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Conversion of Munsell Color Coordinates to Cie-L*a*b* System: Tables and Calculation Examples

Yu. N. Vodyanitskii* and N. P. Kirillova

Department of Soil Science, Moscow State University, Moscow, 119991 Russia

**e-mail: yu.vodyan@mail.ru*

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Abstract—The widely used Munsell optical system is unsuitable for the statistical treatment of data for assessing the role of pigments in soil color. The CIE-L*a*b* system is more efficient for this purpose. This article contains a table for converting data on soil color from one scale to the other based on the example of oxisols (Brazil) and pale (Yakutia) and alluvial (Spain) soils. The advantages of the CIE-L*a*b* system for characterizing soil color have been shown.

Key words: soil color, Fe pigments, soil redness (a*), soil yellowness (b*), redness index (*RR*)

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INTRODUCTION

Diagnostic and classification of many soils is based on the determination of colors of their horizons [6–8, 19]. The main soil pigments are represented by humus (responsible for dark color), calcite ($CaCO_3$) and other carbonates (white), hematite (αFe_2O_3) (red), and goethite ($\alpha FeOOH$) (yellow). The participation of each pigment in the color of soil of a particular genesis is interesting for soil scientists [2, 6]. In the presence of hematite and goethite, soil acquires various tints of brown [1, 2, 4]. Horizon color changes with respect to iron status (oxidized or reduced). For example, when reductive gley conditions predominate, the horizon becomes cold dove-colored [3]. Therefore, soil color may indicate the presence of oxidized or reduced iron. Gley horizon is not formed under aerobic conditions and the soil profile will contain oxidized compounds of free Fe (III), while compounds of reduced iron will be absent. In the contrasting oxidative-reductive regime, both reduced and oxidized iron minerals may be present in soil.

Accurate quantitative characteristic of soil color is required not only for soil classification, but also to solve some other problems, in particular those related to iron chemistry and mineralogy. For example, these are Fe minerals, which determine the color of gleyed horizons in excessively moistened soils [3, 13]. The reduction of Fe (III) (hydr)oxides results in their dissolution, and warm-colored automorphic soils become gleyed dove-colored. Therefore, soil color may provide information on the predominating pigments.

Nevertheless, the used verbal characterization of soil color (for example, gray, light brown, or dark brown) cannot be quantitatively expressed, and the statistical calculations are impossible. Therefore, a verbal color description should be transformed into a quantitative characteristic in order to evaluate the role of particular pigments in soil color. It should be described according to a particular optic system. The Munsell system is the oldest and most widely used in soil science. There are catalogues with color chips, which are used to compare the colors of particular soil horizons. This system has one disadvantage: the cylindrical coordinates make difficult its application for statistical calculations. Scientists use the empirical coefficients based on their own assumptions [10. 12].

The CIE-L*a*b* system was elaborated in 1976 by the International Commission on Illumination. It is a universal color space in the Cartesian coordinates [1, 16. 18]. The system was recognized by many specialists (not only soil scientists) all over the world owing to clear sense of its parameters. The CIEL*a*b* system is suitable for soil scientists because the value of the L* parameter (lightness) is in adverse correlation with the content of dark pigment (humus) in soil. The a* parameter (redness) depends directly on the content of red pigment (hematite), and the b* parameter (yellowness) is related to the yellow pigment (goethite). The CIE-L*a*b* system is widely used at the spectrometric analysis under laboratory conditions [1–4, 16].

Nevertheless, the large amount of data on soil color determined in the field according to the Munsell system cannot be used for further analysis because these data are inadequate for statistic calculations. If they are conversed to another system, the quantitative data may be immediately obtained in the field. This information may concern the rise in redness with the depth in soils formed on hematite-bearing rocks or its decrease in hydromorphic horizons. The quantitative color parameters provide data (in addition to chemical analyses and Moessbauer spectroscopy) on the transformation of clay minerals during the development of the reduction process [11].

The aim of this work is to evaluate the efficiency of the transformation of color coordinates of the Munsell system into the CIE-L*a*b* system by comparing the correlation coefficients between the content of pigments and soil color of the two scales based on the example of soils of different geneses.

MATERIALS AND METHODS

We analyzed soils of various geneses; the data on their color according to the Munsell system were published earlier.

Brazil oxisol. The properties of this soil and data on the changes of its color (according to the Munsell scale) when modeling a long-term (333-day-long) microbiological reduction are given in [13]. The data of the roentgen-diffraction analysis show that the main Fe pigments are represented by hematite and goethite. The quantitative variations in color were evaluated by the redness index, i.e., Rating Redness (*RR*), proposed by Hurst as follows [10]:

$$RR = H \cdot C/V,$$

where *H*, *C,* and *V* are hue, chroma, and value of the color. The data on chroma (*C*) and value (*V*) are taken from Munsell books, and the hue is designated by the numbers. Macedo and Bryant used the following coefficients: 5 for 10R, 4 for 2.5YR, 3 for 5YR, 2 for 7.5YR, and 1 for 10YR [13].

The Rating Redness (*RR*) is used to characterize hematite content [10] because this mineral is the most widespread red pigment in many soils. Another rather widespread pigment, goethite (Fe pigment), is yellow.

Pale soils of Central Yakutia are slightly enriched in free iron oxides, which determine their pale color [5]. The participation of dithionite-soluble iron compounds in them is low, and Moessbauer spectroscopy does not reveal the presence of iron minerals in them, even when cooling the sample to 77 K. In connection with this, there is a question of how the soil color reflects the almost complete absence of Fe minerals. The answer is difficult if we only have data in the Munsell system. Data in the CIE-L*a*b* system make it considerably easier.

Alluvial soils of Spain were investigated in two chronoseries on river terraces [17]; in the Elsa River (Leon province) and Guadalajara River (Cordoba province) valleys. The soils of the former are strongly weathered and are enriched with free iron compounds; the ratio of Fe_{dith} to Fe_{total} is 0.78–0.84. The soils of the latter differ in weathering rate: they are depleted of iron oxides (Fe_{dith}/Fe_{total} = 0.37–0.51) on the lower terraces and are enriched with them (0.62–0.75) on the high terraces. The color was analyzed by the Munsell scale for moist and dry soils.

The soil color according to the Munsell scale was conversed into the CIE-L*a*b* system using the tables generated in the Munsell Conversion program, Version 4.01. In the tables and in the entire system, L*a*b* values are given for a light source of the C type.

The table for data conversion is given below (Table 1). If the Hue color tone is abnormal, i.e., not divisible by 2.5, it should be interpolated using an electronic resource [9]. If the initial data on brightness (*V*) and color saturation (*C*) do not coincide with those given in the table, they are calculated by interpolation at the fixed color tone (*H*).

Numerous measurements of hematite and goethite color according to the CIE-L*a*b* system have shown that redness (a*) and yellowness (b*) appear in both minerals. Hematite color varies significantly with respect to the size of particles and the presence of admixtures in them. According to the Munsell system, it is described as 1.2YR 3.6/5.2 [12]. Using Table 1 and interpolation, we obtain a* ~ 20, b* ~ 16.5, and a*/b* ~ 1.2. The color of goethite particles also varies and is on the average determined as 0.4Y 6/6.9 according to the Munsell scale [12] or a* ~ 8.3, b* ~ 45, and a*/b* ~ 0.2 according to Table 1. Therefore, the relative redness of hematite is better pronounced than goethite.

With respect to the above consideration, hematite content may be evaluated in the CIE-L*a*b* system by a* index (a* index a*I), which is calculated as a*I = a*/b*; and its maximal content is 1.2. Similarly, the goethite content may be evaluated by b* index (b* index b*I), calculated as b*I = b*/a* with the highest value equal to 5.0. We shall use these parameters to characterize color in the CIE-L*a*b* system.

RESULTS AND DISCUSSION

Brazil oxisol. The initial data on the effect of reduction on the oxisol color, its redness criterion (given according to the Munsell system), and indices a*I and b*I proposed in the CIE-L*a*b* system are given in Table 2. It is seen that, upon a reduction, the role of *RR* gradually decreases from 5.25 for the initial soil to 2.00 within 333 days of the reduction. Taking into consideration the monotonic changes in the *RR* effect, Macedo and Bryant came to the conclusion that hematite reduction is preferential compared with goethite [13].

Indices a*I and b*I point to another dynamic of soil reduction. Within a 164-day period, the a*I index only decreased, while hematite was dissolved. After

Table 1. Conversion of color coordinates of the Munsell scale to CIE-L*a*b* system

Value	Chroma							
	1	2	3	4	5	6	7	8
				Hue 2.5R				
8	81.4/2.8/1.2	81.4/5.7/2.3	81.4/10.4/4.2	81.4/14.9/6.1	81.4/19.3/7.8	81.4/23.7/9.5	81.4/28.3/11.3	81.4/32.9/13.3
7	71.6/3.5/1.4	71.6/7/2.8	71.6/11.1/4.3	71.6/15.1/5.8	71.6/19.4/7.5	71.6/23.6/9.2	71.6/27.9/10.9	71.6/32.2/12.6
6	61.7/3.8/1.4	61.7/7.5/2.8	61.7/11.8/4.3	61.7/15.9/5.8	61.7/20.3/7.5	61.7/24.6/9.3	61.7/28.5/10.7	61.7/32.3/12.2
5	51.6/4/1.3	51.6/8/2.7	51.6/12.6/4.2	51.6/17/5.8	51.6/21.4/7.4	51.6/25.8/9	51.6/30.2/10.4	51.6/34.4/12
4	41.2/4.8/1.5	41.2/9.5/3	41.2/14/4.5	41.2/18.5/5.9	41.2/22.9/7.2	41.2/27.2/8.6	41.2/31.6/9.9	41.2/36/11.2
3	30.8/5.5/1.6	30.8/10.8/3.2	30.8/15.6/4.5	30.8/20.3/5.8	30.8/24.6/7	30.8/28.9/8.2	30.8/33.6/9.3	30.8/38.3/10.6
2	20.5/5.3/0.7	20.5/10.6/1.4	20.5/14.9/1.8	20.5/19.3/2.2	20.5/23.4/2.5	20.5/27.6/2.8	20.5/32.2/3	20.5/36.8/3.1
				Hue 5R				
8	81.4/2.9/1.6	81.4/5.7/3.1	81.4/10.4/5.8	81.4/14.9/8.4	81.4/19.1/10.7	81.4/23.2/13.1	81.4/27.9/15.6	81.4/32.4/18.2
7	71.6/3.5/1.8	71.6/7/3.7	71.6/11.1/5.9	71.6/15/8.1	71.6/19.2/10.4	71.6/23.2/12.6	71.6/27.5/14.9	71.6/31.7/17.2
6	61.7/3.8/1.9	61.7/7.5/3.7	61.7/11.7/5.9	61.7/15.8/8.2	61.7/20/10.5	61.7/24.2/12.8	61.7/28/14.9	61.7/31.8/16.9
5	51.6/4/1.9	51.6/7.9/3.8	51.6/12.5/6.1	51.6/16.9/8.4	51.6/21.2/10.7	51.6/25.3/13	51.6/29.6/15.2	51.6/33.7/17.6
4	41.2/4.8/2.2	41.2/9.3/4.5	41.2/13.9/6.7	41.2/18.2/9	41.2/22.5/11.1	41.2/26.5/13.2	41.2/30.9/15.4	41.2/35.1/17.6
3	30.8/5.4/2.2	30.8/10.5/4.6	30.8/15.3/6.6	30.8/19.9/8.8	30.8/24/10.7	30.8/28/12.7	30.8/32.6/14.7	30.8/37/16.9
2	20.5/5.3/1.4	20.5/10.3/2.9	20.5/14.7/4	20.5/19/5.1	20.5/23.1/6.1	20.5/27.2/7.1	20.5/31.9/8.1	20.5/36.6/9.2
				Hue 7.5R				
8	81.4/2.8/2.2	81.4/5.6/4.3	81.4/10.2/7.7	81.4/14.6/11.1	81.4/18.7/14.2	81.4/22.7/17.5	81.4/27/20.9	81.4/31.2/24.4
7	71.6/3.5/2.5	71.6/6.9/5	71.6/10.9/7.8	71.6/14.8/10.8	71.6/18.6/13.7	71.6/22.4/16.7	71.6/26.6/19.9	71.6/30.8/23.2
6	61.7/3.8/2.6	61.7/7.4/5.2	61.7/11.5/8	61.7/15.4/10.9	61.7/19.3/13.7	61.7/23.1/16.5	61.7/27/19.5	61.7/30.7/22.6
5	51.6/3.9/2.5	51.6/7.7/5	51.6/12.1/7.9	51.6/16.4/10.9	51.6/20.5/13.8	51.6/24.4/16.9	51.6/28.5/20	51.6/32.5/23.3
4	41.2/4.7/2.7	41.2/9.1/5.4	41.2/13.6/8.3	41.2/17.8/11.3	41.2/21.9/14	41.2/25.8/16.9	41.2/29.9/19.9	41.2/33.9/23
3	30.8/5.2/2.9	30.8/10.1/5.9	30.8/14.7/8.6	30.8/19/11.5	30.8/23/14.1	30.8/26.9/16.8	30.8/31.2/19.6	30.8/35.4/22.6
2	20.5/5.2/2	20.5/10/4.1	20.5/14.3/6	20.5/18.5/8	20.5/22.5/9.7	20.5/26.4/11.6	20.5/30.8/13.4	20.5/35.2/15.4
				Hue 10R				
7	71.6/3.3/3.1	71.6/6.6/6.3	71.6/10.3/10.1	71.6/13.8/14	71.6/17.5/17.8	71.6/21/21.7	71.6/24.8/25.7	71.6/28.4/29.8
6	61.7/3.7/3.3	61.7/7.2/6.7	61.7/11/10.4	61.7/14.6/14.3	61.7/18.1/17.9	61.7/21.4/21.6	61.7/25/25.4	61.7/28.5/29.3
5	51.6/3.8/3.3	51.6/7.4/6.6	51.6/11.4/10.3	51.6/15.1/14.2	51.6/19/18	51.6/22.7/22.1	51.6/26.5/26	51.6/30.2/30.3
4	41.2/4.5/3.4	41.2/8.6/7	41.2/12.9/10.6	41.2/16.8/14.4	41.2/20.5/17.9	41.2/24/21.7	41.2/27.8/25.4	41.2/31.4/29.5
3	30.8/4.9/3.5	30.8/9.4/7.2	30.8/13.7/10.5	30.8/17.7/14	30.8/21.6/17.2	30.8/25.4/20.8	30.8/29.4/24.2	30.8/33.3/28.2
2	20.5/4.8/2.8	20.5/9.3/5.7	20.5/13.5/8.3	20.5/17.5/11.2	20.5/21.4/13.8	20.5/25.2/16.6	20.5/29.4/19.3	20.5/33.6/22.2
				Hue 2.5YR				
8	81.4/2.6/3.7	81.4/5.2/7.3	81.4/8.8/12.4	81.4/12.3/17.7	81.4/15.5/22.1	81.4/18.5/26.7	81.4/21.9/31.6	81.4/25.1/36.8
7	71.6/3.1/4	71.6/6/8	71.6/9.3/12.4	71.6/12.4/16.9	71.6/15.7/21.5	71.6/18.9/26.3	71.6/22/30.8	71.6/24.9/35.4
6	61.7/3.4/4.2	61.7/6.6/8.5	61.7/9.8/12.7	61.7/12.8/17	61.7/16.2/21.5	61.7/19.4/26.1	61.7/22.5/30.5	61.7/25.5/35.2
5	51.6/3.5/4.2	51.6/6.8/8.3	51.6/10.2/12.6	51.6/13.5/16.9	51.6/16.9/21.5	51.6/20.2/26.3	51.6/23.5/31.1	51.6/26.7/36.4
4	41.2/4/4.3	41.2/7.8/8.8	41.2/11.5/13.1	41.2/15/17.6	41.2/18.1/21.8	41.2/21.2/26.3	41.2/24.3/30.8	41.2/27.2/35.8
3	30.8/4.4/4.2	30.8/8.4/8.6	30.8/12/12.6	30.8/15.4/16.9	30.8/18.9/21.2	30.8/22.2/26	30.8/25.3/30.6	30.8/28.2/36

Table 1. (Contd.)

Value	Chroma 1	2	3	4	5	6	7	8
2	20.5/4.4/3.4	20.5/8.3/7.1	20.5/12.3/10.6	20.5/16/14.5	20.5/19.6/18.1	20.5/22.9/22.2	20.5/26.8/22.2	20.5/30.6/22.2
Hue 5YR								
8	81.4/2.3/4.8	81.4/4.5/9.6	81.4/7.3/15.1	81.4/9.8/20.6	81.4/12.4/25.7	81.4/14.9/31	81.4/17.5/36.7	81.4/20.1/42.7
7	71.6/2.6/5	71.6/5.2/9.9	71.6/7.8/14.9	71.6/10.2/20.1	71.6/12.8/25.3	71.6/15.4/30.8	71.6/17.8/35.8	71.6/20.1/41
6	61.7/2.8/5	61.7/5.5/10.1	61.7/8.2/15	61.7/10.7/20	61.7/13.4/25.3	61.7/16/30.9	61.7/18.6/36.1	61.7/21/41.7
5	51.6/3/4.9	51.6/5.7/9.9	51.6/8.6/14.9	51.6/11.2/20.1	51.6/14.1/25.4	51.6/16.8/31.1	51.6/19.5/36.4	51.6/22/42.3
4	41.2/3.4/5.2	41.2/6.5/10.5	41.2/9.7/15.5	41.2/12.5/20.8	41.2/15.1/25.6	41.2/17.5/30.7	41.2/19.9/35.6	41.2/22.2/41.1
3	30.8/3.7/5	30.8/6.9/10.1	30.8/9.9/14.6	30.8/12.7/19.6	30.8/15.5/24.5	30.8/18.2/30.3	30.8/20.5/35.7	30.8/22.7/39.9
2	20.5/3.7/4.2	20.5/6.9/8.6	20.5/10.3/13.1	20.5/13.3/18.2	20.5/16.3/22.2	20.5/19.1/22.2	20.5/22.2/22.2	
Hue 7.5YR								
8	81.4/1.7/5.8	81.4/3.4/11.6	81.4/5.3/17.3	81.4/7.1/23.2	81.4/9.2/28.8	81.4/11.2/34.6	81.4/13.1/40.7	81.4/15/47
7	71.6/2/5.8	71.6/3.9/11.5	71.6/6/17.1	71.6/8/22.8	71.6/9.9/28.5	71.6/11.7/34.5	71.6/13.6/40.1	71.6/15.3/46
6	61.7/2.2/5.7	61.7/4.3/11.5	61.7/6.5/16.9	61.7/8.5/22.5	61.7/10.5/28.3	61.7/12.5/34.4	61.7/14.4/40.2	61.7/16.3/46.4
5	51.6/2.4/5.5	51.6/4.6/11.1	51.6/6.9/16.8	51.6/9/22.7	51.6/11.3/28.6	51.6/13.4/34.9	51.6/15.3/40.6	51.6/17.1/47
4	41.2/2.8/5.8	41.2/5.3/11.7	41.2/7.8/17.5	41.2/10/23.6	41.2/12/28.7	41.2/13.8/34.4	41.2/15.5/39.7	41.2/17/45.9
3	30.8/2.9/5.5	30.8/5.5/11.2	30.8/7.8/16.4	30.8/9.9/22	30.8/12/27.4	30.8/13.9/33.8	30.8/15.5/39.9	30.8/17.1/39.9
2	20.5/2.9/4.9	20.5/5.3/10	20.5/7.9/15.3	20.5/10.2/21.4	20.5/12.6/22.2	20.5/14.7/22.2	20.5/16.5/22.2	
Hue 10YR								
8	81.4/0.8/6.8	81.4/1.6/13.5	81.4/2.7/19.6	81.4/3.8/25.9	81.4/5/32.1	81.4/6.2/38.5	81.4/7.5/44.8	81.4/8.8/51.4
7	71.6/1/6.6	71.6/2/13.2	71.6/3.3/19.5	71.6/4.4/25.9	71.6/5.7/32	71.6/6.9/38.5	71.6/8.2/44.5	71.6/9.5/50.8
6	61.7/1.3/6.5	61.7/2.4/13.1	61.7/3.8/19.1	61.7/5/25.4	61.7/6.5/31.7	61.7/7.9/38.4	61.7/9.2/44.6	61.7/10.5/51.3
5	51.6/1.4/6.3	51.6/2.8/12.7	51.6/4.4/19	51.6/5.8/25.5	51.6/7.4/31.9	51.6/8.8/38.9	51.6/10.1/44.8	51.6/11.3/51.5
4	41.2/1.7/6.6	41.2/3.2/13.3	41.2/5/19.4	41.2/6.6/26	41.2/8/31.6	41.2/9.3/37.8	41.2/10.4/43.4	41.2/11.5/50.1
3	30.8/1.9/6	30.8/3.5/12.2	30.8/5.1/17.9	30.8/6.6/24.1	30.8/8.1/30	30.8/9.5/37.2	30.8/10.7/39.9	30.8/11.8/39.9
2	20.5/2/5.4	20.5/3.6/11.1	20.5/5.6/17.1	20.5/7.2/22.2	20.5/9/22.2	20.5/10.5/22.2	20.5/11.7/22.2	
Hue 2.5Y								
8	81.4/–0.3/7.5	81.4/–0.4/15	81.4/–0.1/21.5	81.4/0.2/28	81.4/0.8/34.6	81.4/1.3/41.5	81.4/2/47.8	81.4/2.7/54.6
7	71.6/–0.1/7.3	71.6/–0.1/14.6	71.6/0.5/21.1	71.6/1.2/27.8	71.6/1.8/34.3	71.6/2.5/41.2	71.6/3.1/47.6	71.6/3.7/54.4
6	61.7/0.1/7.2	61.7/0.3/14.3	61.7/0.8/20.8	61.7/1.4/27.5	61.7/2.2/34.3	61.7/2.9/41.6	61.7/3.8/48	61.7/4.6/55.2
5	51.6/0.5/6.9	51.6/0.9/13.8	51.6/1.6/20.5	51.6/2.2/27.6	51.6/3.1/34.4	51.6/3.9/42	51.6/4.6/48	51.6/5.3/54.9
4	41.2/0.6/7.1	41.2/1.1/14.2	41.2/2/20.8	41.2/2.9/27.8	41.2/3.7/33.7	41.2/4.4/40.4	41.2/5.1/46.5	41.2/5.8/53.9
3	30.8/0.7/6.4	30.8/1.4/12.9	30.8/2.3/19	30.8/3.1/25.7	30.8/4.1/32.1	30.8/5/39.9	30.8/5.9/39.9	
2	20.5/0.9/5.9	20.5/1.6/11.9	20.5/2.8/18.7	20.5/3.8/22.2	20.5/5.2/22.2			
Hue 5Y								
8	81.4/–1.2/8	81.4/–2.3/15.9	81.4/–3.1/22.7	81.4/–3.8/29.7	81.4/–4.1/36.6	81.4/–4.4/43.7	81.4/–4.4/50.5	81.4/–4.5/57.7
7	71.6/–1/7.7	71.6/–1.9/15.2	71.6/–2.5/22.3	71.6/–3.1/29.4	71.6/–3.2/36.3	71.6/–3.3/43.5	71.6/–3.2/50	71.6/–3/57.2
6	61.7/–0.9/7.6	61.7/–1.7/15	61.7/–2.1/21.9	61.7/–2.5/29	61.7/–2.3/36.1	61.7/–2.2/43.7	61.7/–2/50.5	61.7/–1.8/58.1
5	51.6/–0.8/7.2	51.6/–1.4/14.4	51.6/–1.5/21.6	51.6/–1.6/29.1	51.6/–1.3/36.2	51.6/–1.1/44	51.6/–0.8/50.2	51.6/–0.5/57.3

Table 1. (Contd.)

Value	Chroma							
	1	2	3	4	5	6	7	8
4	41.2/−0.5/7.3	41.2/−0.9/14.6	41.2/−0.8/21.6	41.2/−0.8/29	41.2/−0.5/35.2	41.2/−0.2/42.4	41.2/0.2/48.6	41.2/0.5/56.5
3	30.8/−0.3/6.5	30.8/−0.6/13.1	30.8/−0.3/19.5	30.8/−0.2/26.6	30.8/0.3/33.4	30.8/0.7/39.9	30.8/1/39.9	
2	20.5/−0.1/6	20.5/−0.1/12	20.5/0.3/19.4	20.5/0.7/22.2	20.5/1.2/22.2	20.5/−0.1/6		
Hue 7.5Y								
8	81.4/−2/8.2	81.4/−3.8/16.3	81.4/−5/23.2					
7	71.6/−1.8/7.8	71.6/−3.4/15.4	71.6/−4.6/22.6					
6	61.7/−1.7/7.6	61.7/−3.2/15.2	61.7/−4.3/22.2					
5	51.6/−1.5/7.3	51.6/−2.7/14.5	51.6/−3.8/21.8					
4	41.2/−1.4/7.3	41.2/−2.6/14.5	41.2/−3.4/21.8					
3	30.8/−1.2/6.5	30.8/−2.1/13	30.8/−2.8/19.7					
2	20.5/−1/5.8	20.5/−1.7/11.6	20.5/−2.2/19.4					
Hue 10Y								
8	81.4/−2.7/8.2	81.4/−5.1/16.3						
7	71.6/−2.5/7.7	71.6/−4.8/15.3						
6	61.7/−2.4/7.6	61.7/−4.6/15						
5	51.6/−2.3/7.1	51.6/−4.3/14.1						
4	41.2/−2.3/7	41.2/−4.2/14						
3	30.8/−2/6.3	30.8/−3.7/12.5						
2	20.5/−1.7/5.4	20.5/−3.1/10.8						

Value	Neutral (N)	Chroma = 1					
	L*	10G	5B	5G	5P	5PB	5RP
8	81.4	81.4/−6.1/1.1	81.4/−3/−2.5	81.4/−6.4/2.5	81.4/1.7/−2.1	81.4/−0.2/−2.9	81.4/2.7/−0.1
7.5	76.5						
7	71.6	71.6/−5.8/1	71.6/−3/−2.7	71.6/−6/2.3	71.6/2.2/−2.5	71.6/0/−3.2	71.6/3.3/−0.1
6.5	66.7						
6	61.7	61.7/−5.6/0.8	61.7/−3/−2.8	61.7/−5.8/2.2	61.7/2.6/−2.8	61.7/0/−3.4	61.7/3.7/−0.2
5.5	56.7						
5	51.6	51.6/−5.2/0.7	51.6/−2.9/−3	51.6/−5.4/2	51.6/2.8/−3	51.6/0.2/−3.8	51.6/3.9/−0.3
4.5	46.4						
4	41.2	41.2/−5.1/0.6	41.2/−2.9/−3.2	41.2/−5.1/1.8	41.2/3.5/−3.6	41.2/0.4/−4.3	41.2/4.8/−0.5
3.5	36.0						
3	30.8	30.8/−4.6/0.5	30.8/−2.8/−3.6	30.8/−4.7/1.6	30.8/4/−4.1	30.8/0.5/−4.9	30.8/5.3/−0.8
2.5	25.6						
2	20.5	20.5/−3.9/0.3	20.5/−2.4/−3.3	20.5/−3.9/1.2	20.5/3.8/−3.8	20.5/0.6/−4.7	20.5/5.2/−1.3

Chroma is saturation, value is brightness, Hue is color tone, and neutral (*N*) is the absence of color.

Table 2. Effect of reducing oxisol color in Munsell and CIE-L*a*b* systems (initial data are given according to [13])

Sample	Reduction period, day	Color according to Munsell	*RR*	Color according to CIE-L*a*b*	a*I	b*I
Initial	0	3.25YR 4/6	5.25	41.2/20.1/27.6	0.73	1.37
B	24	3.25YR 4/6	4.50	41.2/17.5/30.7	0.57	1.75
C	27	5YR 4/6	4.50	41.2/17.5/30.7	0.57	1.75
D	33	5YR 4/6	3.75	41.2/17.7/32.4	0.55	1.82
E	57	6.25YR 4/6	3.75	41.2/17.7/32.4	0.55	1.82
F	61	6.25YR 4/6	3.75	41.2/17.7/32.4	0.55	1.82
G	64	6.25YR 4/6	2.25	41.2/11.5/36.1	0.32	3.12
H	100	8.75YR 4/6	2.25	41.2/11.5/36.1	0.32	3.12
I	101	8.75YR 4/6	2.25	41.2/11.5/36.1	0.32	3.12
J	164	8.75YR 4/6	2.25	41.2/11.5/36.1	0.32	3.12
K	333	7.5YR 4/4	2.00	41.2/10.0/23.6	0.42	2.38

that and until the end of the experiment, goethite was also dissolved, which is indicated by a decrease in the b*I index of 3.12–2.38 and the corresponding rise in the a*I index from 0.32 to 0.42. These data enable another interpretation of the experimental results. The soil first undergoes a successive reduction in unstable hematite particles, then of more stable goethite particles (Al-goethite). The authors did not pay attention to this important fact of goethite solution at the late stage of reduction.

The preferential solution of one mineral over the other substantiates the assumption that they compete for electrons released by organic matter. The interpolation of soil color variations in the CIE-L*a*b* system shows another regularity, i.e., the less ordered electron acceptors (hematite) are reduced first and, when the source of available electron acceptors is exhausted, more ordered particles of aluminum goethite are reduced. The hypothesis of the subsequent participation of electron acceptors in reduction–oxidation reactions with respect to the stability of mineral particles is proved in some works by soil microbiologists [14. 20].

Pale soils of Central Yakutia are poorly formed and are characterized by the low content of free iron compounds; i.e., the Fe_{dith}/Fe_{total} ratio is lower than 0.15. Let us calculate their redness and yellowness values. When hematite and goethite are absent and the percentage of free dithionite-soluble iron compounds in relation to the total iron content is small, these values are low; soil redness (a*) is <5.2, yellowness (b*) is <20, and a*I does not exceed 0.35.

A comparison of these data with those on the color of slightly better formed cryohydromorphic soils of the Kolyma Lowland [3] has shown that the latter are characterized by a higher percentage of free dithionite-soluble iron compounds (less than 0.3% of the total iron content). Despite more strongly developed iron oxidation, the redness of cryohydromorphic soils was smaller (a* < 2), though the yellowness remained almost the same (b* < 20), similar to the pale soils of Yakutia. The a*I index of cryohydromorphic soils was equal to 0.10 for the Kolyma Lowland and was two to three times greater than that of the pale soils of Yakutia. The low Fe_{dith}/Fe_{total} ratio obviously very approximately reflects the soil color, which depends greatly on the color of clay minerals in the soils with low iron contents, and the composition of clay minerals differs.

Alluvial soils of Spain. The parameters of color of moist and dry alluvial soils (Table 3) are given according to the Munsell and CIE-L*a*b* systems. Drying affects the soil brightness (*L**); it rises for all soils except one, for which it remains stable. The drying effect on redness and yellowness differs. The growth of a* and b* may be positive or negative.

This change in soil color may be explained by the different rate of formation of these soils. The drying of old weathered soils on the catena of the Elsa River (the Fe_{dith}/Fe_{total} ratio rises to 0.78–0.84) results in a significant decrease in the a*I index from 0.55–0.86 to 0.32–0.57. The lesser redness may be explained by the fact that, during soil drying, organic matter may be oxidized. This results in the reduction of metals with variable valence (manganese and iron) [15]. The reduction of MnO_2 during soil drying has been comprehensively studied. Iron oxides are reduced at lower E_H when compared to manganese and, thus, more time is required for this process.

The regularities of the soils on the catena of the Guadalajara River are different. These soils are younger, in particular on the lower terrace, where the Fe_{dith}/Fe_{total} ratio is only 0.37–0.51. At soil drying, redness rises by 0.2 and 3.9. This rise is probably related to the release of iron from the lattice of clay minerals and

Table 3. Color of soils in Spain given in Munsell and CIE-L*a*b* systems (initial data are given according to [17])

Sample	Moist soil					Dry soil					Growth	
	color according to Munsell system	L*	a*	b*	a*I	color according to Munsell system	L*	a*	b*	a*I	Δa*	Δb*
Elsa River catena												
T3-3	7.5YR 4.5/3.5	46.4	8.5	20.3	0.42	8.5YR 5/4	51.6	7.7	23.8	0.32	–0.8	3.5
T8-2	5YR 3.5/6	36.0	18.1	30.7	0.59	6.5YR 5.5/5.5	56.7	13.3	30.3	0.44	–4.8	–0.4
T10-2	4YR 4/5	41.2	16.3	24.0	0.68	6.5YR 5.5/5	56.7	12.1	27.3	0.44	–4.2	0.3
T20-2	3.5YR 3.5/6	36.0	20.4	28.0	0.73	5YR 5/7	51.6	19.5	36.4	0.54	–0.9	8.4
SP-2	2.5YR 3.8/7	38.6	24.7	30.8	0.80	5YR 5/7	51.6	19.5	36.4	0.54	–5.2	5.6
P-2	2.5YR 4/5.7	41.2	19.6	24.0	0.82	4.5YR 5/7	51.6	20.2	35.4	0.57	0.6	11.4
Guadalajara River catena												
EL-2	7.5YR 4/2.5	41.2	6.5	14.6	0.45	8YR 5/3	51.6	6.4	17.2	0.37	–0.1	2.6
GU-6	6.5YR 4.5/5	46.4	13.0	27.5	0.47	8.5YR 5/4	51.6	7.7	23.8	0.32	–5.3	–3.7
EA-1	4YR 4/4	41.2	13.5	19.6	0.69	5YR 4.5/6	46.4	17.4	31.9	0.56	3.9	11.5
BO-1	2YR 3.5/7	36.0	25.8	29.6	0.87	2YR 3.5/6	36.0	22.6	25.3	0.89	–3.2	–4.3
QT-1	0.5YR 3.5/7	36.0	28.2	26.1	1.08	3YR 4.5/6	46.4	20.2	27.4	0.74	–8.0	1.3

the formation of iron hydroxides. Upon drying older soils on the catena of the Guadalajara River, which is characterized by a greater Fe_{dith}/Fe_{total} ratio (0.62–0.75), the increase in redness is similar to that on the catena of the Elsa River. Therefore, the calculations have shown that the CIE-L*a*b* system may be affectively used to solve different problems of soil science.

CONCLUSIONS

It is inconvenient to use the Munsell system for statistical calculations when evaluating the role of pigments in soil color. Empirical approaches for transforming the system have only been proposed for a small range of color tones and the calculating of the correlation between pigments and soil color may be not precise. A table for converting data on soil color from the Munsell to the CIE-L*a*b* system has been proposed. The efficiency of using the CIE-L*a*b* optic system for characterizing soil processes has been shown based on the example of Brazil oxisol and Yakut pale and Spanish alluvial soils.

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