–700 nm) is obtained. The 400 to 700 nm curve usually has a positive slope and differs markedly from soil to soil (Fig. 2-1). Laboratory measurements for both the visible and the near-infrared range (400–2250 nm) are also carried out (e.g., Stoner et al., 1980; Escadafal, 1989), because they may offer valuable information on soil composition.

## SPECIFYING SOIL COLOR

### Computation of the Commission Internationale de l'Eclairage Tristimulus Values

The color of a soil sample depends not only on its reflectance properties but also on the spectral distribution of the illuminating light. Hence, the radiant energy leaving the sample at a narrow wavelength band,  $d\lambda$ , is given by

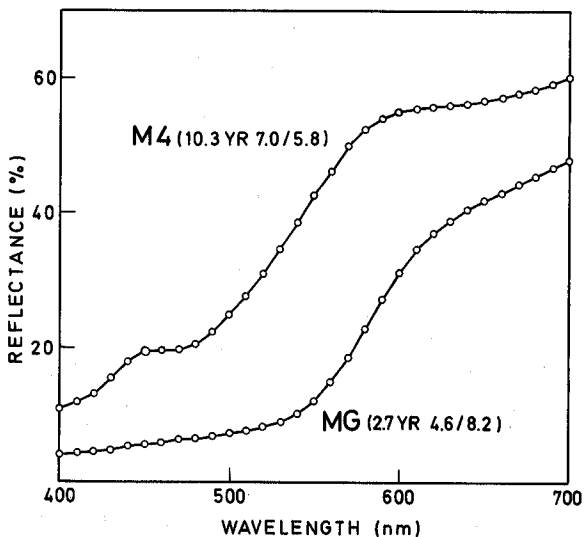


Fig. 2-1. Visible (400-700 nm) spectral reflectance curves of two ground soil samples. M4: yellow B horizon of a Palexeralf; MG: red B horizon of a Haplustox.

$$dS_{\lambda} = \rho_{\lambda} E_{\lambda} d\lambda \quad [1]$$

(Hunter, 1975) where  $\rho_{\lambda}$  is the spectral reflectance and  $E_{\lambda}$  is the energy of the light source at the wavelength ( $\lambda$ ). The  $S_{\lambda}$  spectral distribution curve describes the light that reaches the observer. The human eye, however, does not perceive the  $S_{\lambda}$  curve as such; experiments carried out more than one century ago showed that the eye has three different color-response mechanisms. In a psychophysical sense, the color is identified by three color stimuli. A *color stimulus* is radiant energy of given intensity and spectral composition entering the eye and producing a sensation of color (Judd & Wyszecki, 1975). Research in colorimetry at the beginning of this century was focused on finding three spectral curves able to convert any spectrum to three stimuli. The three spectral curves (*color matching functions*) that are currently used were defined by the Commission Internationale de l'Eclairage (CIE, 1931) for the so-called 1931 CIE Standard Observer (Fig. 2-2). The color of an object is then described by integrating the spectral reflectance, and each of the color-matching functions ( $\bar{x}$ ,  $\bar{y}$ ,  $\bar{z}$ ) of the Standard Observer.

$$X = \int_{400}^{700} \rho_{\lambda} E_{\lambda} \bar{x}_{\lambda} d\lambda \quad [2]$$

$$Y = \int_{400}^{700} \rho_{\lambda} E_{\lambda} \bar{y}_{\lambda} d\lambda \quad [3]$$

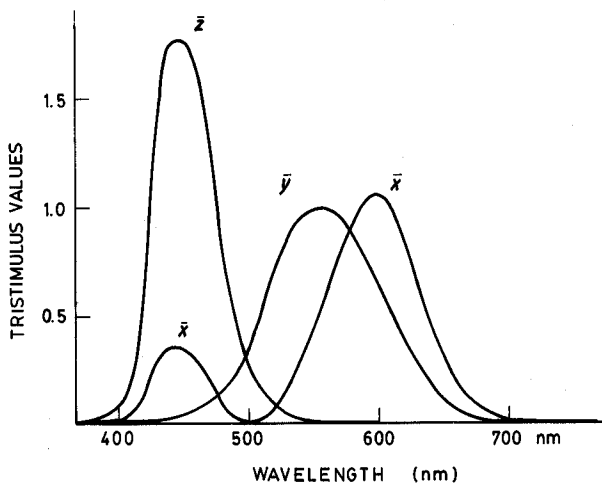


Fig. 2-2. The  $\bar{x}$ ,  $\bar{y}$ , and  $\bar{z}$  color matching response functions of the 1931 CIE Standard Observer. The curves refer to relative amounts of imaginary red, green, and blue light mixed to match each wavelength test color.

$$Z = \int_{400}^{700} \rho_{\lambda} E_{\lambda} \bar{z}_{\lambda} d\lambda \quad [4]$$

where  $X$ ,  $Y$ , and  $Z$  are the *tristimulus values*. The  $Y$  tristimulus value gives the information on lightness, because, by definition, the  $Y$  for perfect white is always 100%. The  $X$  and  $Y$  tristimulus values are converted to the *chromaticity coordinates*,  $x$  and  $y$ , by the formulae

$$x = X/(X + Y + Z) \quad y = Y/(X + Y + Z). \quad [5]$$

Neither  $x$  nor  $y$  correlate directly with any of the meaningful attributes of color appearance. However, in graphs using  $x$  and  $y$  as axes (chromaticity diagrams) the spectral colors form a horseshoe-shaped curve within which all color stimuli fall.

The CIE tristimulus values are easily computed by multiplying, at each wavelength, the spectral reflectance values by the  $\bar{x}$ ,  $\bar{y}$ , and  $\bar{z}$  functions and the spectral curve of the illuminant. The values of the product of  $\bar{x}$ ,  $\bar{y}$ , and  $\bar{z}$  by the spectral curve of the illuminant have been tabulated for several illuminants and different wavelength steps in the 380 to 830 nm range (Wyszecki & Stiles, 1982). Computations can be carried out manually by taking 10-nm steps. Many modern spectrophotometers do this automatically in smaller steps.

It is evident, from Eq. [2] through [4], that the tristimulus values of any object depend on the type of illuminant (i.e.,  $E_{\lambda}$  distribution) used. Conversely, two objects having different reflectance spectra may match under a first illuminant but not under a second. This phenomenon (*metamerism*) (Judd & Wyszecki, 1975) is sometimes experienced by soil scientists who observe that a soil matches a chip of a soil color chart under daylight but not

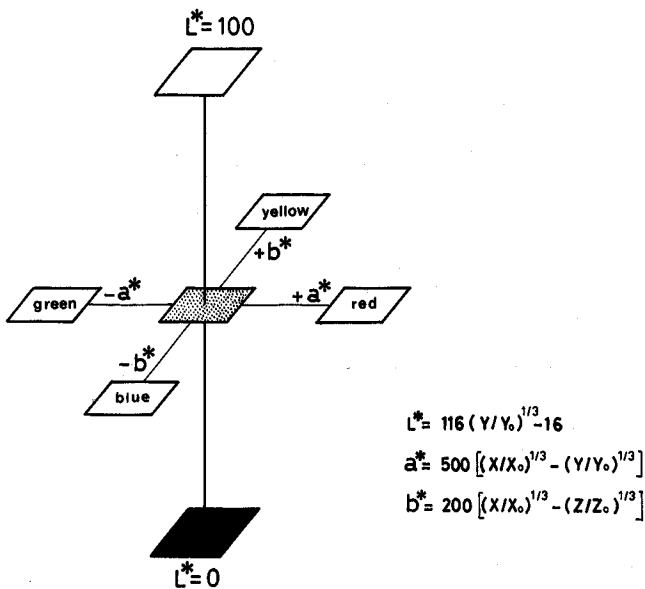


Fig. 2-3. Arrangement of color attributes in the CIE 1976 ( $L^*$   $a^*$   $b^*$ ) color space.

under a fluorescent lamp in the laboratory. Several illuminants were established by the CIE in 1931 (A, B, and C) and 1966 (D series). Many color specifications are in terms of appearance under illuminants C and D65 (“day-light”) (Judd & Wyszecki, 1975).

### Soil Color in Different Systems

The CIE  $x$ ,  $y$ , and  $Y$  values define a space in which the colors achievable under a certain illuminant occupy a *color solid* of well-defined limits. Although the CIE color scales provide an accurate tool to identify color stimuli, the distances between two colors (i.e., between two points in the color space) are poorly correlated with visual differences. For this reason, many attempts to develop psychologically “uniform” color scales have been made since 1931. These color scales are generated by mathematical transformation of the original CIE color space. A detailed description of these scales is given by Wyszecki and Stiles (1982). The recent CIE 1976 ( $L^*$   $a^*$   $b^*$ ) space (CIE, 1978) should be mentioned, because it provides a good way to visualize color: the  $L^*$  axis represents lightness, the  $a^*$  axis redness-greenness, and the  $b^*$  axis yellowness-blueness (Fig. 2-3). This system appears to be promising for soil color description (Melville & Atkinson, 1985) but it has rarely been used for this purpose.

The Munsell system is, by far, the most familiar to soil scientists. This system was published as a book with 40 pages of colored chips, the *Munsell Book of Color* (Munsell Color Co., 1929), and it was designed so that differences in adjacent chips were seen to be equal. The Munsell color solid is cylindrical (Fig. 2-4) and is based on three attributes: (i) hue (H), that is, the

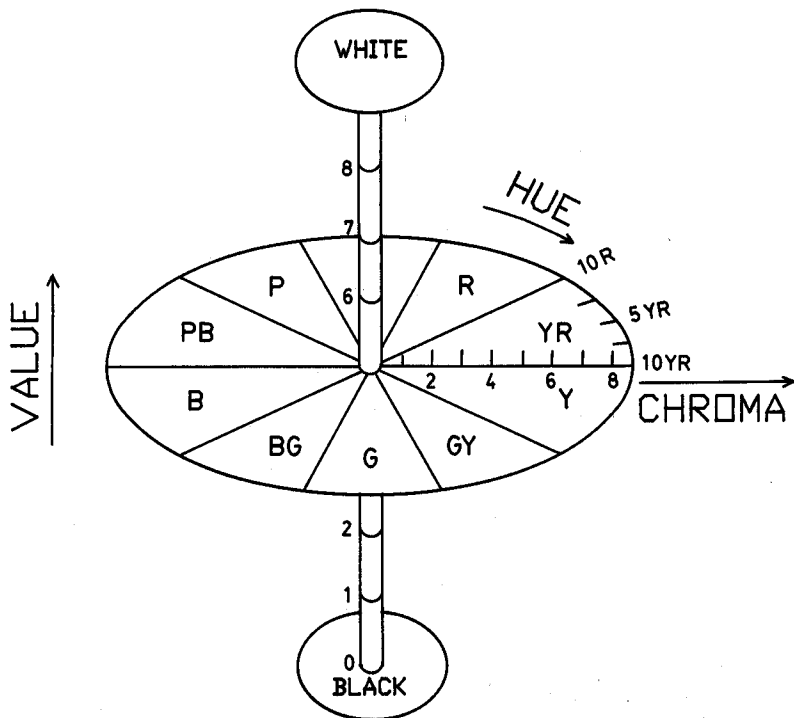


Fig. 2-4. Arrangement of hue, value, and chroma in the Munsell color space.

attribute of color perception denoted by blue, green, red, yellow, and so on; (ii) value (V), representing the lightness, and (iii) chroma (C), that is, degree of difference from black-white or neutral color. Stated somewhat differently, hue is the angular displacement from an arbitrary position, value is the vertical distance to the basal plane (pure black) of the solid, and chroma is the distance to the central black-white axis. The *Munsell Book of Color* was designed to geometrically follow this system of cylindrical coordinates: each book page has chips of the same hue, and the value and chroma of the chips of each page increase from the bottom to the top, and from the left to the right, respectively. The Munsell Soil Color Charts (Munsell Color Co., 1975), including supplementary charts, consist of 10 pages for hues of 5R, 7.5R, 10R, 2.5YR, 5YR, 7.5YR, 10YR, 2.5Y, and 5Y plus the GLEY page (5Y, 5GY, 5G, 5BG, and 5B), that represent different combinations of red (R), yellow (Y), green (G), and blue (B).

The conversion of tristimulus values (referred to CIE standard illuminant C) to Munsell parameters can be easily done because, in the so-called Munsell Renotation System (Newhall et al., 1943), equivalences were established between the Munsell colors and the Y, x, and y CIE values. Conversion is carried out with the help of tables and graphs (ASTM, 1980) or ad hoc computer programs (Fernandez & Schulze, 1987).

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The Munsell System was designed to be a uniform color space. The renotation effort carried out in the 1940s gave good instrumental data on the visually uniform spacing of color. For these reasons, the system has been widely used and has become familiar, not only to soil scientists, but also to many other color observers in science and industry.

## INSTRUMENTAL MEASUREMENT OF SOIL COLOR

### Instrument Types

Diffuse reflection meters have a built-in illuminating device with a source emitting radiant flux at wavelengths of interest (usually from 360–400 to 700–780 nm). For opaque objects, such as soil materials, the incident flux meets the object at a direction close to the perpendicular of the object surface. The reflected flux is sometimes sampled in a few directions only. More frequently, the flux is collected by a white spherical surface (integrating sphere). For some purposes, other geometric conditions are used. The reflected light goes then to a detecting device and the information is processed.

To measure color, two types of instruments operating according to the former principles are used. These are photoelectric tristimulus colorimeters and spectrophotometers. The former have a source-filter-photodetector combination that simulates the CIE Standard Observer functions. Most of the commercially available instruments are precise, easy and fast to operate, and the specimen area that can be viewed is usually large (up to several centimeters). They are, however, relatively inaccurate in the sense that tristimulus values read by these instruments do not usually agree with tristimulus values calculated from spectral reflectance data. In addition, only tristimulus values corresponding to the built-in illuminant (generally C or D65) can be obtained.

Spectrophotometers have wavelength isolation systems, such as gratings, prisms, or systems of filters that provide the true reflectance spectrum of the sample; however, the wavelength-band pass and wavelength accuracy varies widely from the more simple to the more sophisticated models. Both single- and double-beam instruments are available. The first spectrophotometer specifically developed for color measurement was introduced by the General Electric Company<sup>1</sup> in 1928 and has been the reference instrument for several decades. Many of the instruments used for soil color measurements have been transmission spectrophotometers equipped with a reflectance attachment. For instance, Shields et al. (1966) and Torrent et al. (1983) used a Bausch and Lomb Spectronic 20 (Bausch & Lomb, Rochester, NY), Barrón and Torrent (1986) used a Perkin-Elmer Lambda 3 (Perkin-Elmer Corp., Norwalk, CT), and Fernández and Schulze (1987) used a Cary 17 DX

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<sup>1</sup> Mention of trade names is solely for the information of the reader and does not constitute any endorsement by the Universidad de Córdoba over comparable products that are not named.

(Varian Assoc., Instrumentation Group, Sunnyvale, CA). The spectral reflectance data obtained with spectrophotometers are converted to CIE tristimulus values manually or with the help of appropriate software in external or built-in computers. In the last case, color data are obtained in a short time.

Different spectrophotometers that are specifically designed for color measurement are available commercially. Selection must be made taking into account, among other things, precision, accuracy, and the fact that some models give the color data in several systems but do not provide the internally generated reflectance data. Recent models incorporate a flash illuminating system for the simultaneous detection of reflectance in a large number of wavelength bands. For example, the Macbeth Color-Eye 7000 (Macbeth Division of Kollmorgen, Newburgh, NY) has a holographic grating system for 40 bands (10 nm band pass, from 360–750 nm), with a 40-element detector array. Readings are given in  $< 1$  s.

### **Preparation of Reflectance Standards**

The ideal standard, a perfect diffusing, perfect reflecting surface is unattainable in the form of a material standard. In actual spectrophotometric measurements, reference "white standards" are used. For many years, a surface of smoked MgO was adopted as a reference white. At present, pressed MgO or BaSO<sub>4</sub> powders are the most common standards. Both Barrón and Torrent (1986) and Fernández and Schulze (1987) used the latter for soil color measurements. Eastman White Reflectance Standard (Eastman Kodak Co., Rochester, NY) and Merck White Standard DIN 5033 (E. Merck, Darmstadt, Germany) are two of the commercial BaSO<sub>4</sub> white standards, with reflectance values of about 0.98 for the 400 to 700 nm range.

The BaSO<sub>4</sub> or similar powder needs to be carefully packed in the corresponding sample holder. A detailed description of the operating procedure is given by Fernández and Schulze (1987). For most holders  $< 1$  g of BaSO<sub>4</sub> is needed. Thus, it is relatively inexpensive to use, not only as the reference standard, but also as the working standard for daily operations. The use of other secondary working standards (glazed ceramic tile, opal glasses, etc.), which are calibrated against a master standard, is more economical. Frequent recalibration is needed, however, since dust, humidity, exposure to ultraviolet radiation and so forth affect the reflecting properties of these materials.

### **Preparation of Soil Samples**

The manner in which a soil sample is prepared markedly affects color values determined. At present no standard method of preparation has been adopted by soil scientists, making it difficult to compare the results obtained by different authors. Perhaps the only common point is that color is measured using disturbed,  $< 2$  mm or finer, soil materials. To the authors' knowledge there have been no attempts to characterize the color of small, undisturbed soil fragments with the help of diffuse reflectance spectrophotometers. Factors such as specular reflection on ped faces and the presence of



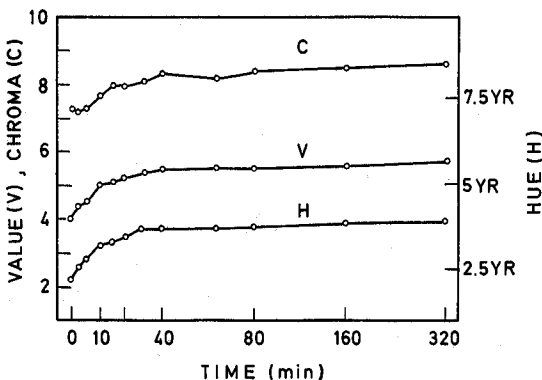


Fig. 2-5. Time course of change in Munsell hue, value, and chroma for the B horizon of a Rhodic Haploxeralf ground in a ball mill.

nonplanar surfaces would affect the reproducibility and the interpretation of data.

The size to which a soil sample should be ground to obtain reproducible reflectance readings depends on the size of the viewing field of the apparatus. Some tristimulus colorimeters permit measuring the color of areas of more than 20 cm<sup>2</sup>. Díaz and Torrent (1989) used a Hunterlab D25 apparatus (Hunter Associates Lab., Inc., Reston, VA) and obtained good reproducibility for <2 mm soil samples placed in containers 5 cm in diameter. For spectrophotometers having viewing fields of 10s of square millimeters, the samples should be thoroughly ground to obtain reproducible results. For soil samples passed through a 35 mesh (500  $\mu$ m) sieve, and using a Bausch and Lomb Spectronic 600 with a reflectance attachment, Shields et al. (1968) found standard deviations of <0.5, 0.1, and 0.1 for Munsell hue, value, and chroma, respectively. Fernández and Schulze (1987) passed soil samples through a 60-mesh (250  $\mu$ m) sieve and found differences between duplicate measurements of <0.2 units for Munsell hue, value, and chroma using a Cary 17 DX spectrophotometer.

Grinding causes dramatic changes in soil color. This is illustrated in Fig. 2-5 for the case of a soil sample ground in a ball mill for different periods of time. The most conspicuous change is the increase in lightness (represented by Munsell value), in accordance with color theory. The changes in the color attributes are fast in the first few minutes but reach nearly constant values after 40 to 60 min. For this reason, Barrón and Torrent (1986) adopted a standard grinding time of 1 h when a ball mill was used to grind the samples. In practice, the same color was obtained when 0.5 g of soil were vigorously hand-ground in an agate mortar for about 10 min.

The former results point to the need for careful standardization of the grinding procedure if results between different laboratories are to be compared. Even routine grinding to pass a 2-mm sieve can give products having different colors, depending on the operating conditions. When only a com-

parison among samples is to be carried out, any grinding procedure can be used, provided that it is exactly the same for all the samples.

Some spectrophotometers have reflectance attachments with vertical sample or horizontal ports that are placed on top of the integrating sphere. This makes it impossible to measure the color of loose powders without the powder falling and damaging, sometimes irreversibly, the integrating sphere. Shields et al. (1966) and Torrent et al. (1983) solved the problem by inverting the Bausch and Lomb Spectronic 20 used in their measurements. In other cases, careful packing of the powder may maintain sample integrity. If none of these solutions is possible, a cover glass must be used. The color measured through a cover glass usually differs little, but not negligibly, from the color measured directly (Shields et al., 1968). The differences can be substantial, and the reproducibility poor, when large air-glass interfaces are present. Careful corrections need to be made when the "true" color of the sample is required. For purposes of comparing samples having similar particle size, the use of cover glasses does not constitute a major problem.

Spectrophotometric determinations of soil color have been mostly carried out on dry samples. In contrast, moist color is the one most commonly determined in the field. Although differences between dry and moist colors give useful information for several purposes, the preparation of moist soil samples poses more problems than that of dry ones. An excess of moisture causes unwanted specular reflection and can create glass-water interfaces when cover glasses are used. Evaporation from the surface of moist, pressed powders during measurement can influence readings. For this reason, even when extreme care is taken, the reproducibility is not so good as for dry samples (Fernández & Schulze, 1987). It is fortunate that the color of many soils does not vary much within a certain moisture interval when the soil is drier than field capacity. Shields et al. (1966) found no significant change between 20 and 40% moisture for chernozemic soils; this interval, however, may be different for other soil types.

## **INSTRUMENTAL VERSUS VISUAL MEASUREMENTS IN THE LABORATORY**

When spectrophotometers are not available, one should take into account that visual evaluation of soil color in the laboratory, if several conditions are met, can be reasonably accurate and precise.

Visual evaluation of color requires the control of: (i) the spectral quality, intensity, and angular size of the light source; (ii) the incident and viewing angles; and (iii) the background. The ASTM (1980) method provides a detailed description of how visual matching with Munsell chips should be done under natural light. The estimated precision of the method for one person is 0.5 units of hue, 0.1 units of value, and 0.1 units of chroma. When artificial "daylight" is used the precision improves. For this purpose, permanent or portable chambers having an adequate geometry and equipped with several illuminants, are commercially available.

Visual estimation of color depends highly on the observer (Wyszecki & Stiles, 1982). Consequently, more than one observer is required to have accurate results. Torrent et al. (1983) reported the results of visual measurements for 100 soil samples and six observers. When outlying observations were discarded, the standard deviation ranges (averages) were 0 to 1.3 (0.5) units for Munsell hue, 0 to 0.5 (0.2) units for value, and 0.1 to 1 (0.4) units for chroma. Although these figures are by no means disappointing, the need for several observers makes visual estimation of soil color time-consuming and, sometimes, impracticable.

## TRANSFORMATION OF SPECTRAL REFLECTANCE AND COLOR DATA

Color and spectral reflectance data can be used in different ways or mathematically manipulated to yield data useful for several purposes. A few examples follow.

1. As mentioned before, a complete description of a soil color requires three parameters, irrespective of the color system used. However, only one or two of these parameters can give useful information on soil composition. For example, Fernández et al. (1988) found that Munsell value was correlated with organic matter content in some soil landscapes.

Empirical color indices that combine the three parameters are also useful. Torrent et al. (1980) modified the index suggested by Hurst (1977) to give a "redness rating" (RR) according to

$$RR = [(10 - H) C]/V \quad [6]$$

where  $V$  and  $C$  are the numerical values of the Munsell value and chroma, respectively, and  $H$  is the figure preceding YR in the Munsell hue so that, for 10 YR,  $H$  is 10 and, for 10 R,  $H$  is 0. This RR has been used to obtain semiquantitative measurements of hematite in soils (Torrent et al., 1983; Torrent & Cabedo, 1986; Kemp, 1985; Boero & Schwertmann, 1987). Two additional redness indices, based on the  $Y$ ,  $x$ , and  $y$  chromaticity coordinates and the CIE 1976 ( $L^* a^* b^*$ ) system were tested by Barrón and Torrent (1986).

2. Derivative spectroscopy is a technique that can be used to magnify the fine structure of spectral curves. The second derivative, which enhances minor convexities and concavities of the original reflectance spectrum, has been employed by Kosmas et al. (1984) to estimate small amounts of goethite in a mixture with kaolinite and in an Oxisol.

3. The Kubelka-Munk theory, which was developed for pigment mixtures (Kubelka & Munk, 1931) can be applied to soils (Barrón & Torrent, 1986). Basically, the theory establishes that the behavior of a pigment mixture with respect to incident light of wavelength  $\lambda$  can be characterized by two coefficients:  $K_\lambda$  (absorption) and  $S_\lambda$  (scattering). The solution of the Kubelka-Munk equation for thick ("opaque") layers indicates that the  $K$  and  $S$  values of a pigment mixture can be obtained from the reflectance values

of two or more mixtures of this pigment mixture with a white standard. It has been shown, in addition, that the  $K$  and  $S$  values of a pigment mixture are simple additive functions of the  $K$  and  $S$  values of the constituent pigments weighted in accordance with the proportion of each pigment. Thus, the theory permits one to predict the effect of a known soil pigment (e.g., hematite) on soil color, or vice versa, to calculate the proportion or the color of a soil pigment from soil reflectance data. Details on the calculation procedures are given by Barrón and Torrent (1986).

## CONCLUSION

Soil color can be easily measured in the laboratory with the help of tristimulus colorimeters or diffuse reflectance spectrophotometers. Commercially available instruments give accurate and precise measurements of the color parameters of the spectral reflectance data, provided the white standards and soil samples are carefully prepared. The color of a soil material depends, among other factors, on the degree of grinding and moisture content. Consequently, a standard procedure for sample preparation must be used when color measurements in different laboratories need to be compared. Spectral reflectance data can be transformed (either manually or by adequate computer programs) not only to the Munsell color notation, but also to color parameters in other systems. Simple "color indices" derived from color parameters are useful for the study of soil composition. Special techniques, such as derivative spectroscopy or the application of the Kubelka-Munk theory can also be used for this purpose.

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