Usual and unusual CIELAB color parameters for the study of peat organic matter properties: Tremoal do Pedrido bog (NW Spain)

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Abstract. We have tested the practical application of color measurements in the study of organic matter properties (C and N content, C/N ratios, degree of peat humification –DPH) of a 335 cm long peat core sampled at Tremoal do Pedrido bog. Usual and unusual CIELAB color parameters were measured on samples that were sectioned at high resolution (slices of 1 cm in thickness). The objective of the study is twofold: (i) describe a rapid, cost-effective and non-destructive method of assessing peat properties without the need of extractions and chemical methods and (ii) contribute to further research on applied colorimetry using the well-known CIELAB coordinates: L*, a*, b*, C*ab and h*ab (‘usual CIELAB color parameters’) and the less well-known CIELAB parameters: [a* x b*], [(a*/b*) x 1000], [1000 x a*/(L* + b*)], [2000 x a*/(L* x b*)] and R_Lab= [a*(a*2+b*2)1/2 1010]/(b* x L*) (‘unusual CIELAB color parameters’). Our findings show that L* and h*ab coordinates as well as [(a*/b*) x 1000], [2000 x a*/(L* x b*)] and R_Lab parameters give the best bivariate Spearman’s correlations. Linear regression equations were calculated to predict peat properties from all CIELAB parameters under study and a notable fit (R^2: 0.65-0.79) was obtained. The evaluation presented here indicates that the determination of usual and unusual CIELAB parameters offers potential for the study of peat organic matter properties and encourages the routine application of this methodology on other peat cores and organic soils.

1. Introduction
There is a significant interest in the development and implementation of new methodologies for color measurement. They can be applied, for example, in the study of environmental and microbial ecology, microbial bioremediation, soil science and materials conservation. In this sense, the study of peatlands using such methods deserves further attention.

Peatlands (Figure 1) are wet ecosystems where reducing and acidic conditions limit the decomposition of plant material, favouring the accumulation of peat: a dark to brown organic substrate...
with high contents of organic carbon. Peatlands are among the most important carbon reservoirs on Earth [1, 2]. They also provide long-term perspectives on past environmental variability, especially on the Holocene (last~12,000 years). Peat accumulation dynamics on peatlands allows the preservation of many biotic and abiotic proxies that can be effectively used to reconstruct past changes on vegetation, soil erosion, climate or human impact [3,4]. Although the use of peat records as a tool in the reconstruction of past environmental conditions started more than a century ago, the most noticeable advances were made in the last few decades [5]: first in the European peatlands, particularly those from the UK and NW Europe, and then in the Southern Hemisphere and tropical regions. In these studies, several authors [e.g. 6-8] reported variations in the color of peat deposits related to changes in the degree of peat degradation and vegetation remains, which were climatically controlled. In this sense, broadly highly decomposed peat is usually dark brown-blackish whereas less decomposed peat is light brown-yellowish in color. A chemical method to determine the degree of peat humification (DPH) was originally developed by Overbeck [9], and later modified by other investigators [10, 11] becoming the standard method. It is based on the colorimetric determination of an alkaline extract of the peat. The absorbance/transmittance is related to the amount of dissolved humic substances and therefore to the degree of humification and the concomitant decomposition of the peat. Since decomposition largely depends on surface moisture on the peatland, a record of humidity variations can be obtained by relating higher transmittance values to increased moisture (i.e. effective precipitation), and low transmittance values to drier conditions (i.e. lower effective precipitation). However, this is a destructive, time consuming method. For this reason, identifying innovative tools for determining changes in peat humification or decomposition is an important goal in the field of paleoenvironmental reconstruction. Techniques based on optical methods, as the instrumental color measurement with a chromameter/colorimeter or spectrophotometer for solids, could be an interesting option.

![Figure 1](image1.png)

**Figure 1.** Color variations in a (left) peat cut and in a (right) fresh peat core.

Used since 1990s, these contact-type color measuring devices provide a low cost technology to quantify soil color related to soil taxonomy, soil quality, and fertility, through quantitative color space models like the widespread accepted in scientific and industrial fields CIELAB color space [12]. Previous research has provided evidence that CIELAB color parameters may be of application in the development of predictive models for different types of soils. Thus, for example, using a hand-held chromameter Lilies et al. [13] demonstrated the suitability of L* (associated to lightness), a* (associated to redness) and b* (associated to yellowness) CIELAB coordinates to predict forest soil C concentrations from the major conifer forest ecosystems in California (USA). Guimarães et al. [14]
worked with the same color coordinates recorded with a spectrophotometer in palaeoecological studies of Amazon wetlands. Similarly, Moritsuka et al. [15] used L* and b* coordinates for statistically estimating total carbon (C), total nitrogen (N) and active iron (Fe) contents in Japanese agricultural soils. In a 2010 publication, Sanmartin et al. [16] described the usefulness of h*ab (which refers to the dominant wavelength and represents the major color perception attribute) in a preliminary approach for the study of the relationship between color changes in a granitic soil (viz. Umbric Regosol) and the temperature reached as a consequence of forest fire. More recently, Cancelo-González et al. [17] followed up on this research with other types of granitic Galician soils, adding Leptic Umbrisol and Humic Cambisol to the aforementioned Umbric Regosol, and different processed burnt samples (undisturbed, homogenized and free of organic matter) and concluded that the severity of forest fire can be estimated by determining variations in soil color and organic matter content. Using a dataset derived from the National Soil Inventory of Scotland-NSIS database (from Scottish soils of 721 locations throughout Scotland, which includes also peatlands soils), Aitkenhead et al. [14] reported successful results for ash, clay, sand, Ca, Mo, Ti, N, C:N ratio, organic matter content, pH and texture, and unsuccessful ones for P and K, all predicted by color measurements represented in the RGB and CIELAB systems. In this study, CIELAB system was found to be better overall predictor of soil characteristics than RGB (Red, Green, and Blue digital values) system. Although the authors point that this is balanced against the ease of use of RGB digital values obtained with a digital camera instead a color-measuring device (for further information, see the reference [18]).

Because most studies on soil color using the CIELAB system (including the above-mentioned works) comprised only the five CIELAB coordinates, viz. L*, a*, b*, C*ab and h*ab, the applicability of CIELAB parameters to soils is unclear. Despite many other CIELAB parameters, such as R_Lab (equation 6), have been used successfully in the study of soils and related environments, their application is still limited. The present study was conducted to shed light in this regard, while for the first time color measurements were employed for the study of a Histosol, a type of soil with cherished information for paleoenvironmental reconstruction and climate studies. We performed colorimetric measurements and recorded CIELAB color parameters, in a 335 cm long core (c. 6600 years) sampled at the Tremoal do Pedrido bog (Xistral Mountains, NW Spain). We hypothesize that CIELAB color parameters may be helpful to assess the organic matter properties (content of C and N, and DPH) of the peat. This study is a first approximation towards developing an understanding of the array of color parameters that can be used to infer Holocene environmental changes using peat cores.

2. Methodology

2.1. Sampling and physico-chemical peat properties analyzed

The peat core used for this study was sampled in Tremoal do Pedrido, a raised bog located in the Xistral Mountains (Figure 2) at an elevation of 695 m a.s.l., and 29 km south of the northern coast of Galicia, NW Spain (for further information, see the reference [19]).

Sampling was done with a Waardenarpeat corer to a depth of 100 cm and a Russian corer below 1m. The peat sections were wrapped in plastic film, protected in PVC hemi-tubes and taken to the laboratory, where they were cut into 1 cm slices, in the upper meter, and 2 cm below. Samples were placed in polyethylene bags and preserved at 4 °C in a freezer.

Before chemical analysis, samples were dried at 35 °C, milled and homogenized. Carbon and N were determined using an elemental analyzer LECO TruSpec CHN. The degree of peat humification (DPH) was determined following the conventional method by extracting humic acids in 8% NaOH and measuring its absorbance at 540 nm in a spectrophotometer [20]. C/N ratios were also calculated, since some authors consider their variations in peat cores are also related to peat decomposition [21].
2.2. Usual and unusual CIELAB color parameters

In most studies (see e.g. [23], [24]) the characterization of soil color is only assessed by examination with the naked eye. Examination based on soil color charts from Munsell color system [25] is considered a standard method, although variation between existing charts can prevent accurate assignment of color to a sample [26]. Viscarra Rossel et al. [27] also demonstrated that color systems based on a Cartesian approach (like the CIELAB system) are more appropriate than the Munsell system for predictive analysis. Furthermore, color is a subjective property that depends on an individual’s perception, and its quantification and representation in a color space is, therefore, a better option.

We have chosen for this study the CIELAB space for several reasons, including: its widespread acceptance in scientific and industrial applications, the opposing character of the coordinates \( L^*a^*b^* \), the association of another set of coordinates, \( L^*C^*a^*_b^* \), with the three color attributes (lightness, chroma and hue), and its analogy relative to the Munsell color system, with which many people are familiar, specially researchers in Soil Science and therefore researchers in peatlands. Furthermore, as already stated, one of the aims of the study was to test a larger number of CIELAB parameters, not just limited to the five coordinates. Thus, the well-known CIELAB coordinates: \( L^*, a^*, b^*, C^* \) and \( h_{ab} \), namely ‘usual’ CIELAB color parameters, and the less well-known CIELAB parameters:

\[
\begin{align*}
[a^* x b^*] & \quad (1) \\
[a^*/b^*] & \quad (2) \\
[(a^*/b^*) x 1000] & \quad (3) \\
[1000 x a^*/(L^* + b^*)] & \quad (4) \\
[2000 x a^*/(L^* x b^*)] & \quad (5) \\
R_{Lab} &= \frac{[a^*(a^{*2}+b^{*2})^{1/2} 10^{16}]}{(b^* x L^*)} \\
& \quad (6)
\end{align*}
\]

namely ‘unusual’ CIELAB color parameters, were recorded with a GretagMacbeth (now XRite) portable spectrophotometer (CE-XTX) for solids, performed on the dried, milled and homogenized samples (Figure 3).
3. Results and discussion

Various modeling and statistical methods have been used to relate soil color characteristics to soil properties and environmental factors. In this study, the color data were used to correlate to the degree of peat humification (DPH) and compositional data of the peat, to determine to which extent peat color reflects changes in peat properties and the related environmental conditions. The relationships between the data were assessed by two tailed bivariate Spearman’s correlations and stepwise linear multiple regression models. Statistical analyses were performed with SPSS (SPSS v21.0 for Windows).

In general terms usual CIELAB parameters (Table 1) result in lower bivariate Spearman’s correlations with peat properties than unusual CIELAB parameters (Table 2). Among the usual CIELAB color parameters, the highest correlations were found for L* (color lightness) and h_ab (the hue angle), while the lowest correlation was found for a*. This suggests that polar coordinates (L*a*b*), rather than Cartesian coordinates (L*a*b*), better reflect peat organic matter properties. Importantly, the former lead to quantification of a color’s similarity to its perceived color, i.e. by taking into account the three attributes of visual assessment [28]. For the unusual parameters, the correlation was higher for (a*/b*) x 1000, 2000 x a*/(L* x b*) and R_Lab. The first two parameters, (a*/b*) x 1000 and 2000 x a*/(L* x b*), have been mainly used to study the pigment content of several food types. R_Lab has been used recently in Quaternary paleosols and sediments on the Balearic Islands (Spain) to determine climatic preconditions for soil reddening [29].

| CIELAB color parameter | C   | N   | C/N  | DPH  |
|------------------------|-----|-----|------|------|
| L*                     | -0.73** | 0.77** | -0.78** | -0.68** |
| a*                     | -0.26** | 0.25** | -0.24** | -0.31** |
| b*                     | -0.64** | 0.66** | -0.67** | -0.65** |
| C*<sub>ab</sub>        | -0.60** | 0.60** | -0.61** | -0.61** |
| h_ab                   | -0.75** | 0.87** | -0.88** | -0.66** |

n = 227, in bold correlation coefficients equal or higher than 0.7 significance level ** p < 0.01
C and N: carbon and nitrogen concentrations
C/N: carbon/nitrogen ratio
DPH: degree of peat humification, i.e. absorbance of the sodium hydroxide extract

Table 1. Bivariate Spearman’s correlation matrix among geochemical data and usual CIELAB color parameters
Table 2. Bivariate Spearman’s correlation matrix among geochemical data and unusual CIELAB color parameters.

| CIELAB color parameter | C   | N   | C/N  | DPH |
|------------------------|-----|-----|------|-----|
| a* x b*                | -0.51** | 0.51** | -0.51** | -0.54** |
| a*/b*                  | 0.68** | -0.76** | 0.78** | 0.55** |
| (a*/b*) x 1000         | 0.75** | -0.86** | 0.88** | 0.66** |
| 1000 x a*/(L*+ b*)     | 0.63** | -0.77** | 0.77** | 0.50** |
| 2000 x a*/(L* x b*)    | 0.77** | -0.85** | 0.86** | 0.71** |
| R_Lab                  | 0.74** | -0.80** | 0.82** | 0.68** |

n = 227, in bold correlation coefficients equal or higher than 0.7 significance level ** p < 0.01; * p < 0.05. Acronyms are defined in Table 1.

Regardless of the group of CIELAB parameters considered (usual or unusual), the highest correlation was found for C/N ratio, followed by N and, to a lesser extent, C content. The DPH always showed the lowest correlation. The sign of N correlation was opposite to the sign of C/N, C and DPH correlations. Strong relationships between soil color and the C/N ratio have been found in previous research (e.g. [14]), and Qian et al. [30] found that color was a strong predictor of soil N content in mineral forest soils.

Stepwise multiple linear regression was applied to obtain simple expressions for estimating peat properties using the CIELAB color parameters considered in this study (Table 3). The results indicate that color parameters are of relatively high predictive value (R^2: 0.65-0.79), particularly for the C/N ratio, followed by C and N; the lowest predictability was always obtained for DPH. No large differences were found regardless of the group of color parameters used. Nevertheless, polar coordinates showed a slightly better prediction for C and DPH and the unusual parameters for N and C/N ratios. Lilies et al. [13] found that the best predictive model for C included L* and a*.

The C/N ratio in peatlands usually increases with depth/age, due to an increase in C and a decrease in N concentrations, and it has been associated to long-term peat decomposition [31]. Thus, the correlations and the regression models imply that decomposition is accompanied by a reduction in lightness, red and yellow components, hue and chroma of the peat. The lower predictive value for the DPH may be due to the fact that it is not a property of the bulk peat or, as recently suggested [21], that both C/N ratios and DPH are related to different aspects of peat decomposition.
Table 3. Stepwise multiple linear regression equations for the prediction of the concentrations in carbon (C) and nitrogen (N), carbon/nitrogen ratio (C/N) and degree of peat humification (i.e. absorbance of sodium hydroxide extract, DPH).

| Parameter | Estimated | Predictive Equation | Adjusted R² |
|-----------|-----------|--------------------|-------------|
| C<sup>a</sup> |          | C = 88.24 – 0.49hab – 0.22L* | 0.69        |
| N<sup>a</sup> |          | N = -5.92 + 0.11hab + 0.04C*ab | 0.68        |
| C/N<sup>a</sup> |          | C/N = 300.24 – 4.12hab – 1.29C*ab + 0.60L* | 0.77        |
| DPH<sup>a</sup> |          | DPH = 2.80 – 0.01L* – 0.03hab – 0.01C*ab | 0.65        |
| C<sup>b</sup> |          | C = 55.47 + 0.02L* + 2.31a* – 1.46b* | 0.73        |
| N<sup>b</sup> |          | N = 1.22 – 0.03L* – 0.41a* + 0.28b* | 0.67        |
| C/N<sup>b</sup> |          | C/N = 41.27 + 0.62L* + 12.28a* – 7.72b* | 0.72        |
| DPH<sup>b</sup> |          | DPH = 0.92 + 0.12a* – 0.09b* | 0.69        |
| C<sup>c</sup> |          | C = 35.27 + 0.04[(a*/b*) x 1000] – 0.04[a* x b*] | 0.70        |
| N<sup>c</sup> |          | N = 3.34 + 0.01[a* x b*] – 0.01[1000 x a*/(L* + b*)] + 0.15[2000 x a*/(L* x b*)] | 0.71        |
| C/N<sup>c</sup> |          | C/N = -36.63 + 0.12[(a*/b*) x 1000] + 0.32[2000 x a*/(L* x b*)] | 0.79        |
| DPH<sup>c</sup> |          | DPH = – 0.28 + 0.02[2000 x a*/(L* x b*)] – 0.49[a*/b*] | 0.66        |

<sup>a</sup> Usual color parameters (polar coordinates): L*, C*ab and hab

<sup>b</sup> Usual color parameters (Cartesian coordinates): L*, a* and b*

<sup>c</sup> Unusual color parameters

4. Conclusions and prospects

These results demonstrate the utility of quantifying the color of the peat to obtain predictive relationships of soil properties and, at the same time, propose new proxies in the field of paleoenvironmental reconstruction and paleoclimate studies. The open question is how to quantify this relationship and provide accurate predictive power for several properties of peatlands. In this regard, it will be worthwhile to further investigate other type of mires and organic soils, (i) increasing the number of samples analyzed, (ii) considering the effect of moisture content on the color (since soil moisture generally increases soil darkness reducing the ability to generate accurate predictive models), (iii) analyzing more in detail short-term changes, (iv) comparing the results with records of other validated proxies and (v) introducing other, more sophisticated, statistical tools as PCR and PLS modeling. In any case, results are encouraging and further investigation to determine the value of color as proxy for Holocene environmental change is warranted.
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