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Digital image analysis for the estimation of cracked areas and the soil shrinkage characteristic curve in clay soils amended with composted sewage sludge

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Abstract

The formation of cracks in clay soils is a physical process with important agricultural repercussions. The specific case occupying us refers to a dryland olive grove (*Olea europaea*) grown on a vertisol in the countryside of Córdoba (Spain). For two consecutive years, rates of 20 Mg ha^{-1} of composted sewage sludge have been applied on this land to attempt to improve the physical and chemical properties of the soil. This study proposes a method for the measurement of cracks in clay soil during a desiccation period in trays. The measurement of the cracked area generated in each treatment (20 Mg ha^{-1} of compost and control) throughout the time, is done on digital photographs, previously orthorectified. The area of cracks generated after a desiccation process decreased by 7% in clay soils amended with composted sewage sludge. Additionally, the soil shrinkage characteristic curve (SSCC) can be obtained.

Key words: organic residues, biosolids, soil physical properties, orthorectify.

Resumen

Análisis de imágenes digitales para la estimación del área de grietas y de la curva característica de contracción de suelos arcillosos enmendados con compost de lodos de depuradora

La formación de grietas en suelos arcillosos es un proceso físico con importantes repercusiones en agricultura. El caso que nos ocupa se refiere a un olivar de secano (*Olea europaea*) cultivado sobre un vertisol de la provincia de Córdoba (España), en el que se ha aplicado durante dos años consecutivos una dosis de 20 Mg ha^{-1} de lodos de depuradora compostados, para intentar mejorar las propiedades físicas y químicas del suelo. Este estudio propone un método para medir las grietas producidas en un suelo arcilloso durante su desecación en bandejas. La medida del área de grietas generada en cada tratamiento (20 Mg ha^{-1} de compost y control) a lo largo del tiempo, se realiza sobre fotografías digitales previamente ortorrectificadas. El área de grietas generada durante el proceso de desecación disminuyó un 7% en el suelo arcilloso tratado con compost de lodos de depuradora. Además, con este proceso podemos obtener la curva característica de contracción del suelo (SSCC).

Palabras clave: residuos orgánicos, biosólidos, propiedades físicas del suelo, ortorrectificación.

Introduction

The formation of cracks associated with changes in volume produced in clay soils with their variation in moisture has an important agronomic repercussion. The existence of cracks and macropores is directly related to the transport of water and solutes in the soil (McCoy *et al*., 1994), so that any excessive increase in the area and size of the cracks in a soil can cause a rapid infiltration of water to deep layers (Mitchell and van Genuchten, 1992), with a possible carrying with it of solutes which could pollute deep waters (Thomas and Phillips, 1979). Tuong *et al*. (1996) obtained flow rates of water in deep soil layers through cracks during irrigation of between 41 and 57% of the total of water applied on the field. Also, soil cracks are the forerunners of gullies, which give rise to a great loss of fertile soil due to erosion (Heede, 1971), as well as facilitating the evaporation of soil water by opening

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up secondary evaporation planes in its profile. The intensity and the formation pattern of cracks in the soil are basically influenced by the content and type of clay minerals present, although other factors also affect it, such as the plant cover distribution (Johnston and Hill, 1944; Dasog *et al*., 1988) or the radicular system of the crop (Fox, 1964; Mitchell and van Genuchten, 1992).

The methods most used in the measurement of volume changes in expansive soils are based on the calculation of the reduction percentage of the volume of a soil, after oven drying it at 105ºC. For this, an altered sample of wet soil is placed in a cylinder with a known volume, is dried, and the new volume of the cylinder of dry soil is measured, immersing it in a viscous liquid and quantifying the volume of liquid displaced. The American Society for Testing Materials (1990) proposes mercury (Hg) as a liquid for the measurement of the final volume of the cylinder of soil. Other authors used kerosene (McIntyre and Stirk, 1954), toluene (Sibley and Williams, 1989) or a silicone-mineral spirits mixture (Overby and DeBano, 1990). These methods are of a limited precision since the liquid in question slowly penetrates the soil macropores and this affects the measurements of the final volume of the soil.

In other works a method has been proposed which attempts to coat a portion of soil (generally a clod) with special materials preventing the entry of water in a liquid state. The volume at each moment can be calculated using the Archimedes' principle, from the difference in weight of the soil portion in the air and the one immersed in distilled water. To impermeabilize the clod, use has been made of diverse materials such as petrol (Monnier *et al*., 1973), paraffin (Johnston and Hill, 1944; Lauritzen, 1948), SARAN F-310 resin dissolved with methyl ethyl ketone (Brasher *et al*., 1966) or flexible rubber membranes (Tariq and Durnford, 1993). The precision is limited because the resin film coating the soil clod is not able to contract in the same proportion as the soil itself, giving an excessively large final volume measurement.

Direct measurement has been employed by other authors, both to estimate the size and depth of cracks in the field (Sharma *et al*., 1995), and to obtain continuous measurements of soil swelling, either by obtaining the diameter and height of cylindrical samples with laser sensors (Braudeau *et al*., 1999) or by measuring the vertical swelling in the field using electronic linear displacement transducers (Coquet, 1998).

Some studies have compared the methods for the measurement of the soil shrinkage characteristic curve (SSCC) and found significant differences according to the method used (Crescimanno and Provenzano, 1999). This gives us an idea of the variability of the measurement of soil swelling obtained with the methods reported, not to mention the operative complications they require and the risks to health implied in working with elements like mercury or saran.

In current studies, new techniques like the digital treatment of images relative to the study of crack sizes (Masciandaro *et al*., 1997; Flowers and Lal, 1999) are being used. Both of these are based on the taken digital images of a certain area of cracked soil and the subsequent calculation of the surface occupied by the cracks, determined by a comparison of the gray-level of the different pixels making up the digital images. Cárdenas-García *et al*. (1998) used the automatic correlation of digital images of the soil to characterize the crack formation process.

This work proposes a method for the measurement of cracked areas and the prediction of the SSCC proposed by Mitchell (1992), using for this purpose the orthorectification and subsequent analysis of digital images taken on different days during the drying process of a clay soil. This method will be applied in the study of application effects of composted sewage sludge to clay soils on the formation and size of cracks, as well as the SSCC obtained.

Material and Methods

Field assay

In March 1998, an assay was initiated to evaluate the effect of the application of composted sewage sludge as an organic amendment in a dryland olive grove in the countryside of Córdoba (Spain). The experimental design was of random blocks with two treatments and four replications, the elementary plot being formed by three olive trees, with a planting distance of 12 × 12 m, leaving watch lines between the different basic plots. One of the treatments consisted of the addition of 20 Mg ha^{-1} of composted sludge, the residue being uniformly applied on the surface with a centrifuge fertilizer and subsequently incorporated with a pass of the cultivator on the first 0.15 m of soil. The other treatment was used as a control, being managed under the traditional tillage system. Sludge application was repeated in March 1999.

The composted sludge was supplied by the Beta Nutror S.A. company, with 20% moisture and 32% organic matter. The raw material for the elaboration of the compost came from a mixture of anaerobic sewage sludge generated by 6 wastewater treatment plants of Madrid (Spain).

The receiving soil in the olive grove was a vertisol, with 52% clay, 36% silt and 12% sand. It has been classified as Chromic Haploxererts (Soil Taxonomy, 1999).

In January 2000, some altered samples were taken from the first 0.15 m of the soil in the treated plots and in the control plots. The four replications of each treatment were air-dried, ground and passed through a 2 mm sieve.

Laboratory assay

Eight plastic trays of 0.35 × 0.25 × 0.05 m were used, four for the treatment to which a layer of oil was applied to prevent their adherence to the soil. In them 1.25 kg of a sample of dry soil was mixed with 750 cm^3 distilled water, leaving it to air-dry at a temperature of 20 ± 2ºC. The drying process of the soil samples lasted 15 days, and the first cracks began the fourth day.

During the soil desiccation period, daily weighings were made of the different trays with their contents on precision scales. Empty trays had previously been weighed. These gravimetric measurements permitted us to find out the loss of water in the soil contained in the different trays throughout the assay.

In addition to the measurements of the moisture during the drying period of the soil samples in the trays, photographs were taken with a reflex type Canon ESO-500 35 mm camera on days 1, 4, 5, 9, 11 and 15.

Taken digital images

The trays were transferred to a table on which a total of 30 marks were made with a black felt-tipped pen. The coordinates X and Y of these marks were known in accordance with an arbitrary system of coordinates selected on the plane of the table. The marks were arranged around the tray and not covered by it. Once the trays were placed in this position, a photograph was taken (Fig. 1) trying to keep the camera as parallel as possible to the table and always at the same distance from the tray.

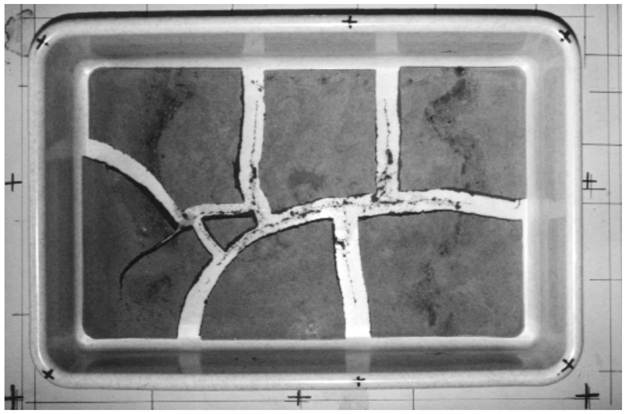

Figure 1. Photograph of the final state of one of the trays and the situation of control points.

A total of 48 photographs were taken (6 days × 8 repetitions) which were developed and scanned to obtain digital images at a resolution of 1,200 × 800 pixels.

Orthorectification of images

The digital images obtained after the process detailed in the above section had an implicit series of geometrical distortions, basically due to the conical projection used for the printing of the image on the film. In addition, the plane of the film and the plane of the work table, on which the trays were placed, were not exactly parallel and the distance of the camera to the plane of the table also underwent small variations from one photograph to another.

The soil surface also generated important errors in the image printed by the conical perspective. Although in the assay being carried out in this work it did not greatly concern us as the surface of the soil on the trays was completely flat, this fact should be taken into account for the application of this method in field assays, in which the microrelief of the soil can be accentuated.

To homogenize all the images and obtain a measurement of the cracks, which could be compared with future measurements taken with this method, it was decided to transform the original digital images into orthophotos. These new photographs were the result of an orthogonal projection of the original image in the film. With the taken of these images of the orthorectified trays, we managed to correct the geometrical distortions of the original images.

The images free from geometrical distortions were obtained by establishing mathematical relationships between the coordinates of the control points measured in the image (u, v) and the coordinates of these same points measured on the work table (x, y). In our case, quadratic polynomial transformations were used.

To obtain the coefficients of these equations, an equation system was established with the coordinates of the control points, requiring, in the case of quadratic equations, a minimum of 6 control points. In this work, between 10 and 15 control points were used from the 30 initially marked on the work table. In each photograph, it was also attempted to ensure that they were well distributed around it.

Once the implicit form of the function relating the coordinates of a point in the image (u, v) with the coordinates on the work table (x, y) was known, we were able to fill in an image free of geometric distortions, initially empty, transferring each pixel of the original image to the corrected image by means of the mathematical relationships obtained.

Obviously, in a rectification process, the position of the pixels in the original image does not exactly correspond to the position in the corrected image, so that it is necessary to combine the intensity of the neighboring pixels in order to obtain the final value desired. In this work, a bilinear interpolation was used, which makes three linear interpolations with the four pixels surrounding each point.

The orthorectification of the images of the soil trays was made by an IDRISI™ v.2 (Eastman, 1997). As a result of these transformations orthophotos of the 48 images of the soil trays were obtained. Each of these free distortion images was made up of 450 × 350 pixels.

Measurement of the cracked area by digitisation of the orthophotos

Once the definitive free distortion images had been obtained, it was necessary to measure the area of the cracks formed throughout the desiccation process of the soil contained in the trays, with the aim of observing the possible effect of the organic amendments on their formation process and size.

The area of cracks was calculated by inserting the image rectified in AutoCAD™, making it coincide with the coordinates of the control points and then digitalizing the soil polygons generated after the cracking process (Fig. 2). Once these polygons were obtained, we verified the total area and perimeter of the different soil portions. With these parameters, adimensional compactness values were generated (square perimeter divided by its area), which gave us an idea of the number and size of the soil fragments created in the cracking of the soil.

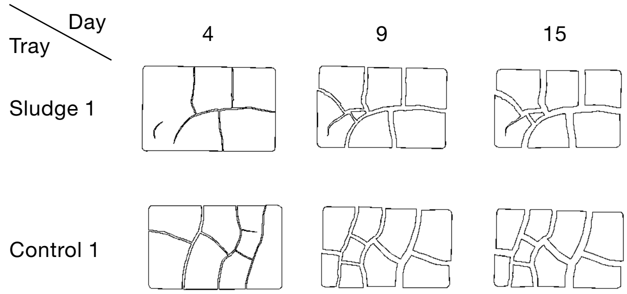

Figure 2. Digitisation of two of the assay trays (control 1 and sludge 1) in three days during the desiccation process of the soil.

Statistical analysis

All data were statistically evaluated by analysis of variance (ANOVA). The possible differences in the area of cracks, the compactness and the perimeter were analyzed. Moisture was incorporated into the statistical model as a covariable. Duncan's multiple range test at $P < 0.05$ was used for comparison of means.

Results and Discussion

Orthorectification of images

The errors committed in the IDRISI rectification give a root mean square (RMS), which describes the positional error of the control points in relation to the mathematical equations calculated. United States map precision standards require a RMS which is less than half of the resolution of the initial image (Eastman, 1997). In our case the resolution of the initial photographs was 0.43 mm pixel^{-1} and the mean RMS obtained in the 48 images was 0.126 mm.

The differences in the cracked area measured in the original photographs and in the orthorectified ones ranged between 3.4% for the trays with the highest percentage of cracks, and 7.2% for those which showed a lower surface occupied by cracks, always in favour of the orthorectified images.

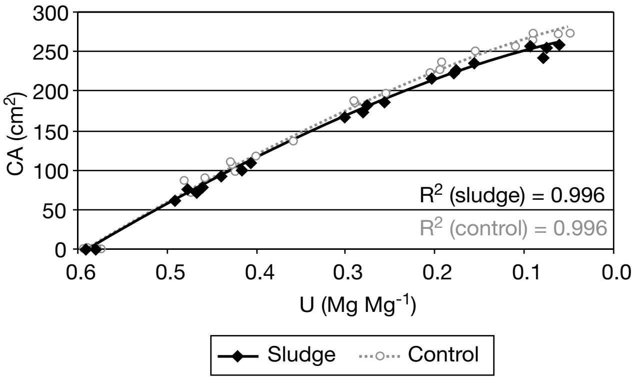

Figure 3. Generation of crack area (CA) with respect to the gravimetric moisture (U) in the sludge and control treatments.

Cracks in the soil

In Fig. 3 we can see the representation of the cracked area (CA) generated in each tray with respect to the gravimetric moisture (U), expressed in so many per one. The crack area increases in the treatment of composted sludge and in the control, during the soil desiccation process, following a very similar trend. For the same moisture, however, the cracked area in the trays with the sludge was always less than the cracked area in the control trays. These differences between treatments are accentuated when the cracked area is greater, i.e., when the soil moisture decreases. The point distributions fit a second order polynomial curve ($r^2 > 0.99$) very well.

The differences with respect to the crack area between the two treatments assayed and grouping the values per days were statistically significant ($p < 0.05$), taking the moisture as a covariable for the analysis of variance model (Table 1). The only day on which there were no significant differences was the first day that the cracks were measured (day 4). The area of cracks generated after a soil desiccation process diminished by 7% in the clay soil amended with composted sewage sludge.

Table 1. Statistical results in the cracked area in different treatments

Day	Sludge CA (cm²)	Control CA (cm²)	P	F
4	71.45	86.21	0.1070	3.85
5	100.64	117.18	0.0085	17.61
9	176.84	197.29	0.0044	24.15
11	224.83	242.04	0.0161	12.70
15	252.90	270.48	0.0122	14.68

CA: crack area. P: probability. F: F of Snedecor.

Logan *et al*. (1996) and Lindsay and Logan (1998), did not detect any variations in soil swelling after the addition of sewage sludge at doses varying between 50 and 300 Mg ha^{-1}. This was possibly due to the fact that the soils on which the sludge was applied were soils with a clay content of less than 30%. Other authors increased the organic matter in a clay loam soil by the application of plant residues for several years, obtaining a reduction in a surface cracking area (Sharma *et al*., 1995; Bhushan and Sharma, 2002).

Cracking pattern

The compactness values measured in the cracked soil in the trays, with respect to the time measured in days (Fig. 4) acceptably fit a third order polynomial curve ($r^2 > 0.94$). The difference between the mean values of the compactness of the soil with sludge and the control continue to increase until they reach a maximum at towards approximately half of the assay, subsequently remaining constant for both treatments and always favourable to the control treatment. The differences were in no case statistically significant ($p < 0.05$) due to the variability obtained in the different replications. Other works, in which the cracks produced in clayey soils amended with organic matter were estimated, seem to suggest that the cracks formed after the incorporation of organic amendments were smaller than those occurring in the control plots (Masciandaro *et al*., 1997; Bhushan and Sharma, 2002).

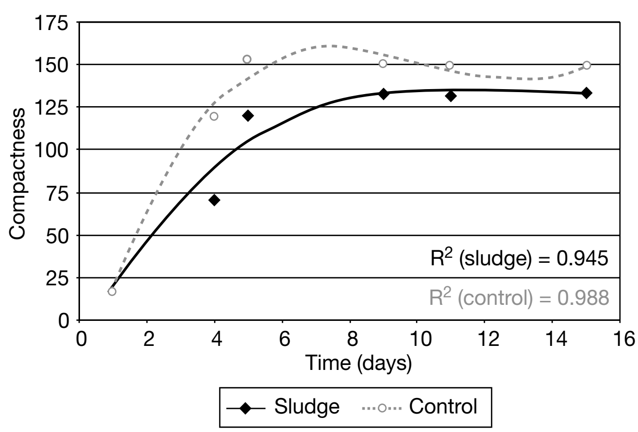

Figure 4. Representation of the compactness (square perimeter divided by its area) during the soil desiccation process.

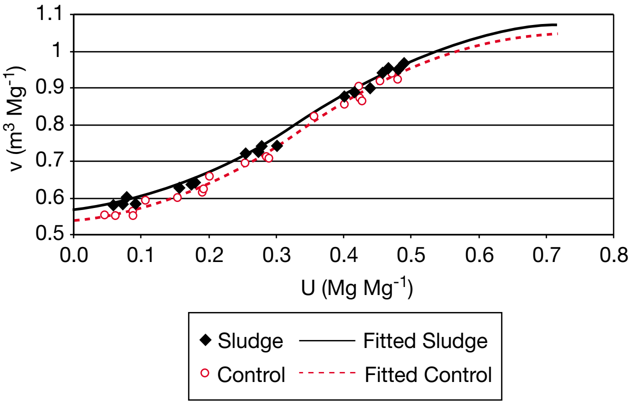

Figure 5. SSCC for the two treatments assayed. U: gravimetric moisture. v: specific volume. The curves were fitted to the Nelder model (1961).

SSCC

The method described in this work can be used, in addition to observing differences in the formation and size of the cracks in a soil submitted to different treatments, to obtain the Soil Shrinkage Characteristic Curve (SSCC). Fig. 5 shows the SSCC of our clay soil, with and without the application of sewage sludge. On the abscissa axis the gravimetric moisture (U) is represented and in the ordinates the specific volume (v), defined as the inverse of the bulk density of the soil, is represented.

The moisture values were directly measured during the assay by weighing the different trays with their contents on precision scales, with a previous knowledge of the weight of the empty tray and of the dry soil. To obtain v we had to calculate the bulk density, which equals the weight of the dry soil divided by its volume. The weight of the dry soil was known because 1.25 kg of dry soil was used per tray. To calculate the volume of soil at each moment, we based ourselves on the fact that soil shrinkage is isotropic (Bronswijk, 1990), so that, by knowing the reduction in the surface of the soil deposited in the trays, we were able to deduce the reduction in height of the initial prism due to the loss of moisture. The initial height of the soil in the trays was measured at the beginning of the assay, and was 1.9 cm.

The data obtained were fitted for both treatments following the logistic model of Nelder (1961) [equation 1], whose parameters and regression coefficients appear in Table 2.

$$\nu = a + \frac{b}{(1 + e^{(-c(U-d))})} \quad [1]$$

Table 2. Parameters of the data observed in the crack assay fitting the logistic model of the SSCC (Nelder, 1961) for the two treatments

	a	b	c	d	r^2
Sludge	1.097	–0.562	–8.118	0.351	0.997
Control	1.062	–0.547	–9.031	0.341	0.990

According to several authors, the bulk density of the soil diminishes with the addition of different types of sewage sludge (Gupta *et al.*, 1977; Metzger and Yaron, 1987; Tester, 1990; Logan *et al.*, 1996). It would seem clear that this diminution is related to the amount of organic matter contributed (Khaleel *et al.*, 1981; Lindsay and Logan, 1998; Aggelides and Londra, 2000). This was confirmed in the results obtained in the SSCC (Fig. 5) in which it is noted that the specific volume (v) values of the SSCC of the soil treated with composted sewage sludge were always higher than those obtained in the control treatment, for any gravimetric moisture. Perhaps, this was due to the diminution caused by the sludge in the bulk density of the soil treated.

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