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Dear Dr. Paddy French:

Please find attached paper entitled "Using a mobile phone as a Munsell soil-colour sensor". We have thought in Sensors and Actuators A as the best paper to publish the results of our work related developing a method and a mobile app that can recognize soil colour. Figures are in MS. Office format, if there is any problem with this fact please contact us.

Thank you very much.

Best Regards.

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Using a mobile phone as a Munsell soil-colour sensor

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Abstract

An Android application for soil-colour classification is presented in this work. Until now, soil colours have been determined in most cases by a visual comparison between the soil sample and the standard chips of the Munsell Soil Colour Charts. The objective here is to assess whether a mobile-phone camera is able to replace these standard colour charts and, therefore, provide an objective evaluation of soil colour under controlled illumination. For this, we have developed an application that takes a picture of the soil to classify, allowing the user to select the area of interest and, after *RGB* image-processing, shows the results on the screen of the mobile phone, i.e. the Hue, Value, and Chroma values of the Munsell system (*HVC* coordinates). Because *RGB* is a device-dependent colour space, we have firstly calibrated the system using the 238 chips of the Munsell Soil Colour Charts in order to build the transformation *RGB-HVC* models. Subsequently, the application has been tested on 40 colour samples of the Natural Colour System (NCS) Atlas and 30 samples of real soils. The results revealed that the application developed gives low colour differences in the calibration chips (on the average, 2.03 CIELAB units with a standard deviation of 1.04), and higher (on the average, 6.49 and 4.68 CIELAB units, with a standard deviation of 2.06 and 2.32, for the NCS and real soil samples, respectively), but still acceptable, for the other sets of samples.

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Highlights

- We have checked is a mobile-phone camera phone is able to measure soil colour.
- A mobile-phone camera has been calibrated to obtain HVC and XYZ colour coordinates.
- Results show that our models have similar accuracy than a panel of observers.
- An Andoid app has been developed to simplify this colour measurement.

1. Introduction

Specifying colour by the Munsell system is a simple visual method used by artists, designers, scientists, engineers, and government regulators as an alternative to the more precise, costly, and complex method based on spectrometric measurements and the use of CIE systems [1-3]. For example, in the natural sciences, it is a usual practice to identify and record the colours of specimens such as human skin, flowers, foliage, minerals, and soils. Specifically in soil science, Munsell colour has far-reaching implications for examination, description, and classification of soils [4, 5], as well as in studying soil genesis and evaluation, being a valuable indicator of soil structure and components [6, 7]. Soil colours are usually determined by visual comparison, seeking the closest match between the soil sample and one of the standard chips contained in the so-called Munsell Soil Colour Charts, i.e. artificially coloured papers mounted on constant Hue cards, showing Value (lightness) and Chroma (colour intensity) variations in the vertical and horizontal directions, respectively. Thus, the Munsell designation of that chip (Hue H, Value V, and Chroma C) is assigned to the soil sample under study.

Several problems have been described previously in relation to identifying the colour of soil specimens using Munsell Soil Colour Charts, all of them related to the three main factors affecting the psychophysical character of colour: illumination conditions, sample characteristics, and the observer's capabilities [8]. Standardization of the illumination has been an adopted solution to facilitate the use of the Munsell Soil Colour Charts [9], although changes in natural daylight may play a role in the field [10]. Colour differences among chips with the same designation in Munsell Soil Colour Charts from different manufacturers, editions, and degrees of use have also been reported, with an average of 3.7 CIEDE2000 units [11]. Observer variability has also been studied, reporting a mean inter-observer variability of 5.0 CIELAB units from different soil scientists performing colour judgments on the same soil sample under controlled illumination conditions [12].

Currently, the increasing demand of soil data for applications such as precision agriculture and dynamic models for monitoring environmental change has spurred the development of proximal soil sensors. The rationale is to collect larger amounts of data using simpler, cheaper, faster, and less laborious techniques than conventional soil analyses, even at the cost of less accuracy. Since soil colour is related to soil components, and, by extension, properties or conditions depending on them [12], proximal soil-colour sensing may provide an integral way of comparing soils, including evolution, degradation, pedoclimate, and fertility analyses. Digital cameras have already been proposed as proximal soil-colour sensors [13, 14], for which their potential is supported by the possibility of gaining reliable colour information from *RGB* digital images. Currently, the only colour measure by pixels is related to *RGB* signals, and several authors [15] have reported computational solutions that allow digital images to be transformed into the standard CIELAB colour space from each pixel of the digital *RGB* image. In this paper, we seek *ad hoc* solutions in the gamut of the Munsell Soil Colour Charts, performing the immediate computational conversion on the same platform that produced the *RGB* image. In this case, as pointed out in the literature [16, 17], the *RGB* colour space is device-dependent, signifying that the *RGB* values vary when the device is different. Therefore, it is necessary to develop a transformation to establish the Munsell coordinates (*HVC*) from the *RGB* information provided by our specific device.

The requirements for Munsell soil-colour measurements are available or can be implemented in current typical mobile phones. This includes a high-resolution digital camera, with a low-power high-performance processor at running frequencies of up to 1 GHz, sophisticated operating systems offering multi-tasking, Java support, and options for installing and running externally developed applications. Initially mobile phones with built-in cameras were used as imaging devices to collect and transmit digital data to an off-site laboratory or external computer, which processed the information and returned the analysis results to the phone. Thus, mobile phones used for biological and forensic applications [18] have proved useful in telemedicine[19], and they have also been used for bad-smell monitoring of the living environment [20]. In addition, a mobile phone has recently been used for on-site signal or data processing to determine specific analyte concentrations from single-use chemical reactive membranes [21]. In the present study, a more complex analytical procedure is required of the mobile phone, on the one hand, because of the greater colour gamut involved in Munsell soil colours, usually reddish, brownish or yellowish from dark to light and variable intensity, and, on the other hand, because the principles of colorimetry must be taken into account for the calculations.

Our overall goal was to investigate the potential of a mobile phone to capture soil-colour images and process them with a colorimetric rationale, returning the Munsell notations corresponding to the digital *RGB* captured images. To do so, our specific objectives were: (i) to develop a custom image-processing application for the mobile phone; (ii) to build a model and estimate its parameters for establishing Munsell notations from *RGB* measurements; (iii) to implement the image processing and the conversion model *RGB*-Munsell, making them work together as a software in the mobile phone; and (iv) to assess the accuracy achieved by the mobile phone with respect to that of a commercial spectroradiometer and spectrophotometer using the CIE systems.

2. Material and Method

To ascertain whether a mobile phone camera can replace the use of Munsell Soil Colour Charts and a subjective evaluation of soil colour under controlled illumination, we followed the methodological approach shown in Figure 1. Firstly, the *RGB* sensor was calibrated and then, tested twice. Samples were measured by three different devices (mobile phone, spectrophotometer, and spectroradiometer) and for different three colour spaces (Munsell, *HVC*, and *XYZ*). Models were developed to relate mobile-phone measurements with measurements from the spectrophotometer and spectroradiometer (as our spectrophotometer provides *HVC* coordinates, but the spectroradiometer does not, we used both of these two devices).

2.1. Samples

Firstly, it is necessary to relate *RGB* colour coordinates (device-dependent) with CIE tristimulus values *XYZ* and Munsell coordinates *HVC* (device-independent). For this calibration, we used a recent edition of the Munsell Soil Colour Charts [22] to build two models from RGB digital images. The charts include 238 standard colour chips with their corresponding Munsell notations, placed on seven Hue charts from red to yellow: 10R, 2.5YR, 5YR, 7.5YR, 10YR, 2.5Y, and 5Y (H = 10, 12.5, 15, 17.5, 20, 22.5, and 25, respectively). In each Hue chart, the chips are arranged by visual steps of Value (2/ to 8/) and Chroma (/1 to /8). It can be assumed that any natural soil colour is represented in these standard charts, considering the possibility of intermediate colours between neighbouring chips.

Subsequently, for assessing the accuracy and reliability of colours measured by the mobile phone and the performance of the models, we selected 40 colour samples from the Natural Colour System (NCS) Atlas. Like the Munsell Atlas, the NCS Atlas is based on colour perception and is produced as a book of chips. Spectrophotometric measurements performed by a Konica Minolta 2600d spectrophotometer (Tokyo, Japan) were used to establish the Munsell notations *HVC* and to choose 40 NCS chips in an effort to sample the colour gamut of the Munsell Soil Colour Charts. The spectrophotometer measures spectral reflectance (from 380 to 780 nm, 5nm steps) and computes Munsell notation (*HVC*) of each sample. Our selection comprised Munsell Hues between 0.1 YR and 5.5 Y, Values between 2.8/ and 8.2/ and Chromas between 0.5/ and 8/.

In addition, 15 soils were taken from Mediterranean Entisols and Inceptisols [9] to prepare two groups of colour samples which were placed in circular plastic containers (15 mm in diameter and 4 mm thick). The first group consisted of 15 samples having particles less than 2 mm in size, and the second one consisted of other 15 samples of the same soil material, which was ground and homogenized in an agate mortar until obtaining a powder with particle size of less than 50 µm. Once the upper open surface of containers was levelled, spectrophotometric measurements with the Minolta 2600d were used as reference, ranging between 8.8YR 4.5/4 and 2.6Y 5.1/2.3.

2.2. Instruments and software

Today, there is a wide range of operating systems for developing applications in mobile phones such as Android, Symbian, BlackBerry or Windows Mobile. For the application here presented, Android was selected as operating system for the following reasons. Firstly, Android is becoming well established in most communication devices such as mobile phones, netbooks, tablets, and even in electrical appliances (e.g. microwaves and washing machines). Secondly, Android uses open code and a free license, allowing a wide community of developers to expand and improve the functionality of this operating system. Java is the language used by Android, enabling the use of libraries and other applications previously developed for this language.

In this way, the device used as an instrument was a mobile phone HTC Desire HD (HTC Corporation, Taiwan), which runs Android 2.2. The size of the phone was 4.84”×2.68”×0.46”, weighing 164 grams. The main characteristics of this mobile phone include a 4.3” touch-sensitive screen with a resolution of 800×480 pixels and an integrated camera up to 8 megapixels, which uses a CMOS sensor with autofocus function. The camera allows acquisition of the images of aforementioned standard chips of the Munsell Soil Colour Charts, NCS colour samples and soil-colour samples. Additional technical details of the camera in the HTC Desire HD mobile phone were unavailable.

A Konica Minolta CS2000 spectroradiometer (Tokyo, Japan) was used as the reference instrument to characterize the mobile-phone camera. In this sense, we verified whether the *RGB* signals of the phone camera agreed with the conventional spectroradiometric colour measurement. This device measured the reflected spectral power distribution (from 380 to 780 nm, 2nm steps) of any sample, and the corresponding tristimulus values *XYZ* were computed by the device using the CIE 1964 standard colorimetric observer.

The ASTM standard D 1535 strongly recommends daylight illuminating equipment for Munsell colour determinations by charts. Consequently, a GretagMacbeth Spectralight III lighting booth (X-Rite, Switzerland) equipped with a D65 simulator has been used as the light source in this work. The spectral accuracy and temporal stability of the D65 source in this lighting booth are satisfactory and its colour reproduction is very good [23]. The dimensions of the viewing booth were 70×94×62 cm (height x width x depth) and its D65 source was made by a combination of halogen lamps with appropriate filters.

2.3. Measurement procedure inside the lighting booth

To gather colour information from the chips in the Munsell Soil Colour Charts, we had to process the photographs taken with the built-in mobile-phone camera. All the pictures taken were saved in JPEG format, since this is the default format in the HTC Desire HD phone. The images were processed inside the mobile phone using software developed by us, with no need of external equipment to extract colour information. The measurement geometry used to acquire the pictures during the calibration process in the laboratory is presented in Figure 2.

Each Munsell Hue chart was placed inside the booth, on a grey surface tilted 45º with respect to the horizontal plane of the cabin. The surface faced both the phone and the spectroradiometer (Figure 2). To avoid the flat correction of the camera and differences in light intensity due to the distance from the sample to the light sources, we took all the pictures (one for each Munsell chip) using the selected chip at the same position, so that the region of interest in each case was consistently the centre of the image. The mobile-phone camera and the spectroradiometer were kept at fixed positions and focused on the centre of each chip in order to establish a relation between the information provided by these two instruments. The spectroradiometer measured the X_{10} Y_{10} Z_{10} tristimulus values of each chip while the mobile phone extracted the *RGB* information. In addition, a PTFE reference white, provided by the manufacturer of our spectroradiometer, was placed inside the lighting booth next to each Munsell chart and was used to minimize the effect of the automatic exposure time and white balance of the mobile-phone camera.

During the calibration process, the spectroradiometer and mobile device were attached (Figure 2). Thus, the optical axis of the spectroradiometer was perpendicular to the sample, the optical head of the instrument being placed at a constant distance of 55 cm from the sample. The distance between the sample and both devices was fixed because this affected the number of pixels in the area on interest that could be taken into account to establish the coordinates *RGB* and, therefore, the *HVC* Munsell coordinates; and this could also affect the intensity of lighting on the sensor according to the inverse-square law.

The mobile device was placed under the optical head of the spectroradiometer using an anchoring system to avoid its movement during the calibration process. Since both devices had to be focused on the centre of the same chip, the tilt angle of the mobile phone was slightly different from that of the optical axis of the spectroradiometer. As shown in Figure 2b, measurements were performed in a dark room where the photographs of the chips were illuminated only by the light source of the cabin. NCS samples were measured exactly under the same conditions than Munsell samples. The soil samples analysed for testing the application were measured using the same system with no tilt of the grey surface.

The built-in camera of the HTC Desire HD mobile phone has different parameters available, which must be fixed before taking photographs. The ISO (International Organization for Standardization) parameter determines how sensitive the image sensor is to the environmental light. Usually, the image sensor is calibrated to provide the best image with the lowest ISO. Since all of our photographs were taken under daylight illumination, the ISO chosen was 100, in a range from 100 to 800. With respect to the white balances, the daylight option was selected bearing in mind that the mobile phone was to be used in high luminance, that of the lighting booth at the plane of the samples being approximately 1400 lx. With this option, we ensured that the mobile phone applied the same correction to all the images made. The grid of the camera made it possible to identify the central area of the photograph to situate the region of interest of each chip exclusively in this area. Since the colour of the samples under daylight was the object of our study, the double LED flash incorporated in our mobile phone was disabled so as not to modify the *RGB* coordinates of the image.

2.4. Implemented software in the mobile phone

Although the phone software has a white balance algorithm, as mentioned above, the manufacturer does not provide information on this correction and thus we could not avoid it. A secondary white balance was included in order to minimize effects of the possible variations of the light source. To apply this secondary balance to all the photos taken, we used the aforementioned Konica Minolta PTFE reference white. In this way, once that the application started in the mobile phone, the first step was to calibrate the system by taking a photograph of this reference white placed in our booth at the same position than the Munsell Soil Colour Chart (see Figure 3b). With this purpose, an option of calibration was included in the main menu of the application developed. From this menu, it was also possible to process an image taken from the camera directly, to obtain the information *in situ*, or load a picture previously saved (see Figure 3a).

From this measurement of the reference white, we set its *R*, *G*, and *B* coordinates (see Figure 3c), which correspond to the maximum possible *RGB* values in the picture. The *R, G*, and *B* coordinates of the reference white were saved by the application, for future use until a new calibration was required. In a previous study [21], it has been demonstrated that the mode of *R*, *G*, and *B* values is more suitable for the analysis of non-homogeneous areas than that of the mean values, since the former avoids the potential influence of small areas in the picture that are not of interest, removing the effect of noisy pixels from heterogeneous areas. After the calibration, the images for each chip were taken with the mobile phone (Figure 2) and the mode of the *R*, *G*, and *B* coordinates determined for each chip was normalized using the mode of the *RGB* values from the reference white, making sure that all the chips were in the appropriate range of the *RGB* colour space. This normalization was made for each pixel following

Eq. 1, where n=8 in our current device, this representing the number of bits per pixel for each colour channel [24].

$$RGB_{normalized}=2^{n}\ RGB_{acquired}/RGB_{white} \tag{1}$$

The image processing took place inside the same device, eliminating the need of external elements, such as computers, for further processing. Since the software designed and installed in the mobile device allowed selection of the area of interest in the photos, the statistical mode was established for each coordinate taking into account only the cropped area while the background of the image did not affect the calculations, either (see Figure 3d). Once the chip was positioned inside the cutting area, the colour information of each pixel was set directly from the screen of our phone in order to determine the statistical mode for R, G, and B of the set of pixels belonging to the chip photographed. This process had to be repeated for each chip of the Munsell charts in order to gain the complete *RGB* information of the Munsell Soil Colour Charts. For each chip, the corresponding *RGB* information was shown on the screen of the phone and saved to be used for the formulation of the equations which relate *RGB* and *HVC* colour notations.

2.5 Calibration models to implement in the mobile phone

As mentioned in Section 2.1, any digital camera can set *RGB* coordinates and these coordinates depend on the spectral sensitivity of the camera sensor, so that the *RGB* colour space is a device-dependent colour space. On the other hand, our final objective was to find Munsell *HVC* coordinates (i.e. Hue, Value, and Chroma coordinates, respectively), and these colour coordinates are “device independent” providing all the necessary information for the soil-colour classification in accordance with the Munsell System. In this section, we explain the way to relate device-dependent and device-independent colour coordinates. To do so, we use the method proposed in the literature [17, 25].

If we assume a linear relationship between *RGB* and any device-independent space, such as *XYZ*, we can write:

$$i=dT \tag{2}$$

where i contains the device-independent colour coordinates ($3x1$ matrix), d are the device-dependent coordinates ($3x1$ matrix), and T must be a 3x3 matrix with the linear transformation. In this case, by measuring only 3 samples, we can determine each of the nine parameters of matrix *T*. If the relationship between spaces is unique, we can also write the reciprocal transform

$$d=iT^{-1} \quad (3)$$

However, Johnson [26] noted that it is better to use a non-linear transformation and write a polynomial transform between colour spaces, and in this case matrix *T* dimension is 3x*n,* where *n* is the degree of the polynomial. Under these conditions, it may be impossible to calculate T^{-1}, but we can compute the pseudo-inverse matrix proposed by Penrose [27], which is a 3x*n* matrix, providing the nearest relationship between vectors *i* and *d*.

In previous works [17, 25], this method has been successfully used to relate tristimulus values *XYZ* and *RGB* values. In our case, we computed different polynomial relationships to establish each of the Munsell coordinates, too. In this way, we compared the *RGB* response of the mobile phone sensor with response from two different colour devices (spectrophotometer and spectroradiometer), providing two different colour specifications: *HVC* and *XYZ* colour coordinates, respectively.

3. Results and Discussion

3.1. Calibration models: transformations from RGB to XYZ and HVC

As stated above, from the *RGB*, *HVC*, and *XYZ* values measured, we computed different polynomial models that relate device-dependent colour coordinates (*RGB*) to device-independent colour coordinates (*HVC* or *XYZ*) by the pseudo-inverse method [27]. Table 1 shows different models tested, from a very simple linear model (1st row) to a 23-term polynomial complex dependence. The first column shows the terms of the polynomials, the second column shows the average of Pearson's correlation coefficient between *XYZ* values measured by the spectroradiometer and predicted by each model, the third column shows the average of Pearson's correlation coefficient between *HVC* Munsell coordinates measured by the spectrophotometer and values predicted by each model, while the fourth column provides the CIELAB colour differences from *XYZ* predictions of the models and spectroradiometric measurements. All these models have been computed by using the 238 Munsell chips in the Munsell Soil Colour Charts.

Number of terms in the polynomial	*r* for XYZ models	*r* for HVC models	ΔE^*_{ab}

[1,R,G,B]	0.9811	0.9090	9.65
[1,R,G,B,RGB]	0.9943	0.9101	6.03
[1,R,G,B,RG,RB,GB]	0.9965	0.9246	3.44
[1,R,G,B,RG,RB,GB,RGB]	0.9965	0.9259	3.39
[1,R,G,B,RG,RB,GB,R^2,G^2,B^2]	0.9973	0.9547	2.14
[1,R,G,B,RG,RB,GB,R^2,G^2,B^2,RGB]	0.9973	0.9562	2.07
[1,R,G,B,RG,RB,GB,R^2,G^2,B^2,RGB,R^3,G^3,B^3]	0.9974	0.9568	1.85
[1,R,G,B,RG,RB,GB,R^2,G^2,B^2,RGB,R^2G,G^2B,B^2R, R^2B,G^2R,B^2G,R^3,G^3,B^3,R^2GB,RG^2B,RGB^2]	0.9980	0.9695	1.75
[1,G,B,RG,R^2,G^2,RGB,B^3]	0.9972	0.9407	2.03

Table 1. Summary of the results found using different models

We chose the cubic models with 8 coefficients (last row of Table 1), because their correlation coefficients are substantially higher, the average CIELAB colour difference is relatively small, and it has few coefficients, simplifying the computational work to be made by the mobile phone. The HVC mathematical model is shown in Eq. 4, where ϕ represents *H, V* or *C* coordinates and the eight lower-case letters have the values shown in Table 2:

$$\phi(RGB) = a + bG + cB + dRG + eR^2 + fG^2 + gRGB + hB^3 \qquad (4)$$

	a	b	c	d	e
H	10.5649	0.4622	-0.2192	-0.00254	0.000192
V	2.3252	0.0303	-0.0069	-5.36E-05	4.33E-05
C	1.8311	0.0157	-0.0351	-0.00038	0.000289
	f	**g**	**h**	**r**	
H	0.000609	7.98E-06	-4.64E-06	0.8878	
V	-1.61E-05	2.40E-07	-2.96E-08	0.9505	
C	0.000163	-3.00E-07	2.25E-07	0.9837	

Table 2: Coefficients of the models built to compute HVC from RGB. The end column shows Pearson's correlation coefficients for each model.

Table 2 shows that the linear correlation coefficient for the *H* coordinate is lower than for the other ones. This is not a surprising result, given that the Munsell Colour System is a cylindrical system where *H* is the angular coordinate, and therefore when the radial coordinate *C* is low the uncertainty in the angular coordinate is higher [7].

As mentioned above, the calibration process is intended to make the spectroradiometric measurements of the tristimulus values of a given sample identical to the ones found using the mobile phone. To check the quality of the models implemented in the software of our mobile phone, we proposed the same functional dependence as in the previous Eq. (4), to go from *RGB* values to *XYZ*. Eq. 5 and Table 3 summarise the results for the adopted model providing the *XYZ* tristimulus values. Linear correlation coefficients were computed between each of the tristimulus values given by the model and values directly measured by the spectroradiometer, as shown in Table 3.

$$\phi'(RGB) = a' + b'G + c'B + d'RG + e'R^2 + f'G^2 + g'RGB + h'B^3 \qquad (5)$$

	a'	***b'***	***c'***	***d'***	***e'***
X	1.350194	0.075939	-0.00821	0.000105	0.000381
Y	0.724558	0.114619	-0.0172	-3.20E-04	3.06E-04
Z	-2.12908	0.10279	0.087903	-0.00048	0.000104
	f'	***g'***	***h'***	***r***	
X	0.000124	2.79E-06	-1.31E-06	0.9971	
Y	0.000604	3.08E-06	-1.54E-06	0.9972	
Z	0.000174	2.41E-06	2.13E-06	0.9973	

Table 3: Coefficients of the models built to compute XYZ from RGB. The end column shows Pearson's correlation coefficients for each model..

Table 3 shows high values of all correlation coefficients, suggesting that these *XYZ* models based on *RGB* values from the mobile phone camera are quite accurate; in particular, they are more accurate than *HVC* models. Now it is possible to compute the colour difference between the colour measured by the mobile phone and colour measured by the spectroradiometer. Following International Commission on Illumination (CIE) recommendations, we used CIELAB colour-difference formula as a measurement of the quality of the model.

Figure 4 shows the percentage of Munsell samples that have a CIELAB colour difference below different fixed values (e.g. lower than 0.5, lower than 1, etc.). The average value of these colour differences was 2.03 CIELAB units (Table 1) with a standard deviation of 1.04. It is noteworthy that more than 90% of the samples used in the calibration (238 chips) were measured by the mobile phone with accuracy below 3 CIELAB units. Based on these results, the mobile phone appears to provide accurate colour information on the Munsell samples. The specific accuracy achieved by the mobile phone using different sets of samples than those employed for the calibration (238 chips) will be analysed in the next section.

3.2. Validation

The proposed measurement system was applied to two different sets of samples to test the reliability of the mobile phone used as Munsell soil-colour sensor. These two sets of samples were measured inside the same colour booth and illumination described above, following the same process used for the calibration, in order to study the response of the mobile phone for a set of samples in the colour gamut of real soil samples but different from those employed for the calibration.

Firstly, we selected 40 samples of the NCS Atlas to establish the corresponding HVC coordinates. These were selected from spectrophotometric measurements trying to sample the full colour range of the Munsell Soil Colour Charts. Figure 5 shows the differences between the Munsell coordinates determined from the mobile phone (using the model described in the calibration) and the ones provided by our spectrophotometer for these 40 NCS samples. As can be seen, the differences range between [0-8] for the Munsell Hue, with a 70% of the samples inside the [0–2] interval. For Munsell Value and Chroma the range of differences was dramatically lower than for Munsell Hue: [0-2] units in both cases, most of the NCS samples being within the interval [0-1]. Also, the average values of the differences are shown for each interval in Fig. 5, using red dots with error bars and the right y-axis.

Figure 6 shows the percentage of NCS samples that have a CIELAB colour difference below different fixed values. The mean value of these colour differences is 6.49 CIELAB units with a standard deviation of 2.03. Around 50% of the samples used (40 chips) were measured by the mobile phone with an accuracy of below 6 CIELAB units.

Finally, the Android application in our mobile phone was tested in real soil samples under the same conditions used during the calibration. The set used in this validation process was composed of 15 soil samples with a particle-size < 2 mm (Figure 7a) and 15 soil samples with a particle-size < 0.05 mm (Figure 7b); that is, a total of 30 real soil samples. A picture was taken of each sample and, selecting the area of interest, the corresponding *HVC* values were established.

Figure 8 presents the differences between the soil colour established with the mobile-phone application and the values provided by the spectrophotometer. In comparison with NCS samples, the soil samples gave better results. Hue differences went from -2 to 5; 63% of the samples were determined with an error of less than 2 units, which was lower than the standard hue step (2.5 units) in the Munsell Soil Colour Charts. For Value and Chroma, most of the samples had an error of less than 1 Munsell units.

The histogram in Figure 9 shows the CIELAB colour differences (the soil colour determined with the mobile phone minus the spectrophotometric soil colour) below different fixed values. The mean value of these colour differences was 4.68 CIELAB units with a standard deviation of 2.32. More than 70% of the samples used were measured by the mobile phone with acceptable accuracy (error less than 6 CIELAB units). It also bears mentioning that visual assessments performed by soil scientists using Munsell Soil Colour Charts reported a variability of around 5.0 CIELAB (units) [12], very similar to the one found using our mobile-phone application with soil samples.

4. Conclusions

In conclusion, Table 4 presents the colour differences of each of the 3 groups of tested colour samples, in terms of differences in *HVC* Munsell coordinates as well as CIELAB colour differences. The results for the calibration process were good, since the Munsell coordinates showed almost no differences, and in CIELAB terms we found a low average value of colour difference of 2.03 CIELAB units (note that colour differences around 1.0 CIELAB units were quite similar to the colour threshold detected by normal human observers in different experiments [28]). When we used the models with other sets of samples, as those from the NCS Atlas or real soil samples, as might be expected, our results proved worse than for calibration, especially for CIELAB differences between spectroradiometer and our mobile-phone application. We should take into account that these sets of samples were taken randomly to test the mobile-phone application once the models were developed. A fuller analysis of these samples showed that many of them were near the limits of the model, which may explain the worse results shown in Table 4 for NCS samples and soil samples. In any case, our method demonstrates that it is possible to use a conventional mobile phone as a soil-colour sensor under controlled illumination conditions, since this device may achieve accuracy similar to that of panels of soil scientists under similar viewing conditions [12].

Group of samples	Colour parameter	Mean value	Standard deviation

Munsell Soil Colour Charts (calibration)	ΔH	<0.001	2.23
	ΔV	<0.001	0.52
	ΔC	<0.001	0.38
	ΔE^*_{ab}	2.03	1.04
NCS colour chips	ΔH	0.13	2.38
	ΔV	0.65	0.23
	ΔC	0.11	0.48
	ΔE^*_{ab}	6.49	2.06
Soil colour samples	ΔH	1.70	1.51
	ΔV	0.65	0.51
	ΔC	0.20	0.31
	ΔE^*_{ab}	4.68	2.32

Table 4: Colour differences between mobile-phone application predictions and colour measured by a spectrophotometer (for HVC) and a spectroradiometer (for CIELAB).

Acknowledgements

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Figures

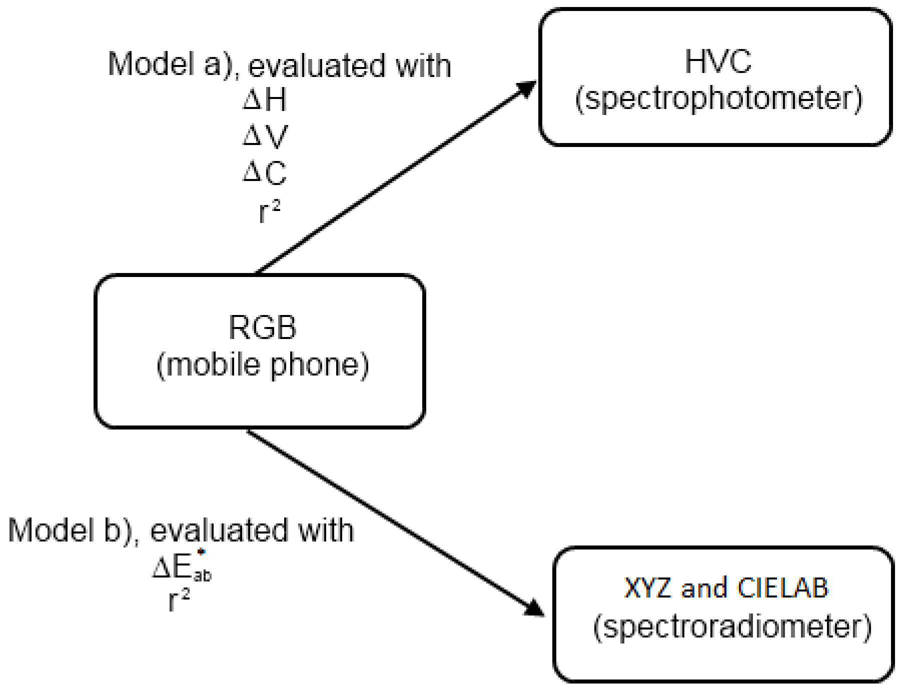
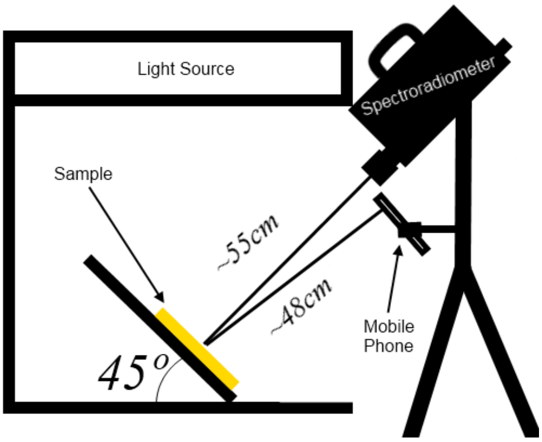


Figure 1: Scheme followed in this work.



(a)

(b)

Figure 2: (a) Scheme of the measurement process. (b) Photograph of the experimental setup during the calibration process (the reference white is placed at the right of each Munsell Hue chart containing chips with different Value and Chroma).

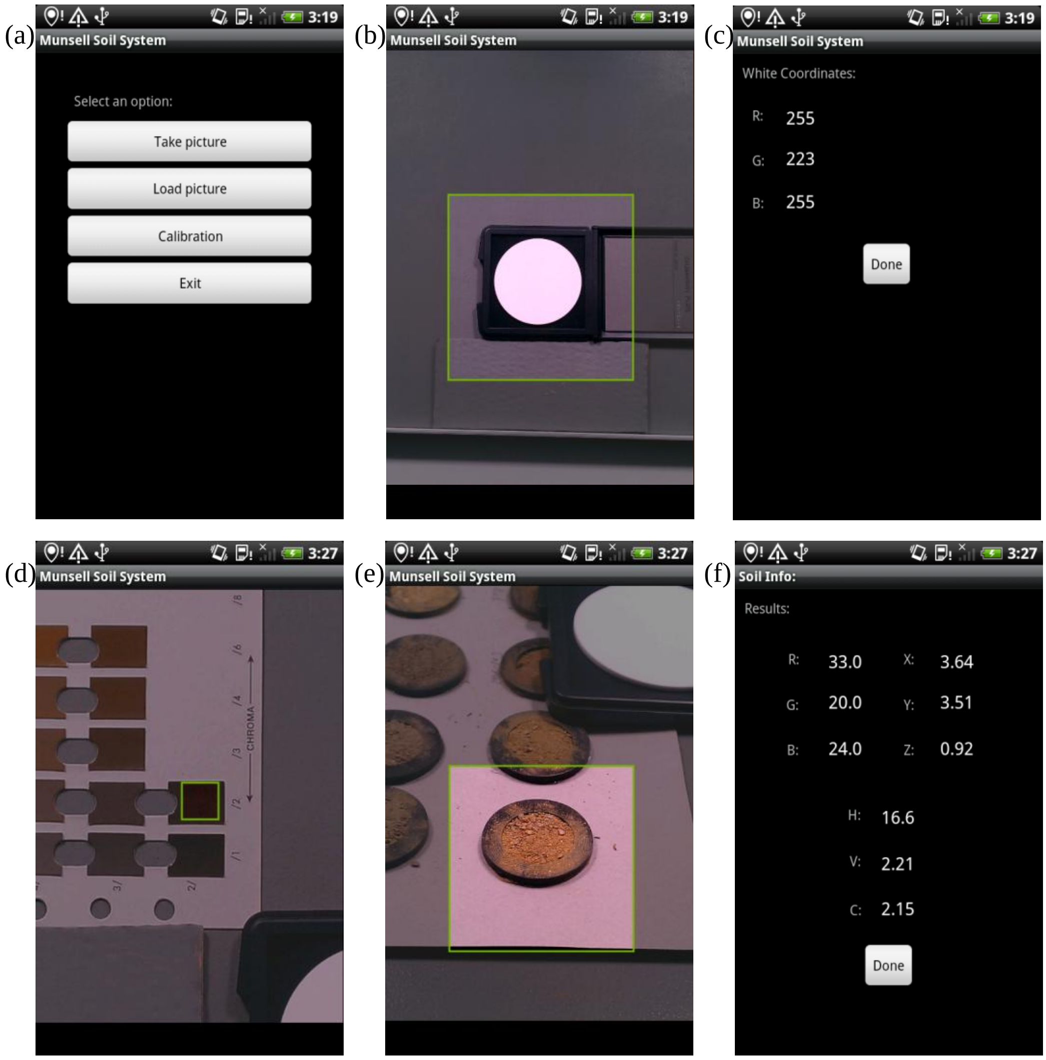


Figure 3: Screen of the phone at three different steps: (a) main menu; (b) calibration using a reference white; (c) *RGB* coordinates of this reference white; (d) selection of the area of interest for one chip of the Munsel Soil Colour Charts; (e) example of a picture using a real soil sample; and (f) the corresponding colour information of this soil sample.

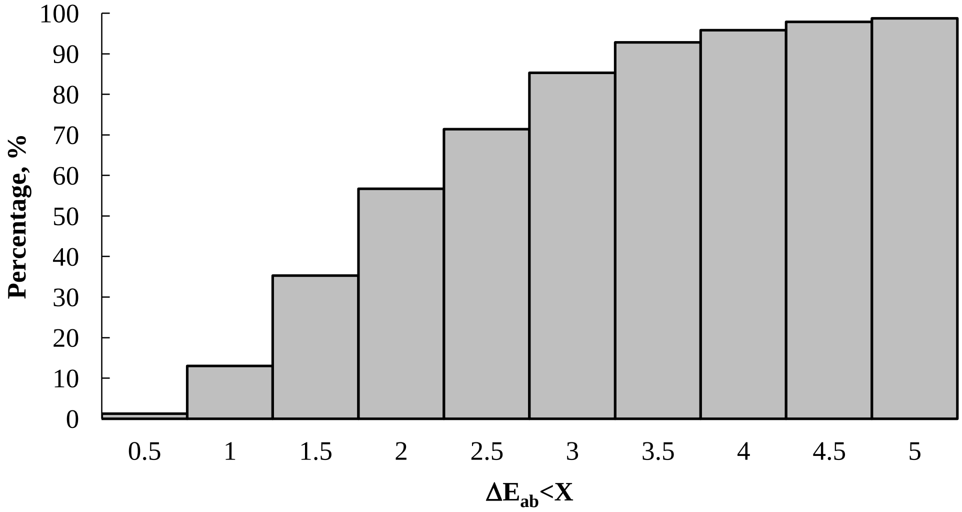


Figure 4: Percentage of 238 Munsell Soil Colour chips classified by our mobile phone application with a CIELAB colour difference lower than different fixed X values.

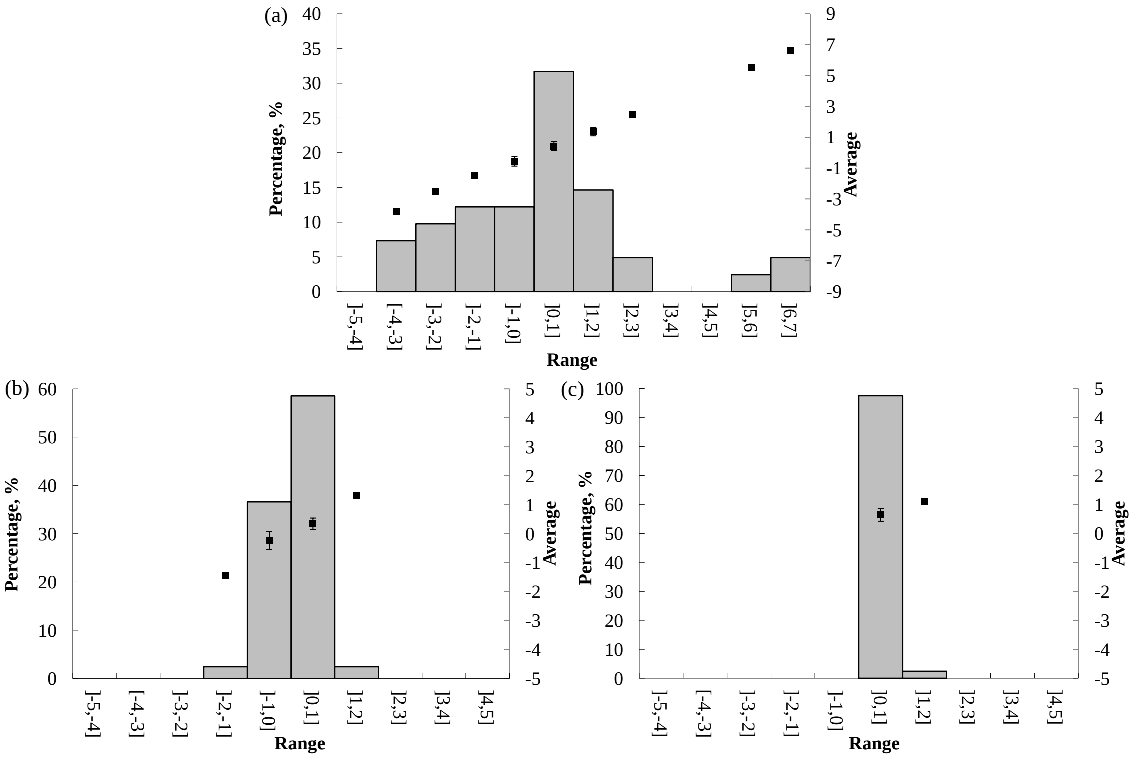


Figure 5: Differences between the mobile phone results and measured spectrophotometric Munsell Hue (a), Value (b), and Chroma (c) for 40 NCS samples.

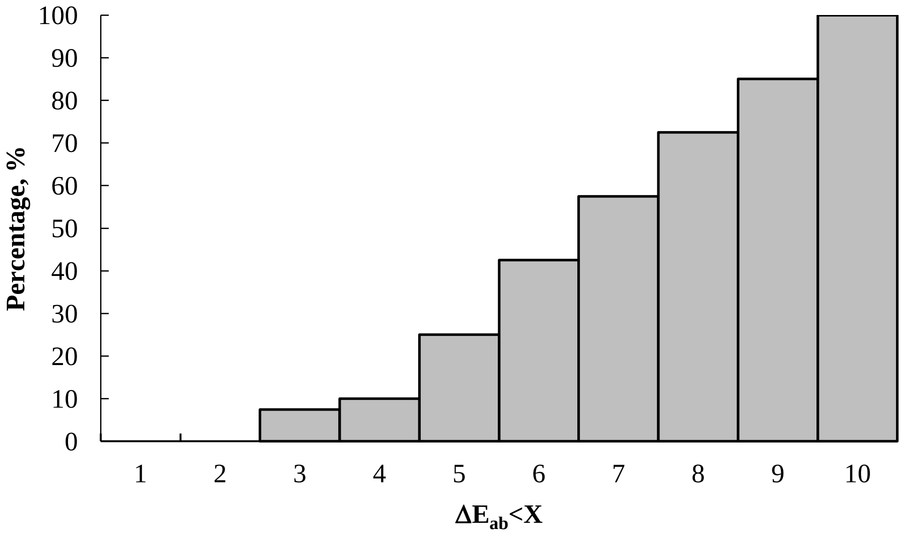


Figure 6: Percentage of 40 NCS colour samples classified by our mobile-phone application with a CIELAB colour difference lower than different fixed X values.

(a)  **(b)** 

Figure 7: Example of soil samples used in the validation process of the system in two particle sizes: (a) < 2 mm and (b) < 0.05 mm.

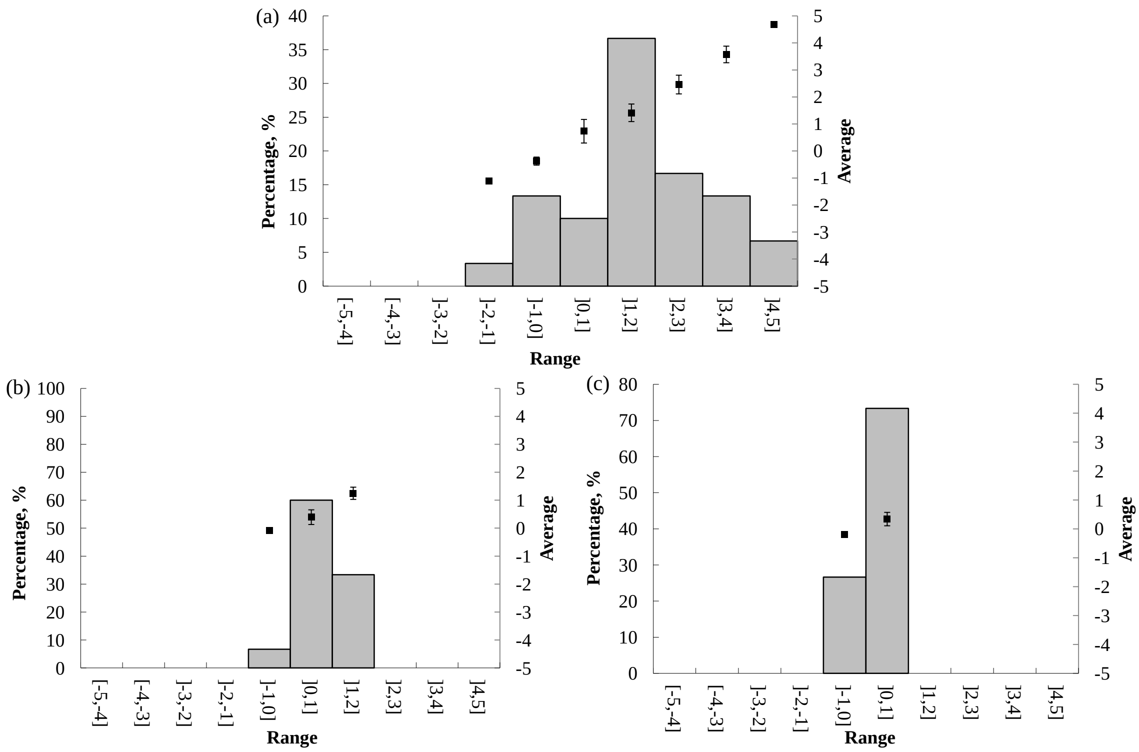


Figure 8: Differences between the mobile-phone results and spectrophotometric measurements of Munsell colour coordinates Hue (a), Value (b), and Chroma (c) for 30 soil samples.

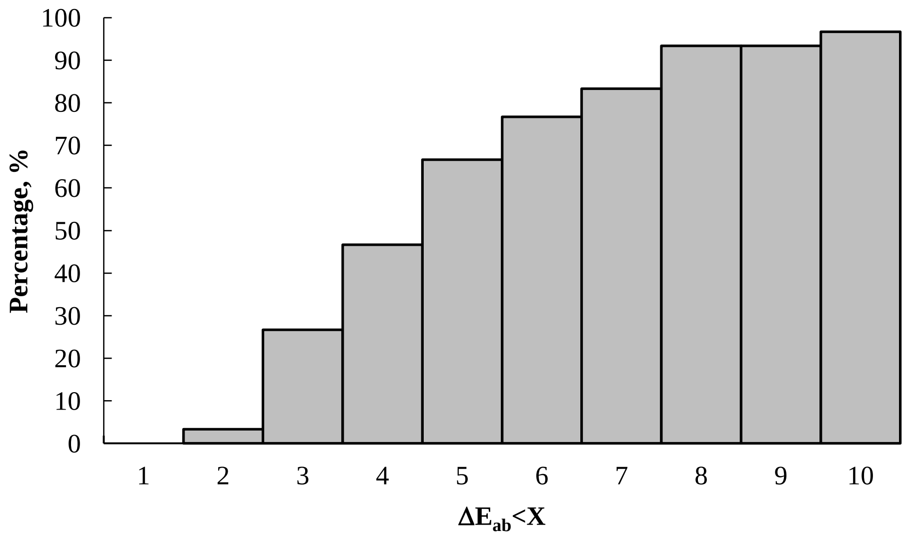


Figure 9: Percentage of 30 soil samples classified by our mobile-phone application with a CIELAB colour difference lower than different fixed X value

Highlights

- We have checked is a mobile-phone camera phone is able to measure soil colour.
- A mobile-phone camera has been calibrated to obtain HVC and XYZ colour coordinates.
- Results show that our models have similar accuracy than a panel of observers.
- An Andoid app has been developed to simplify this colour measurement.