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Quantifying the uncertainty of soil colour measurements with Munsell charts using a modified attribute agreement analysis

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ABSTRACT

The use of Munsell colour charts is the classical way of determining colour information in soil science. The procedure is well-known and consists of visually comparing soil samples with colour chips contained in the charts. This visual approach has several drawbacks and although the chart-based procedure is routinely used, it is not easy to find systematic studies on the accuracy of this methodology. In this paper, we seek to gain insight into the strengths and weaknesses of using soil colour charts as a colour measurement device. The tool used to conduct our study is a modification to the attribute agreement analysis (AAA) method which consists of finding matches between colour standards and colour designations obtained by several appraisers. In the experiment, standards were obtained using a trichromatic colorimeter coupled to a computer program that implements the k nearest neighbour (k-NN) classification algorithm. In order to do the experiment, 276 soil samples were observed twice by four trained appraisers (2208 data records). The naïve count of matches across all the records in the dataset gave < 5% of agreement for all three colour components Hue, Value and Chroma. The modified AAA criterion implemented in the study gave a clear increase in all indicators with values ranging from 82.2% to 100% in the agreement within appraisers, 39.5% in the agreement between appraisers, and 42.8% in the agreement of appraisers vs. standards. Results also show that users of the Munsell charts tend to mostly report correct Hues but higher Values and Chromas than true soil colours.

1. Introduction

In the context of soil science, agriculture and forestry, colour is considered as an intrinsic physical characteristic that plays a key role in the characterization of soils (Simonson, 1993; Thwaites, 2006; Cook, 2008; Ibáñez-Asensio et al., 2013) as well as in classification tasks (FAO, 2014; Soil Survey Staff, 2014). Although being a classic topic, colour is still the subject of recent soil research (Rabenhorst et al., 2014a; Johns et al., 2015; Han et al., 2016; Fan et al., 2017; Aitkenhead et al., 2018).

The first attempts to communicating soil colour consisted basically in the publication of lists of colour names without references to standards. It was not until the late 1920s that advances in colour science allowed the United States Department of Agriculture (USDA) for the first satisfactory attempt to standardise soil colour communication using rotating colour disks. A few years later, the first colour charts specifically designed for soil measurements were distributed to carry out field trials (Simonson, 1993). Those early implementations of the charts evolved into the current charts that encode colour with three components: Hue, Value and Chroma (Munsell Color, 2000). Fig. 1 contains a representation of the Munsell wheel representing principal and secondary Hues.

Recent approaches to measuring colour include the use of computer programs coupled to colour sensors such as colorimeters, spectrophotometers and digital still cameras (Levin et al., 2005; Viscarra Rossel et al., 2008; Moreno-Ramón et al., 2014), and the modelling of colour data together with other remotely or nearly sensed data in site-specific agriculture (Guertal and Hall, 1990; Escadafal and Huete, 1992; Mathieu et al., 1998).

Interested readers can find detailed information on colour fundamentals, colour spaces, vocabulary, formulae, laboratory setup and the use of soil colour charts in the literature (Melville and Atkinson, 1985; Simonson, 1993; Soil Survey Division Staff, 1993; Torrent and Barrón, 1993; Munsell Color, 2000; CIE, 2004; Westland et al., 2012). The definition and handling of colour spaces are the relevant parts to this paper. All colour spaces define stimuli with three attributes: two chromatic coordinates and one achromatic coordinate (Table 1).

As stated above, colour is used in soil classification as a determining

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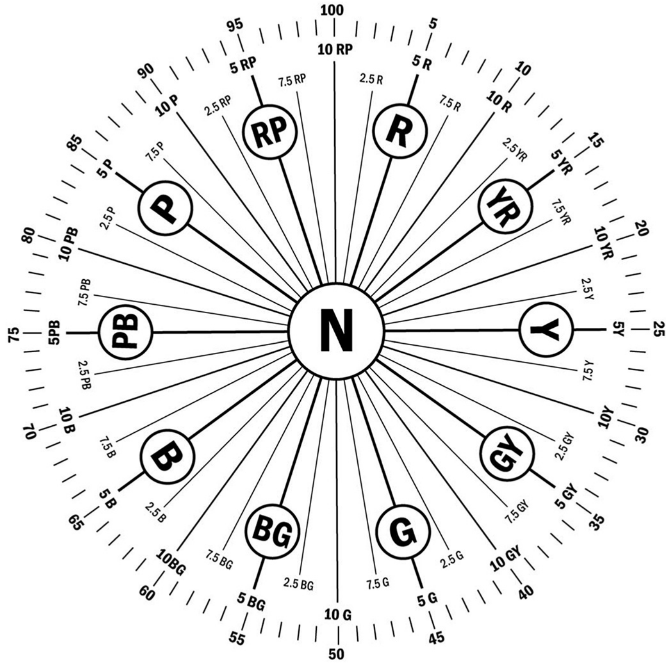

Fig. 1. Munsell wheel showing the Hue space in alphanumeric and numeric representations. The Value axis is normal to this circle and ranges from 0 (black) to 100 (white). The Chroma attribute is measured radially from the center (neutral) to the perimeter (saturated colour).

Table 1
Colour spaces commonly used in soil science and their chromatic and achromatic attributes.

Colour space	Chromatic atrributes	Achromatic attribute
Munsell	Hue and Chroma	Value
CIE xyY [a]	Chromaticity coordinates (xy)	Luminance (Y)
CIELAB [b]	Red-green axis (a*) and yellow-blue axis (b*)	Lightness (L*)

[a,b] Chromaticity coordinates (xy) and a*b* coordinates can be transformed into Hue and Chroma correlates.

attribute and is a potential indicator of pedogenesis processes (e.g. weathering or redox processes), the origin of the parent material, or the presence of organic matter, to name just a few. It is commonly accepted that soil colour also reflects the presence of principal soil constituents such as humus, iron hydroxides, silicic acid, kaolinite and calcium carbonates, and manganese, nitrogen or phosphorus oxides (Christensen et al., 2004; Schwertmann, 1993; Simonson, 1993; Torrent and Barrón, 2003).

Indeed, colour is the first property that can be defined when starting a soil profile description to determine its horizons. The importance of colour was recognised in the earliest soil classification systems. In the Chinese classification system (2500 ybp) soils were classified into three categories and nine classes, and colour was one of the key properties to carry out the classification (Krasilnikov et al., 2010).

In modern classification systems, soil colour is used as a diagnostic criterion for materials and horizons, as well as a key qualifier for group assignments (FAO, 2014). In the particular case of the Soil Taxonomy system, there are several diagnostic characteristics where colour is involved in the classification itself. For instance, seven of the eight possible types of epipedons require specific levels of Munsell Value and Chroma (Soil Survey Staff, 2014).

The relevance of colour in soil classification systems and other soil studies is, therefore, a matter of fact, and its correct designation improves soil classification outcomes. However, measuring and communicating soil colour is not a trivial task and difficulties may arise due to a number of factors such as observation setup, environment conditions, technical training and so on (see Section 1.2).

1.1. CIE colour spaces

The modern approach to soil colour science involves the use of the *Commission Internationale de l'Éclairage* (CIE) recommendations and colour spaces that are briefly described in this Section. The CIE 1931 XYZ space (Schanda, 2007) has been recognised as the first physically- and physiologically-based standard colour space. Although little used today in its original form, other spaces such as the CIE xyY or the CIELAB colour spaces derive directly from the CIE XYZ space by means of well-known mathematical transformations. The XYZ coordinates are called the tristimulus values which are obtained by summation of the product of three functions: the spectral reflectance of the object, the relative spectral power distribution of the light source, and the colour matching functions, over wavelengths ranging from 380 nm to 780 nm (CIE, 2004; Schanda, 2007).

The formulas to transform XYZ are well documented in the literature (CIE, 2004) and are given here for reference. The xy chromaticity coordinates are just normalisations of the tristimulus values:

$$x = X/(X + Y + Z)$$

$$y = Y/(X + Y + Z)$$

The CIELAB colour space is the most widely used colour space today. The formulas to transform XYZ to CIELAB are more involved, but still based on functions of tristimulus values:

$$L^* = 116\,(Y/Y_n)^{1/3} - 16$$

$$a^* = 500\,((X/X_n)^{1/3} + (Y/Y_n)^{1/3})$$

$$b^* = 200\,((Y/Y_n)^{1/3} + (Z/Z_n)^{1/3})$$

where X_n, Y_n, and Z_n are the tristimulus values of the reference white. It should be noted that accurate preparation and measurement of white reflectance standards have many practical advantages and they must be used in the soil laboratory when high accuracy and precision are required (Torrent et al., 1983; Torrent and Barrón, 1993).

The advantage of CIELAB over other spaces is twofold. First, it is closer to human vision correlates than the other spaces (see Table 1). Secondly, and most important, the CIELAB space is uniform (actually quasi-uniform) over the entire chromatic domain, which means that differences between colours have the same magnitude regardless of its position in space.

This characteristic allowed for the definition of a closed formula to compute colour differences based on the Euclidean distance between two colour stimuli (CIE., 2004):

$$\Delta E^*_{ab} = ((L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2)^{1/2}$$

where L_1^* a_1^* b_1^* and L_2^* a_2^* b_2^* are the CIELAB coordinates of the two stimuli.

1.2. Uncertainty in soil colour measurements

Although CIE spaces are physically-based, mathematically-oriented and more reliable than colour charts, common practice usually requires using both methods. That way, soil scientists can conduct all the computations in the CIE domain and communicate colour using the common Munsell notation system of colour charts. It should be noted, albeit, that determining soil colours from colour charts is subjected to certain degree of uncertainty due to psychophysical and physical factors amongst others (Baumgardner et al., 1985; Torrent and Barrón, 2008). Observation errors in soil colour identification were identified as early as in 1966, or indeed even earlier as extracted from reports by