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MODELING THE RELATIONSHIPS BETWEEN MUNSELL SOIL COLOR AND SOIL SPECTRAL PROPERTIES

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Commission V.

5th Symposium of the Working Group Remote Sensing

'REMOTE SENSING IS A TOOL FOR SOIL SCIENTISTS'

Budapest, Hungary

11—15 April, 1988

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ABSTRACT

A new approach of the relationships between soil color and soil spectral properties is studied using colorimetric concepts. Spectral reflectance of 84 highly varied soil samples were determined in the laboratory with a spectrophotometer. Colors were also visually estimated using Munsell soil color charts. The comparison between chromaticity coordinates computed from the spectral reflectance curves, and Munsell color converted into the same coordinates, showed good agreement. Thus, the color aspect of a soil sample can be predicted from its spectral reflectance. Usually the reverse is not true, as two objects with the same color aspect may have different reflectance curves. This phenomenon, known as *metamerism*, was observed only once among our soil samples. This allowed to use a multiple linear regression model to predict the visible reflectance curve from the Munsell color. With these results, soil spectral properties can be estimated from colors noted in the field. This has numerous applications in remote sensing.

INTRODUCTION

Many vernacular names of soils are related with color. This applies as well to the scientific names derived from them ; see chernozem, for instance, which means black earth.

Color has been chosen as a classifying criterium by a great number of classification systems, and quite often right from the second hierarchical level, that is the sub-class, the major group or the sub-group, depending on the system. As is the case with some regional soil classifications (SEGALEN, 1977).

From a detailed statistical analysis of pedological information, GIRARD M.C. (1983) showed that 3 out of the 15 variables sufficient to characterize a sample volume were concerned with color.

Several authors have looked into the methodology for the evaluation and measurement of soil color, and their consequences on the part played by this criterium in classifications (SHIELDS et al., 1966 ; KARMANOV, 1970 ; MELVILLE and ATKINSON, 1985).

In the meantime, the study of the relationships existing between soil spectral properties and soil composition has developed (GERBERMANN and NEHER, 1979 ; KRISHNAN et al., 1980 ; STONER et al., 1980). Moreover, the influence of soil color on the measurements obtained by remote sensing has focused increasing interest and has been the subject of very recent studies (GIRARD, 1985 ; HUETE et al., 1984 ; COURAULT, 1986 ; ESCADAFAL and POUGET, 1986).

Using the concepts and the results already reported in French elsewhere (ESCADAFAL et al, 1988), this paper aims at clarifying the physical nature of the relationships between spectral reflectance, colorimetric measurements and soil color evaluated on the field.

A - ELEMENTS OF COLORIMETRY APPLYING TO SOILS

Every individual has his own system of reference in terms of color, and "red", "purple" or "dark brown" may represent quite different realities depending on the observer, to say nothing of all the nuances that may be added.

The purpose of colorimetry is precisely to establish the relationship between visual perceptions and the physical characteristics of the objects and of the light which gives them shape, by stating certain conventions and conditions of application.

It is to NEWTON that we owe the first research on light and the nature of colors. He showed that white light was nothing but a balanced mixture of all colors, each of them having a specific and stable character.

This first principle demonstrates that the color of an object depends in particular on the way it reflects the light depending on whether it reflects more or less certain parts of the spectrum, it will have a color or another.

This property of light reflection according to the wavelength is the spectral reflectance.

1 - The R,G,B trichromatic system

When MAXWELL showed that any color could be reproduced by mixing three other colors, he laid the foundations of the trichromatic system, further completed and summarized by GRASSMAN into the three following rules :

- two lights of very different spectral composition may produce identical color sensations,
- therefore the reasoning must bear on the color aspect and not on the real composition of light,
- all colors may be reproduced by adding three independent colored lights referred to as primary colors. By definition, a primary color cannot be reproduced by mixing the two others.

In the trichromatic system so defined, colors may be reproduced by vectors, of which they have all the properties, such as additivity, in particular.

By experience, the set of primary colors which allow to reproduce most of them has proved to be red, green and blue. The Commission Internationale de l'Eclairage (C.I.E., 1931) has normalized this Red, Green, Blue system by adopting the following wavelengths :

$$\lambda(R) = 700 \text{ nm}$$
$$\lambda(G) = 546 \text{ nm}$$
$$\lambda(B) = 436 \text{ nm}$$

They were chosen according to the results of empirical tests showing that it was this set that allowed to reproduce the widest range of colors.

In this system, any color "$\vec{C}$" can be represented by its r,g,b coordinates within the R,G,B cartesian system :

$$\text{(I)} \qquad \vec{C} = r\,.\,\vec{R} + g\,.\,\vec{G} + b\,.\,\vec{B}$$

The units are chosen so that white is obtained when $r = g = b = 1$. The median axis then corresponds to the grey axis (from black to white), which is the achromatic axis.

The colored sensation curves for an average observer, also called mixing functions, represent the red, green and blue percentages to be mixed in order to obtain the sensation corresponding to each monochromatic radiation of the visible spectrum. A negative term r clearly appears with a minimum about 510 nm (fig. 1).

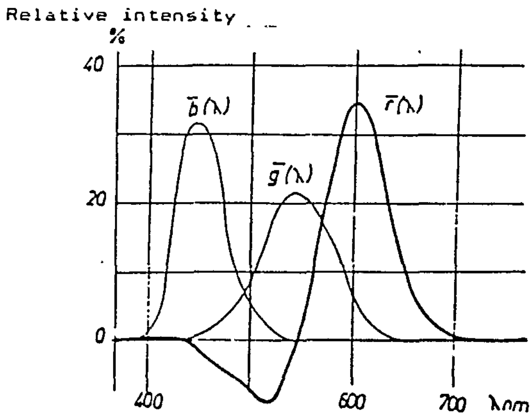

Fig. 1 -*Reproducing monochromatic colours by mixing red, green and blue (colour matching functions of the C.I.E. standard observer - 1931).*

The existence of the colored sensation curves constitutes the very basis of colorimetry and has important consequences, as explained below.

a) Computation of an object color

Since these curves allow to compute the R,G,B components of any theoretical object with monochromatic reflection capacity, by applying the laws of additivity, it is possible to compute these same components for a real object of any reflectance curve. The latter is then considered as the sum of the elementary monochromatic reflectance values on the set of the visible spectrum wavelengths.

This is what is expressed in the following equations :

(II)

$$R = k \int_{380nm}^{770nm} C(\lambda) \, . \, H(\lambda) \, . \, \bar{r}(\lambda) \, d\lambda$$

$$G = k \int_{380nm}^{770nm} C(\lambda) \, . \, H(\lambda) \, . \, \bar{g}(\lambda) \, d\lambda$$

$$B = k \int_{380nm}^{770nm} C(\lambda) \, . \, H(\lambda) \, . \, \bar{b}(\lambda) \, d\lambda$$

with $C(\lambda)$: spectral reflectance
$H(\lambda)$: light flux

Thus, by convolution of the three mixing functions ($\bar{r}$, $\bar{g}$, $\bar{b}$) with the reflectance curve of an object, one can compute the colored sensation it produces under a given light.

In order to normalize the observing conditions, the C.I.E. has defined the spectral distribution curves of energy for different types of light sources. These are the standard illuminants including, in particular, the C type for daylight, which was defined in 1931, and the D65 type, more recently recommended. The charts used in colorimetric computation often refer to them (WYSZECKI and STILES, 1982).

In short, an object with given spectral properties under a light of given composition, will appear to the average observer under one and only one particular color, which can be determined by computation.

b) Metamerism

This term denotes the phenomenon by which objects of different spectral properties can produce the same colored sensation.

Thus, an object that is highly reflectant in the red and green, will appear yellow, as well as an object reflectant in the monochromatic yellow wavelengths.

In order that two objects appear with to be the same color, their reflectance curve must be such that the equations (II) satisfy these relations :

$$\text{(III)}\quad R = k \int_{380nm}^{770nm} C1(\lambda)\ .\ H1(\lambda)\ .\ \bar{r}(\lambda)\ d\lambda \quad = k \int_{380nm}^{770nm} C2(\lambda)\ .\ H2(\lambda)\ .\ \bar{r}(\lambda)\ d\lambda$$

the same applying to G and B.

This system of equations is quite complex to solve and the conditions of metamerism are still being subject to practical and theoretical studies (Ch. GOILLOT, oral communication, 1987).

As concerns the practical consequences of this phenomenon, it is worth mentioning that two colors are usually metameric under a given light H(λ). In this case, the system of equations (III) is simplified, the only different term between the two sides of the equation being the spectral reflectance C(λ).

The most interesting illustration of the subject we are concerned with, is the case of the color samples from the Munsell charts. They are elaborated from mixed pigments reproducing a colored sensation. The reflectance curve of the Munsell sample 10 YR 6/6 (yellow brown) for instance, is clearly different from that of a soil which appears in this color under daylight (fig. 2). These two curves are metameric under this light, which they are probably not under another light.

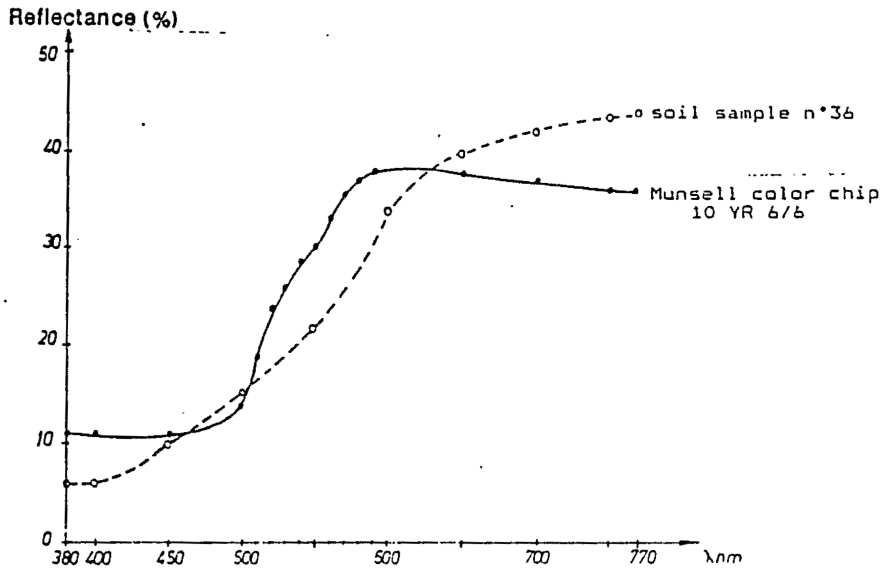

Fig. 2-*Example of the reflectance curves of a soil sample and of its corresponding Munsell color chip.*

Thus, the notation of a soil sample color obtained by comparison between the Munsell charts under artificial light can give quite different results from those obtained on the field.

According to color chroma, there exists a more or less great number of possible metamers. By definition, monochromatic colors can only correspond to one reflectance curve ; contrary to white which can be produced by a great number of different spectral reflectance curves.

In the range of soil colors, which are relatively little saturated, one can predict a high degree of metamerism. Highly elaborated computation methods have been developed (TAKAHAMA and NAYATANI, 1975), which permit, in particular, to predict the number of metamers for a given color.

As far as we are concerned, one of the most important practical results is the fact that the reflectance curves of objects whose colors are metameric must necessarily intersect. The theoretical study of this aspect was conducted in particular by simuration (OHTA and WYSZECKI, 1977) revealing 3 intersects, and most often 4 or 5.

2 - The color notation system of the C.I.E.

The fact that the R,G,B system underlying the scientific study of colors. uses negative colors is a disadvantage. For convenience sake, the C.I.E. proceeded to a system change, in order to facilitate computation, by defining the trichromatic components X,Y,Z :

$$\text{(IV)} \quad \begin{aligned} X &= 2.7659\,R + 1.7519\,G + 1.1302\,B \\ Y &= R + 4.5909\,G + 0.06012\,B \\ Z &= 0.0565\,G + 5.5944\,B \end{aligned}$$

These components were chosen so that Y corresponds to the brightness according to its definition, consequently X and Z have no physical reality

The trichromatic coordinates x,y,z are deduced from (IV) according to the relation :

$$\frac{x}{X} = \frac{y}{Y} = \frac{z}{Z} = \frac{1}{X+Y+Z}$$

Then, a given color is most often identified by its component Y and its coordinates x and y. This system of notation is the international scientific system currently in use. However, in the following, we have given preference to the R,G,B notation, which appears to describe colors in a more physical.sense.

B - Colorimetric study of a series of various soil samples

1 - Color computation according to spectral reflectance curves

Colorimetric computation is based on the determination of the spectral reflectance curve of the studied objects. This can be performed in the laboratory on 1 cm2 samples, by means of a spectrophotometer.

By definition, reflectance is the hemispheric reflectivity, therefore, the method standardized by the C.I.E. uses an integrating sphere, in order to eliminate any parasitic radiance and perform precise measurements.

This method is used in industry and in the laboratories for all kinds of colorimetric determination, it has already been applied to soils (SHIELDS et al., 1966) and to rocks (CERVELLE et al., 1977).

In this work, we have studied the reflectance curves of a set of 84 soil samples of very different color and composition.They were measured with a DK2 Beckmann spectrophotometer on air-dried and 2-mm sieved samples placed in glass covered boxes.

All the reflectance curves of these samples have in common the characteristic of always being regular and increasing in the visible spectrum. The slope is generally slow at the beginning, and can steadily or suddenly increase afterwards, and finally bend or not. In all cases, the slope is never negative (increasing monotonous function, in the largest sense).

These observations come close to those made by COMBE (1984) and TRAUBE (1985). Similarly, CONDIT (1970), who analyzed statistically the reflectance curves of 285 samples representing a wide range of soils in the U.S.A., showed that the observed curves were all increasing in the visible range.

By applying the colorimetric laws, it is possible to compute the color corresponding to each curve and obtain the X,Y,Z coordinates for each soil sample under a given light. So did we, by using the charts providing the values of $H(\lambda).\bar{x}(\lambda)$, $H(\lambda).\bar{y}(\lambda)$, and $H(\lambda).\bar{z}(\lambda)$ for the C-illuminant, according to a 10 nm step (WISEZCKI and STILES, 1982).

2 - **Reversed reflectance-color relation model**

If then, the computation of the relation between soil spectral properties in the visible domain and the colored aspect poses no difficulty, on the other hand, we have seen that the phenomenon of metamerism goes against the reversal of this relation. In theory, it is not possible to predict the spectral behavior of an object according to its color.

Yet, the case of soils is slightly different, owing to the fact that the reflectance curves are monotonous and increasing in the visible. It follows that the probability for two soils of same color to present intersected reflectance curves is very little. In other words, we can consider that the phenomenon of metamerism has very little chance to occur in the case of soils. Then, one can reasonably hope to be able to establish a bijective relationship between color and spectral properties.

In order to verify this assumption, we have tested the multiple correlations between the computed color : Rc, Gc, Bc (deduced from X,Y,Z values by inverting equation IV) and the spectral reflectance RF(λ) on the different wavelengths (λ) according to the following model :

$$RF(\lambda) = a_{\lambda}.Rc + b_{\lambda}.Gc + c_{\lambda}.Bc + d_{\lambda}$$

For wavelengths from 400 to 750 nm sampled every 50 nm, the coefficients we have obtained for our series of 84 samples are listed in table 1.

TABLE 1

Multiple linear regression coefficients between reflectance RF (λ) and colour Rc, Gc, Bc.

λ(nm)	aλ	bλ	cλ	dλ	r(mult.)
400	0	0	0,0393	− 0,521	0,985
450	0	0	0,0477	− 0,120	0,999
500	0	0,0190	0,0356	− 0,075	0,999
550	0,0046	0,0477	0,0046	− 0,020	0,998
600	0,0498	0,0062	0,0059	− 0,239	0,999
650	0,0719	− 0,0248	0,0181	+ 0,435	0,998
700	0,0801	− 0,0345	0,0225	+ 1,558	0,995
750	0,0868	− 0,0544	0,0371	+ 4,242	0,980

(Rc, Gc, Bc × 10^{4}).

The very high correlation coefficients obtained show that it is possible to reconstruct the spectral reflectance curve from the R,G,B values. The average variation between the observed and modelized values is 0,5% for wavelengths from 500 to 600 nm and 1,5% at the spectrum extremes about 400 and 700 nm.

Figure 3 illustrates this result with five curves representative of the variety of the studied samples. They show that for the whole set of samples, the modelized curve follows almost perfectly the real curve.

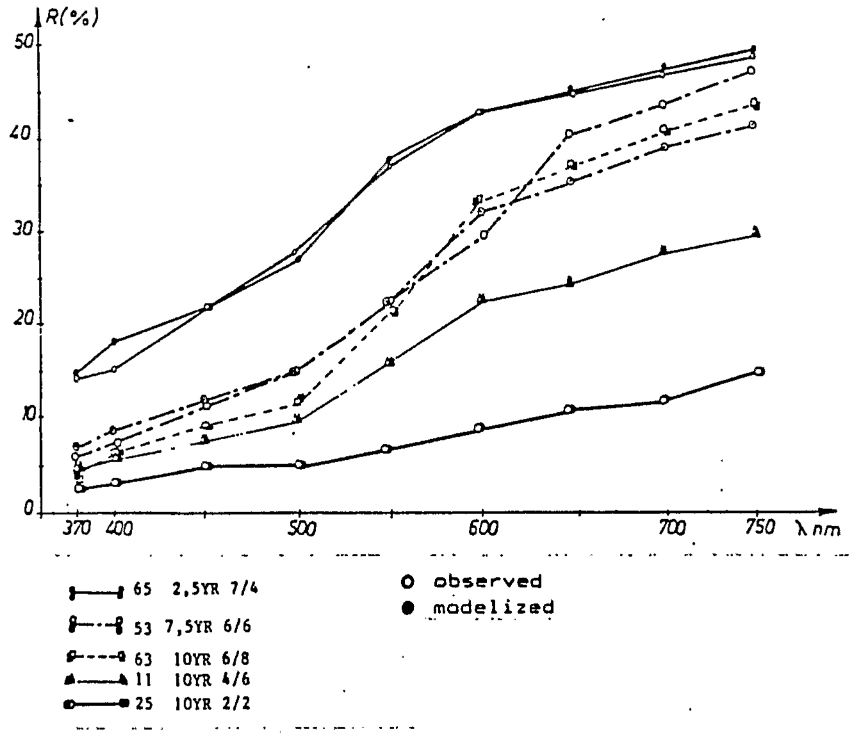

Fig. 3 - *Spectral reflectance curves for 5 soil samples extracted from the studied set (observed and predicted values).*

Only one case (No 53) out of 84 shows a significant variation between the observed and the modelized values for wavelengths 600 to 750 nm. Still, the R,G,B values corresponding to the modelized curve and those obtained for the measured curve are identical.

In other words, though the reflectance curve of the sample No 53 is clearly different from the expected curve, it produces the same colored sensation, this is the only case of metamerism we have found.

We have explained so far how to apply colorimetric computation to soils and under which conditions, with respect to a very low frequency of metamerism, the relation between soil spectral properties and soil colors can be reversed.

C - EVALUATION OF SOIL COLOR ON THE FIELD

An accurate determination of soil color requires spectrophotometric measurements in laboratory, which are not, at present, currently performed in routine work. On the other hand, soil scientists evaluate and systematically record the color when they describe pits and drill holes on the field.

1 - Use of the Munsell system

Right at the start of soil science, it rapidly proved necessary to codify this visual evaluation of color by a comparison with colored standards, for color already appeared as an essential datum.

After several attempts, American soil scientists came to the idea of conceiving a range of standard colors suited to the most common soil colors (PENDLETON and NICKERSON, 1951). This was achieved with the collaboration of the Munsell Society, which, marketed a set of soil color charts (Munsell Soil Color Charts, 1950).

In accordance with the recommendation of the U.S. Department of Agriculture, the use of Munsell charts was adopted by the whole group of American soil scientists, and after them, by a large part of the international pedological community.

The Munsell system is organized in a manner that seems quite natural, colors are hierarchized by distinguishing first the hue, then the value, and finally, the chroma, which expresses color saturation.

Soil color is most often compared on the field, in daylight, with the chart colors. By moving the soil sample under the provided windows placed under each colored sample, the sample that is closest to the soil sample is identified and its coordinates recorded (hue, value, chroma).

The precision of this color determination method greatly depends on the attention paid to its application, as MELVILLE and ATKINSON (1985) recently reminded.

The set of all the hues of the Munsell system is distributed on a circle, but the soil color atlas only contains red to green yellow hues (10R to 5GY). At the periphery of a given value, one can observe saturated hues, and near the center, colors of decreasing chroma. As in the case of the C.I.E. triangle, the achromatic axis representing the grey range goes through the center. In brief, in this system, a given color is characterized by coordinates of a cylindrical type (fig. 4).

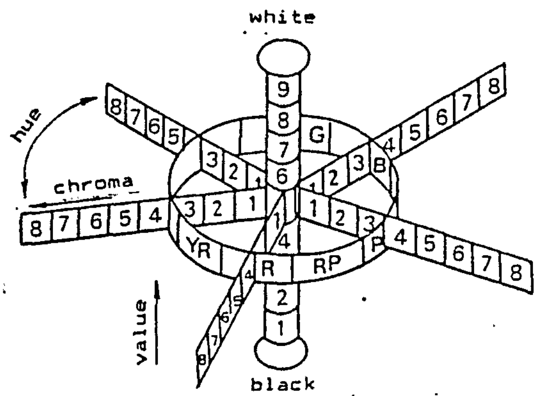

Fig. 4 *The cylindrical coordinates of the Munsell color system.*

2 - Relationships between the Munsell system and the C.I.E. system

We have seen that in the C.I.E. system, colors are identified according to cartesian coordinates. A simple change of system could then allow to go from one color notation system to the other.

In fact, it is not as simple as it may seem, because the Munsell system was empirically developed, so that the spacing between different color samples seemed regular, in order to meet the colorist's needs. The work done by the C.I.E., and especially by MacADAM, demonstrated, on the contrary, that in the R,G,B space, the distances between colors do not follow a euclidean but riemannian metric (KOWALISKI, 1978).

In other words, the geometry of the Munsell color space and that of the international system are not of the same nature, therefore, it is not possible to go directly from one system to the other. Let us mention, for instance, that the brightness varies with the square of the value.

In order to establish the transition between Munsell notation and the C.I.E. system, the most rigorous method consists in measuring the reflectance curve of each chip of the color charts. The coefficients x,y,Y or R,G,B must then be deduced by computation for the light under which the charts are observed.

Such calculations have already been done for a light of the C-illuminant type and are available under the form of tables, which allow to go from one system to the other (WISZECKI and STILES, 1982).

3 - Comparison between computed colors and colors evaluated on the field

We have tried to use this possibility, in order to compare the Rc,Gc,Bc coefficients previously computed for each of our 84 samples, with the colors estimated on the field by means of the Munsell code. After converting the latter into the C.I.E. notation, we obtain the "evaluated" coefficients : Ra,Ga,Ba.

The linear correlations obtained between the series of computed values and the series of observed values are the following :

$$Rc = 0.713\ Ra + 0{,}00821 \qquad r = 0.95$$
$$Gc = 0.766\ Ga + 0{,}00693 \qquad r = 0.94$$
$$Bc = 0.764\ Ba + 0{,}0078 \qquad r = 0.91$$

Since the Munsell colors are recorded in integer terms of value and chroma, discrete values are compared with continuous values. Consequently, the correlation results may be considered satisfactory.

Let us mention also, that one unit error on the brightness produces an error on the Ra,Ga,Ba coefficients, all the more significant as the soils are clearer.

Finally, color determination by means of Munsell charts has been made in daylight, whose composition is known to be rather fluctuating, and not under C-illuminant light. This may account for the systematic deviation observed between estimated (Ra,Ga,Ba) and computed (Rc,Gc,Bc) values.

This comparison shows that the colors recorded on the field with Munsell code allow to obtain a good approximation of the trichromatic coefficients usually determined in the laboratory.

On the other hand, we have demonstrated, that from these same trichromatic coefficients, it was possible to obtain, by modelization, a very good estimation of the soil spectral reflectance curve.

The last two points lead us to conclude that *the simple fact of recording the soil color on the field enables us to approach its spectral properties* in the visible domain.

CONCLUSION

In order to clarify the physical bases of the study of the relationship between color and other soil data, we have applied a certain number of colorimetric calculations to a series of 84 very different soil samples.

This work has shown that "soil color" data recorded on the field could be interpreted much more precisely than by merely using rough data expressed in terms of hue, value and chroma.

Indeed, as metamerism rarely occurs, we could modelize, from color, the soil spectral properties that are at its origin.

Soil color estimation constitutes easily obtained and quite reliable data, provided certain precautions are taken. They are widely available, in particular, in a great number of soil maps.

Though not reaching the accuracy of laboratory spectrophotometric measurements, color estimation allows a fast characterization of soil spectral behavior in the visible domain. These results are now being applied to the study of the relationship between the color, the nature and organization of soil constituents.

From a more general point of view, we do hope that this work, by giving a physical meaning to the Munsell notation classically used by soil scientists, will contribute to simplifying the interpretation of the nature and of the role of soil color.

ACKNOWLEDGEMENTS

Our most grateful thanks go to M. CERVELLE, directeur de recherches at the Laboratoire de Minéralogie-cristallographie de l'Université Pierre et Marie-Curie (Paris VI, France), for giving us the trichromatic coefficient computation program, and to Dr. GOILLOT and Dr. F.M. SCHMITT, professors respectively at the Institut National Agronomique and at the Ecole Nationale Supérieure des Télécommunications for their advice on colorimetry.

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