Soil colour designation using Adobe Photoshop™ in estimating soil fertility restoration by *Acacia auriculiformis* plantation on degraded land

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Using Adobe Photoshop™, we applied soil colour designation with the RGB (red, green, blue) and the CMYK (cyan, magenta, yellow, black) schemes in monitoring rehabilitative effects by *Acacia auriculiformis* on a degraded land. Soils were sampled from dry evergreen forest (the original vegetation), bare ground (the most severely degraded) and *A. auriculiformis* plantation plot for the rehabilitative experiment. Single soil physico-chemical and colour variables showed few significant differences between the soils of the evergreen forest and the *Acacia* plantation, while multivariate profiles of these soils were discriminated by discriminant analysis using the physico-chemical or the colour dataset. These results indicate: (i) linkages between degradation–rehabilitation gradient and changes in soil colour; (ii) that the *Acacia* plantation soil was still in rehabilitation, though it largely restored the original soil conditions. Applicability of soil colour designation in monitoring rehabilitative effects on degraded lands was suggested.

Keywords: *Acacia auriculiformis*, land degradation and rehabilitation, multivariate soil profiling, soil colour.

SOIL quality changes depending on management practices. Various soil variables respond to the same impact differently, making the variation a multidimensional property. Hence, in evaluating quality of a soil, it is advantageous to obtain its multivariate profile[1]. Soil colour designation in a multivariate manner was expected to be a method for multivariate profiling of soils. Soil colour is often associated with soil quality[2]. Soil colour standards were developed, and the Munsell colour system[3] became the most widely accepted by the 1990.

The Munsell colour designation scheme is different from the RGB (red, green, blue) scheme, in which soil colour is more easily related to reflactance[4]. This advantage attributes to a set of orthogonal Cartesian coordinates related to soil spectral properties[5]. Scientists had been aware of the above differences between the colour designation schemes[3]. However, not many studies have tested the RGB scheme in designating soil colour[2,4,6], because the Munsell colour charts work well for many purposes. Therefore, it was not an absolute need for many laboratories to designate soil colours with the RGB scheme.

Continuous measures offer precise multivariate profiles of soils. Continuous measures can designate all colours, including those, in the strict sense, that do not exist in the Munsell charts[4]. For designating soil colours with the Munsell scheme in a continuous manner, some special tools have been used[7]. For the RGB scheme, recently, a simple and feasible method was shown to be applicable in food colour designation using the Adobe Photoshop™ software[8]. In this study, we designated soil colours using the software. In addition to the RGB scheme, we also tested the CMYK (cyan, magenta, yellow, black) scheme that has a complementary relationship with the RGB scheme[6].

We compared colours of soils over a land degradation–rehabilitation gradient in Sakaerat, Thailand[9]. Soils were sampled in evergreen forest (the original vegetative type), bare ground (the most severely degraded) and *Acacia* plantation plots for the rehabilitative experiment. The digital images of the soils were analysed using the Adobe software to obtain the multivariate profiles. Then, rehabilitative effects of the *Acacia* plantation were investigated.

The Sakaerat Environmental Research Station, Wang Nam Kiao District, Nakhon Ratchasima (14°30′N, 101°55′E) was established in 1967. At that time, most of the area had already been disturbed by human activities[10]. The area is 7808 ha and the altitude ranges from 250 to 762 m asl. The climate is classified as savanna[11]. The area includes dry evergreen forest, dry deciduous forest and plantation plots as the major vegetative types[9]. The vegetative types are distributed in a mosaic pattern in the northeastern part of the site. Bare ground having no vegetation as a result of past human activities, is also scattered in the mosaic. The soil is originally an Orthic Acrisol, according to the FAO/UNESCO scheme[12].

In this work, dry evergreen forest, *Acacia* plantation and bare-ground soils were compared. The vegetative types were randomly distributed. Thus the vegetative mosaic was regarded as a completely randomized design[9]. The numbers of replications were 7, 7 and 6 for dry evergreen forest, *Acacia* plantation and bare ground respectively. All the sampling points were on slight slopes (less than 10°).

The dry evergreen forest is primarily dominated by *Hopea ferrea* and *Shorea* spp. that form the upper storey 20 to 40 m above ground. A typical dry evergreen forest fosters more than 1000 trees/ha (trunk diameter at breast height >5 cm), the total basal area at 1.3 m height exceeds 30 sq. m/ha and the above-ground biomass is over 200 tonnes/ha[13].

Acacia auriculiformis plantation plots were scattered in the area. The *Acacia* plots were established in 1986–87 in areas that were subjected to slash and burn shifting cultivation[10]. For cultivation, the original vegetation was removed and the biomass was burned. The cleared area was cultivated by the people for a few years, and then abandoned when the soil quality deteriorated to the extent that it did not support crop production. Some of the abandoned areas were converted to plantation plots of *Acacia mangium*,

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Eucalyptus camaldulensis and other tree species. *A. auriculiformis* was one of the introduced tree species.

The bare ground soil has been intensively deprived of nutrients and has lost conditions seen in forest soils. At these sampling points, restoration of vegetative cover did not occur and the harsh conditions for plants make the bare ground remain so. Morphological features of bare ground can still be seen at some points in the site. For typical bare ground, the A horizon cannot be recognized. The uppermost horizon is reddish-brown, rich in gravel, and has few roots and other plant organs/debris. The boundary between the uppermost horizon and the deeper horizon is not clear, while the horizon deeper than 50 cm is pale orange.

To investigate the effects of wet to dry seasonal transition, soils were sampled on 25 and 26 September, 25 and 26 November and 24 and 25 December 2005 (Figure 1). Sampling was done within 26 h, in which the area had negligible precipitation (<1 mm). At each sampling point, 100 ml core samplers, 5 cm in diameter, were inserted from the surface to a depth of 5.1 cm. A circle, 10 m in diameter was established, and eight soil cores were randomly taken within the circle. In addition, two other cores were randomly taken in the circle for soil moisture and bulk density measurements. The eight soil cores were immediately placed into a single plastic bag, mixed, brought to the laboratory, air-dried, passed through 2 mm sieve, then analysed/profiled.

For physico-chemical analysis of the soils, the following methods were applied, as previously reported[9]. Soil moisture content and bulk density were determined using oven-drying at 105°C for 48 h. The air-dried and sieved soil was suspended in water at a soil-to-solution ratio of 1 : 5 and reciprocally shaken at room temperature for 1 h at 120 rpm to determine its pH. Soil organic matter was determined using the loss of ignition method. Exchangeable cations (Ca, K, Mg and Na) were extracted with 1 M ammonium acetate (pH 7.0). Ca, K and Na contents were determined with a flame photometer. The sum of Ca and Mg contents was determined using the eriochrome black titration method, then the Ca content was subtracted from the sum to determine the Mg content. Exchangeable acidity (Al and H) was determined by titration. Available phosphorus was determined using the Bray II method. Cation exchange capacity was calculated as the sum of the four exchangeable cations (Ca, K, Na and Mg) and the exchangeable acidity.

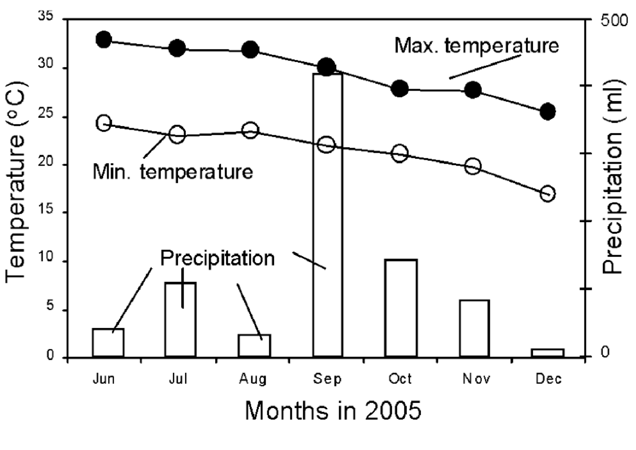

Figure 1. Precipitation and temperature during the study period.

Soil fertility index[14] and soil evaluation factor[15] were calculated to quantify the intensity of land degradation in the study site[9]. The following equations were used to calculate integrative soil quality indices[15]:

Soil fertility index = pH + organic matter (%, dry soil basis) + available P (mg/kg dry soil) + exch K (c eq/kg dry soil) + exch Ca (c eq/kg dry soil) + exch Mg (c eq/kg dry soil) – exch Al (c eq/kg dry soil). (1)

Soil evaluation factor = [Exch K (c eq/kg dry soil) + exch Ca (c eq/kg dry soil) + exch Mg (c eq/kg dry soil) – log(1 + exch Al (c eq/kg dry soil))] × organic matter (%, dry soil) + 5. (2)

The air-dried and sieved soil sample was placed on a plastic bottle cap with a diameter of 2.5 cm and a depth of 3 mm. The surface was levelled and photographs were taken under a photon flux of 4.97 μmol/s/sq. m using a camera (Olympus Camedia C-5060 Wide Zoom) in the night-shooting mode. The distance between the soil sample and main body of the camera was 1 m.

The images were analysed with the computer software, Adobe Photoshop™ 7.0. An RGB or a CMYK value was measured for the image[8]. The RGB is an additive colour scheme that uses transmitted light to display colours based on various proportions and intensities of three primary colours, red, green and blue, to obtain a certain colour. The three primary colours should combine to transmit all light and thus produce white colour. The CMYK scheme is based on the light-absorbing quality of the colour. As white light strikes translucent inks, certain visible wavelengths are absorbed while others are reflected. Three primary ink colours (cyan, magenta and yellow) are used to create other colours. The three primary colours should combine to absorb all light and produce black colour. However, when digital objectives are printed, a muddy brown is produced instead of black colour due to impurities in the inks. Thus, black colour is added. For this reason, the Adobe software provides a value of blackness for a pixel in the digital image. By stopping the pointer at a randomly chosen pixel, values of CMYK and RGB were recorded. This measurement was done in four replications for each soil sample. The average coefficients of variance ($n = 4$) for all the 60 soil samples were: C, 2.44%; M, 2.16%; Y, 2.50%; K, 5.55%; R, 4.02%; G, 3.90%, and B, 5.03%.

Table 1. Soil physico-chemical characteristics, values of soil quality indices and results of repeated measures analysis of variance

	Separation of averages for vegetative types at each sampling time									Significance of sources of variation (*P* value)		
	September			November			December					
Physico-chemical variable	BG*	*Acacia*	DEF	BG	*Acacia*	DEF	BG	*Acacia*	DEF	Vegetation (*V*)	Sampling time (*S*)	$V \times S$
Moisture content (%)	11.9^{b}	24.1^{a}	25.7^{a}	4.45^{b}	18.1^{a}	21.7^{a}	3.43^{b}	8.67^{a}	10.1^{a}	0.000	0.000	0.000
Bulk density (kg/l)	1.15^{ab}	1.12^{a}	1.00^{b}	1.40^{a}	1.16^{b}	1.02^{b}	1.43^{a}	1.12^{ab}	0.96^{b}	0.000	0.008	0.011
pH	5.88^{a}	6.30^{a}	5.88^{a}	5.52^{a}	6.01^{a}	5.83^{a}	5.90^{a}	6.30^{a}	6.37^{a}	0.129	0.028	0.619
Organic matter (%)	3.61^{b}	6.33^{a}	4.95^{a}	3.73^{b}	5.22^{ab}	5.31^{a}	3.13^{b}	5.52^{ab}	5.58^{a}	0.004	0.780	0.269
Bray II P (mg/kg)	2.50^{a}	4.16^{a}	5.61^{a}	2.71^{a}	3.93^{a}	4.68^{a}	4.07^{a}	5.05^{a}	4.69^{a}	0.008	0.167	0.224
Exch K (m eq/kg dry soil)	2.99^{a}	4.73^{a}	4.57^{a}	2.97^{a}	5.84^{a}	4.19^{a}	2.38^{b}	4.50^{a}	4.38^{a}	0.009	0.728	0.890
Exch Ca (m eq/kg dry soil)	12.1^{b}	31.6^{a}	17.2^{ab}	15.1^{a}	35.6^{a}	31.8^{a}	15.8^{a}	31.5^{a}	31.7^{a}	0.018	0.220	0.632
Exch Mg (m eq/kg dry soil)	19.7^{a}	34.4^{a}	29.6^{a}	20.4^{a}	32.2^{a}	33.7^{a}	20.1^{b}	38.1^{ab}	43.2^{a}	0.020	0.206	0.578
Exch Na (m eq/kg dry soil)	0.29^{a}	0.26^{a}	0.19^{a}	0.22^{a}	0.33^{a}	0.15^{a}	0.21^{a}	0.17^{a}	0.12^{a}	0.149	0.239	0.644
CEC (m eq/kg dry soil)	42.3^{a}	72.7^{a}	55.9^{a}	48.3^{a}	77.8^{a}	75.6^{a}	48.3^{a}	77.1^{a}	80.8^{a}	0.053	0.268	0.777
Exch Al (m eq/kg dry soil)	1.90^{a}	0.40^{a}	0.87^{a}	2.38^{a}	1.10^{a}	1.68^{a}	2.08^{a}	1.05^{a}	1.00^{a}	0.074	0.204	0.947
Exch H (m eq/kg dry soil)	6.30^{a}	1.39^{a}	3.41^{a}	7.33^{a}	2.72^{a}	4.08^{a}	7.78^{a}	1.83^{a}	0.49^{a}	0.151	0.744	0.857
Soil fertility index	13.6^{b}	23.5^{a}	20.7^{a}	13.4^{b}	21.4^{ab}	21.1^{a}	14.9^{b}	23.2^{a}	23.6^{a}	0.000	0.424	0.917
Soil evaluation factor	16.1^{b}	51.3^{a}	29.5^{a}	19.0^{b}	51.3^{a}	41.3^{a}	15.7^{b}	48.7^{ab}	49.9^{a}	0.007	0.706	0.728

*BG, *Acacia* and DEF in the mean separation columns indicate bare ground, *Acacia* plantation and dry evergreen forest respectively. For each month and each soil physico-chemical variable, the means indexed by the same letters do not differ significantly at $P = 0.05$, according to the Dunnett T3 *t*-test.

Analysis of variance of each of the soil physico-chemical variables, the values of soil fertility index and soil evaluation factor, and the CMYK/RGB values was performed using the statistical software, SPSS 10.0.1 (SPSS Inc.). Repeated measures analysis of variance was chosen hypothesizing vegetation and sampling time to be the significant sources of variation. Raw CMYK or RGB values for the four replications were averaged, and then used for repeated measures analysis of variance. Dunnett T3 *t*-test was used to examine the significant differences between means. To measure the power of the profiling method to discriminate among soils, discriminant analysis was performed with the SPSS software. The putting independent together method was chosen. Wilk's lambda statistics was determined in the discriminant analysis. Wilk's lambda is the most widely used statistic in determining the difference between/among multivariate profiles[16]. If the means among compared groups for each variable are equal, Wilk's lambda becomes 1. The more different the profiles, the closer Wilk's lambda comes to 0.

Most of the physico-chemical variables reflected the degrading/rehabilitative effects significantly (Table 1, $P < 0.05$). The land degradation was explained by high values of bulk density and low values of moisture content, organic matter content, basic cations (K, Ca, Mg), available phosphorus and integrative soil quality indices. At a significance level of $P = 0.05$, values of every single physico-chemical variable did not differ between the *Acacia* plantation and the evergreen forest soils, except for the bulk density values in September. The bare-ground soil was shown to be significantly poorer than the other soils in some soil physico-chemical variables. Effects of the wet-to-dry seasonal transition were pronounced as changes in soil moisture content, bulk density and pH.

According to the analysis of variance, among the colour designation variables, C and R values most significantly showed degrading/rehabilitative effects (Table 2). Values of the other variables did not show significant differences among the soils. Variations in M and Y values showed significant effects of the seasonal transition at $P = 0.05$. The interaction between the sources of variation was not significant for all the variables ($P > 0.072$).

Table 3 summarizes results of the discriminant analysis. Using the physico-chemical data, the soils were discriminated relatively well. Only two cases of misclassification occurred for the September and the November soil sample sets. These results indicate differences between the physico-chemical profiles of the *Acacia* plantation and the evergreen forest soils when the multivariate profiles were compared, though the single physico-chemical variables did not show significant differences between these soils. Analysing the RGB or the CMYK dataset, the soils were discriminated more clearly when using the raw values.

Discriminant score plots were provided by analysing the raw values (Figure 2). The colour designation schemes showed the land degradation–rehabilitation gradient in the discriminant score plots, indicating that soil colour profiles were different between the *Acacia* plantation and the evergreen forest. The CMYK profiles were clearly discriminated among the soil sample groups taken in September and November. In December, the RGB profiles showed clearer differences among the soil sample groups than the CMYK profiles. These contrasts between the RGB and the CMYK schemes imply a complementary relationship between the colour designation schemes[6]. The physico-chemical profiles also showed the land degradation–rehabilitation gradient in the discriminant score plots. The colour designation schemes provided the discriminant score plots showing similar discriminatory patterns to that of the physico-chemical profiles.

Under similar geo-climatic conditions in Costa Rica, linkages between the variation in soil colour and land degradation/rehabilitation were reported[17]. Determinants of soil colour were known. Soil minerals have different colours and thus the composition is reflected as the soil colour[18]. Land degradation may result in soil mineralogical changes. For example, allophene loses its structure when the soil environment becomes acidic[19]. In the land degradation, the soil could have experienced such mineralogical changes, and the changes could be a legacy seen in the

Table 2. Values of CMYK and RGB colour intensity for soil samples and results of repeated measures analysis of variance

	Separation of averages for vegetative types at each sampling time									Significance of sources of variation (P value)		
	September			November			December					
Colour	BG*	*Acacia*	DEF	BG	*Acacia*	DEF	BG	*Acacia*	DEF	Vegetation (V)	Sampling time (S)	$V \times S$
C	49.1^a	52.1^a	52.9^a	47.2^b	53.5^a	54.5^a	48.6^b	52.9^{ab}	56.0^a	0.001	0.183	0.073
M	56.4^a	55.2^a	54.9^a	57.7^a	54.8^a	56.2^a	59.5^a	57.5^a	58.8^a	0.262	0.000	0.737
Y	71.9^a	70.1^a	71.9^a	73.7^a	70.6^a	72.3^a	69.3^a	68.9^a	66.6^a	0.532	0.000	0.229
K	34.2^a	35.2^a	36.2^a	34.3^a	36.6^a	41.2^a	35.7^a	37.8^a	41.6^a	0.197	0.133	0.746
R	104^a	101^a	95.9^a	107^a	96.0^{ab}	89.5^b	103^a	93.0^{ab}	84.5^b	0.000	0.095	0.656
G	84.6^a	86.5^a	82.7^a	84.0^a	82.9^a	78.0^a	80.7^a	78.8^a	72.6^a	0.150	0.066	0.949
B	61.9^a	66.7^a	63.3^a	61.9^a	64.7^a	62.2^a	65.6^a	63.6^a	61.6^a	0.654	0.939	0.909

For each month and each colour variable, the means indexed by the same letters do not differ significantly at $P = 0.05$, according to the Dunnett T3 *t*-test.

Table 3. Results of discriminant analysis of the physico-chemical, the RGB and the CMYK datasets

			Predicted sample group								
			September			November			December		
Dataset	Calculation	Sample group (vegetative type)	Bare ground	*Acacia* plantation	Evergreen forest	Bare ground	*Acacia* plantation	Evergreen forest	Bare ground	*Acacia* plantation	Evergreen forest
Physico-chemical	–	Bare ground	6	0	0	6	0	0	6	0	0
		Acacia plantation	0	6	**1***	0	6	**1**	0	7	0
		Evergreen forest	0	0	7	0	0	7	0	0	7
RGB	Raw value	Bare ground	6	0	0	6	0	0	6	0	0
		Acacia plantation	0	6	**1**	0	5	**2**	0	7	0
		Evergreen forest	0	**1**	6	0	**1**	6	0	0	7
	Averaged	Bare ground	4	**1**	**1**	6	0	0	6	0	0
		Acacia plantation	0	5	**2**	0	5	**2**	0	5	**2**
		Evergreen forest	**2**	**1**	4	0	**4**	3	0	**3**	4
CMYK	Raw value	Bare ground	6	0	0	6	0	0	6	0	0
		Acacia plantation	0	7	0	0	7	0	0	7	0
		Evergreen forest	0	0	7	0	0	7	0	**1**	6
	Averaged	Bare ground	6	0	0	6	0	0	5	**1**	0
		Acacia plantation	0	5	**2**	0	5	**2**	0	6	**1**
		Evergreen forest	0	**2**	5	0	**2**	5	**1**	**2**	4

*The bold numbers indicate misclassification.

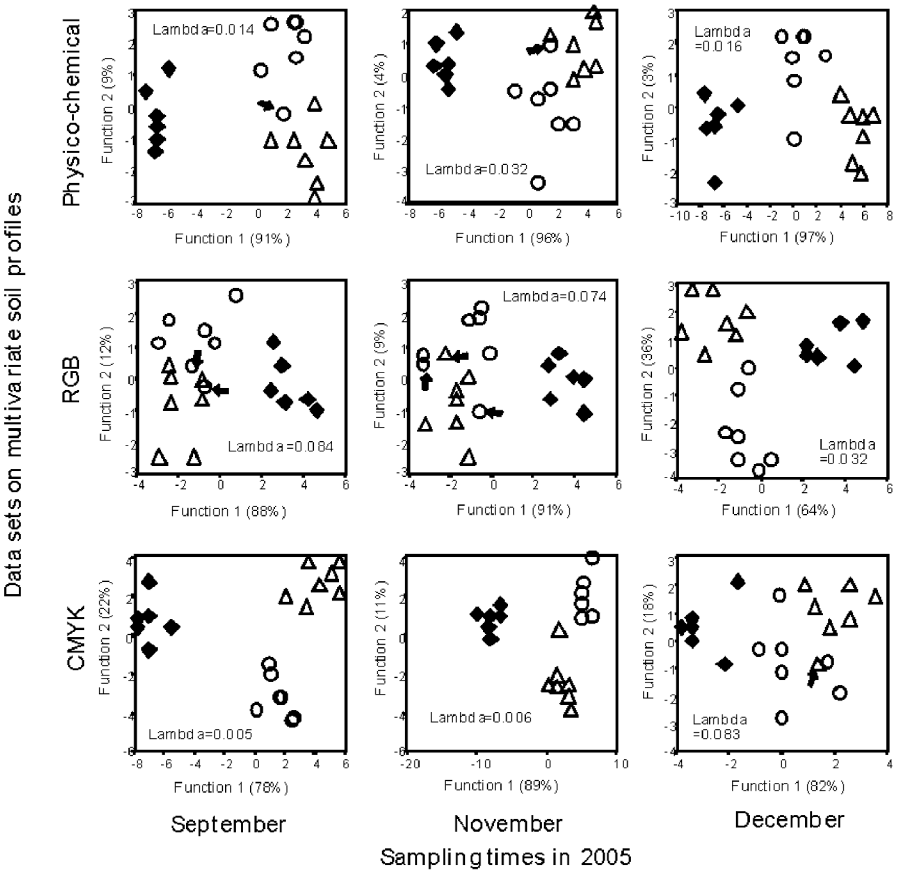

Figure 2. Discriminant score plots based on the physico-chemical and the colour profiles. The diamond, the open circle and the triangle indicate bare ground, *Acacia* plantation and dry evergreen forest respectively. Values in parentheses indicate percentage of variability explained by the discriminant function. Arrow indicates misclassification. (See Table 3 for misclassification.)

Acacia plantation soil. Differences in organic matter quality may also have contributed to discrimination between the *Acacia* plantation and the evergreen forest soils[20]. The wet-to-dry seasonal transition was suggested to determine soil organic matter content[21] as well as to cause soil mineralogical changes[22], followed by changes in soil colour.

These factors could be the sources of the variation in soil colour.

At present, it is hard to conclude full restoration of the *Acacia* plantation soil, though few single soil variables showed statistically significant differences between the evergreen forest and the *Acacia* plantation soils. Slight soil environmental changes ($P > 0.10$) may significantly associate with other soil variables such as soil enzyme activity[23]. Rather, the *Acacia* plantation soil was being restored, as indicated by the discriminant score plots (Figure 2) which still discriminate between the evergreen forest and the *Acacia* plantation soils (Table 3). Hence, in the current research site, the period of 18 or 19 years occupied by the *Acacia* plantation appeared inadequate to fully restore the degraded soil[24,25]. The *Acacia* plantation soil and the ecosystem seemed to be in succession towards the climax that would appear after more decades[26].

This study shows that soil colour designation may be an alternative for monitoring soil quality in rehabilitative or restorative land-management practices. It is thought to be better to take all the soils under question within a limited time, because seasonal effects on soil colour profile were pronounced. Each sample must be profiled with four or more replicates and the raw values should be directly used. The discriminatory power is a prerequisite for successful soil profiling and use of information[27,28]. The soil colour designation schemes do not require expensive and complicated soil analytical tools. The schemes require a digital camera and the Adobe software only. These tools enable objective soil colour designation based on the continuous measures. Soil colour designation is a simple, cost-effective and less labour intensive method for evaluating rehabilitative and restorative effects of a land management practice, such as planting a tree species on degraded land. Soil colour profiling would be worth testing in other cases aiming at land-resource conservation.

1. Sena, M. M., Poppi, R. J., Frighetto, R. T. S. and Valarini, P. J., Avaliação do uso de métodos quimiométricos em análise de solos. *Quim. Nova*, 2000, **23**, 547–556.
2. Escadafal, E., Girard, M. C. and Courault, D., Munsell soil color and soil reflectance in the visible spectral bands of Landsat MSS and TM data. *Remote Sensing Environ.*, 1989, **27**, 37–46.
3. Simonson, R. W., Soil color standards and terms for field use – History of their development. In *Soil Color* (eds Bigham, J. M. and Ciolkosz, E. J.), Soil Science Society of America, Inc., Spec. Publ. No. 31, Madison, Wisconsin, USA, 1993, pp. 1–20.
4. Mattikalli, N. M., Soil color modeling for the visible and near-infrared bands of Landsat sensors using laboratory spectral measurements. *Remote Sensing Environ.*, 1997, **59**, 14–28.
5. Fernandez, R. Z. and Schulze, D. G., Calculation of soil color from reflectance spectra. *Soil Sci. Soc. Am. J.*, 1987, **51**, 1277–1282.
6. Toulios, L. G., Toulios, M. G. and Lipimenou, E., Soil color relationships with reflectance spectra. *Geocarto Int.*, 1998, **13**, 35–42.
7. Torrent, J. and Barrón, V., Laboratory measurement of soil color: Theory and practice. In *Soil Color* (eds Bigham, J. M. and Ciolkosz, E. J.), Soil Science Society of America, Inc., Spec. Publ. No. 31, Madison, Wisconsin, USA, 1993, pp. 21–34.
8. Yam, K. L. and Papadakis, S. E., A simple digital imaging method for measuring and analyzing color of food surfaces. *J. Food Eng.*, 2004, **61**, 137–142.
9. Doi, R. and Sakurai, K., Principal components derived from soil physico-chemical data explained a land degradation gradient, and suggested the applicability of new indexes for estimation of soil productivity in the Sakaerat Environmental Research Station, Thailand. *Int. J. Sust. Dev. World Ecol.*, 2004, **11**, 298–311.
10. Kaeoniam, P., Khoorat, P., Sunthornsan, W., Issareeya, M., Cherdchun, C. and Buachum, W., A study of illegal deforestation in the reserved forest area at the Sakaerat Environmental Research Station. Environmental and Ecological Research Department, Applied Scientific Research Corporation of Thailand, Bangkok, 1976.
11. Köppen, W., *Grundriss der Klimakunde*, Walter de Gruyter, Berlin, 1931.
12. FAO/UNESCO, Soil map of the world. IX, Southeast Asia. UNESCO, Paris, France, 1979.
13. Kanzaki, M., Yoda, K. and Dhanmanonda, K., Mosaic structure and tree growth pattern in a monodomoionant tropical seasonal evergreen forest in Thailand. In *Vegetation Science in Forestry* (eds Box, E. O. *et al.*), Kluwer, The Netherlands, 1995, pp. 495–513.
14. Moran, E. F., Brondizion, E. S., Tucker, J. M., da Silva-Forsberg, M. C., McCracken, S. and Falesi, I., Effects of soil fertility and land-use on forest succession in Amazônia. *For. Ecol. Manage.*, 2000, **139**, 93–108.
15. Lu, D., Moran, E. and Mausel, P., Linking Amazonian secondary succession forest growth to soil properties. *Land Degrad. Dev.*, 2002, **13**, 331–343.
16. Zar, J. H., *Biostatistical Analysis*, Prentice-Hall, New Jersey, 1999.
17. Carpenter, F. L., Mayorga, S. P., Quintero, E. G. and Schroeder, M., Land-use and erosion of a Costa Rican Ultisol affect soil chemistry, mycorrhizal fungi and early regeneration. *For. Ecol. Manage.*, 2001, **144**, 1–17.
18. Scheinost, A. C. and Schwertmann, U., Color identification of iron oxides and hydroxysulfates: Use and limitations. *Soil Sci. Soc. Am. J.*, 1999, **63**, 1463–1471.
19. Matsukawa, S., Katoh, H. and Kameyama, K., Acid buffering capacity of primary minerals weathering in Allophanic soils. *Soil Phys. Cond. Plant Growth Jpn.*, 1998, **80**, 41–47.
20. Spielvogel, S., Knicker, H. and Kögel-Knabner, I., Soil organic matter composition and soil lightness. *J. Plant Nutr. Soil Sci.*, 2004, **167**, 545–555.
21. Kitayama, K., Aiba, S., Kimura, K. and Kikuzawa, K., Fine-litterfall dynamics in hill and mountain forests on Mount Kinabalu in the 1996 Masting Year. *Tropics*, 1998, **7**, 309–317.
22. Cogger, C. G. and Kennedy, P. E., Seasonally saturated soils in the Puget lowland I. Saturation, reduction, and color patterns. *Soil Sci.*, 1992, **153**, 421–433.
23. Jha, D. K., Sharma, G. D. and Mishra, R. R., Soil microbial population numbers and enzyme activities in relation to altitude and forest degradation. *Soil Biol. Biochem.*, 1992, **24**, 761–767.
24. Yemefack, M., Rossiter, D. G. and Njomgang, R., Multi-scale characterization of soil variability within an agricultural landscape mosaic system in southern Cameroon. *Geoderma*, 2005, **125**, 117–143.
25. Young, A., *Agroforestry for Soil Management*, CAB International and ICRAF, New York, 1997, 2nd edn.
26. Chazdon, R. L., Tropical forest recovery: Legacies of human impact and natural disturbances. *Perspect. Plant Ecol.*, 2003, **6**, 51–71.
27. Jhonson, J. B., Phytosociology and gradient analysis of a subalpine treed fen in Rocky Mountain National Park, Colorado. *Can. J. Bot.*, 1996, **74**, 1203–1218.
28. Kourtev, P., Ehrenfeld, J. G. and Huang, W., Effects of exotic plant species on soil properties in hardwood forests of New Jersy. *Water Air Soil Pollut.*, 1998, **105**, 493–501.

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