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Soil quality assessment of an oil-contaminated tropical Alfisol amended with organic wastes using image analysis of pore space

J.K. Adesodun [a,*], D.A. Davidson [b], J.S.C. Mbagwu [c]

[a] Department of Soil Science and Land Management, University of Agriculture, P. M. B. 2240, Abeokuta 110001, Ogun-State, Nigeria
[b] School of Biological and Environmental Sciences, University of Stirling, FK9 4LA, Scotland, UK
[c] Department of Soil Science, University of Nigeria, Nsukka, Enugu-State, Nigeria

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ABSTRACT

Petroleum products are the most common source of pollution in Nigeria. We studied changes of the pore space of a soil contaminated with petroleum products by image analysis; and also assessed the applicability of fractal scaling of the pore surfaces to estimate soil degradation. The main-plot treatments include control (C), cow dung (CD), poultry manure (PM), and pig waste (PW) each applied at 10 Mg/ha; sub-plot treatments were control (0%), 0.5%, 2.5% and 5% spent oil (SP) applied at 10, 50 and 100 Mg/ha respectively with four replications. The results show that treatment with waste-lubricating oil (spent oil) led to increases in pore space parameters, *viz.* area, perimeter, count number (hole count), equivalent cylindrical diameter and shape. However, treatment with only organic wastes shows that PM increased these parameters and percent macroporosity over CD and PW. At the 0.5% oil level, the order of this increase was CD>PM>PW while at the 2.5% and 5% oil contamination levels the sequence was PM>PW>CD. This indicates that addition of CD had a greater effect on increasing void space at low oil concentrations, whilst PM was better at high contamination levels. The calculated pore surface dimension (D_sD_s) was between 2.30 and 2.80, showing that the pore outlines exhibit fractal behaviour. Oil contaminated soil supplemented with organic wastes showed that the D_s followed 0.5%SP>2.5%SP>5%SP, indicating increases in irregularity of the soil pores with decrease in oil concentrations. This study demonstrates the applicability of fractal scaling for evaluating pore space of soils amended with cow dung, poultry manure, and pig waste.

1. Introduction

Contamination of soil and groundwater with petroleum products is the most common type of pollution in Nigeria. The waste-lubricating oil, obtained after servicing and subsequent draining from automobile, generators and industrial machines is disposed off indiscriminately in Nigeria (Anoliefo and Vwioko, 1995). This indiscriminate disposal of oily wastes or oil spill may lead to the formation of oily scum. Consequently, oily scum on soil surfaces impedes the entrance of oxygen and water to the soil. The anaerobic condition created in the subsoil would aid the persistence of the oil (Amadi et al., 1996). In this study, addition of organic wastes, *viz.* cow dung (CD), poultry manure (PM) and pig waste (PW), to some contaminated plots was to add nutrients to stimulate biodegradation of the spent oil. The choice of CD, PM, and PW was because these wastes are abundant in Nigeria, and are cheap.

Soil porosity is widely recognized as the best indicator of soil structural quality. According to Ringrose-Voase and Bullock (1984), most techniques for measuring pores have been volumetric, e.g. water desorption, nitrogen sorption, and mercury intrusion, from which pore size distributions are derived, assuming a particular shape, usually cylindrical. The results of such measurements can then be incorporated into physical models to predict the behaviour of the soil with respect to water movement or aeration (Ringrose-Voase and Bullock, 1984). They further stated that the match between these models and observed behaviour has been unsatisfactory. Pagliai and Vignozzi (2003) reported that quantification of the pore space in terms of shape, size, continuity, orientation and arrangement of pores in soil allows investigation of modification as induced by anthropogenic activities. Using image analysis, it is now possible to make automated measures of soil porosity from thin sections (Pagliai and Vignozzi, 2003). Measurement of void space by image analysis is relevant to such topics as sealing, compaction and cementation, and can be used to study the effect of soil fauna and flora on soil structure and the effect of porosity and structure on root penetration (Murphy et al., 1977).

In addition to quantifying soil porosity using micromorphology, assessment of soil quality as reflected by recent management practices

* Corresponding author. Tel.: +234 8033469381.
E-mail addresses: jadesodun@yahoo.com, adesodunjk@unaab.edu.ng (J.K. Adesodun), d.a.davidson@stir.ac.uk (D.A. Davidson), joembagwu2003@yahoo.com (J.S.C. Mbagwu).

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can also be expressed in fractal dimensions of pore surfaces. Pachepsky et al. (1996) noted that while micromorphological data give abundant information on soil pore arrangement, fractal geometry could be used as tools for quantifying irregular and rugged boundaries.

Fractal geometry was originated by Mandelbrot (1982), and expanded upon by Feder (1988). Mandelbrot showed that length of coastline measured at different scales could be related to each other by a power function the exponent of which he called the “fractal dimension”. Perfect and Kay (1995) further stated that fractal geometry offers both descriptive and predictive opportunities for soil scientists. They also noted that fractals provide a unique quantitative framework for integrating soil biological, chemical, and physical phenomena over a range of spatial and temporal scales.

There are several fractal systems of interest such as mass fractals, pore fractals, fractal dimension of the pore-solid interface and spectral dimension (Anderson et al., 1996; Pachepsky et al., 1996; Gimenez et al., 1997; Ogawa et al., 1999). In general, the mass M of a fractal object (length, surface and volume) depends on the scale of measurement δ, following the relationship mentioned by Kampichler and Hauser (1993):

$$M(\delta)\approx\left(\delta^{d-D}\right) \quad (1)$$

where d denotes the Euclidean dimension, and D is the fractal dimension. In Euclidean geometry, the topological dimension of a point is zero, unity for a line and two for an area (Oleschko et al., 1998). For example, area A of a fractal surface is measured as (Kampichler and Hauser, 1993):

$$A(\delta)\approx\delta^{2-D}. \quad (2)$$

Consequently the fractal dimension for most fractal sets of interest should be between 0 and 1 for the linear fractal dimension, and between 1 and 2 for the areal fractal dimension (Oleschko et al., 1998).

When an isotropic 3-dimensional soil sample is intersected by a plane, then the intersected soil pores can be identified as 2-dimensional patches (Kampichler and Hauser, 1993). A simple relationship exists between the fractal dimension of a patch perimeter, D_p and the corresponding pore surface dimension D_s (Mandelbrot, 1987):

$$D_p = D_s - 1. \quad (3)$$

The analysis of D_s can be performed on images from soil thin sections (Protz et al., 1987; Ringrose-Voase, 1987; Moran et al., 1989; Bartoli et al., 1991). To estimate the boundary dimension of patches, the relationship between area and perimeter (A–P relationship) serves as a convenient method (Lovejoy, 1982; Krummel et al., 1987; Mandelbrot, 1987). The A–P relation is a measurement of the contortion of the perimeter. The degree of roughness can be quantified by the dimension D_p of the perimeter given by the solution of (Kampichler and Hauser, 1993):

$$P\approx A^{Dp/2}. \quad (4)$$

For smooth shapes $D_p = 1$, and $P \approx A^{1/2}$, whereas for highly contorted shapes, where the perimeter attempts to fold back on itself, thus filling the plane, D_p approaches 2 (Kampichler and Hauser, 1993). Thus, the slope (b) of the regression of Eq. (4) in the logarithmic form (i.e. In P against In A) equals $D_p/2$.

Irregularity of pore and particle outlines or surfaces reflect pore surface roughness. Irregularity is viewed as one of the essential properties of soil pore boundaries (Murphy et al., 1977; Pagliai et al., 1984; Ringrose-Voase, 1990; Pachepsky et al., 1996) and of surfaces of soil peds and particles (Orford, 1981; Clark, 1981). Studies have shown that the irregularity of many natural boundaries obey fractal laws (Mandelbrot, 1982). Pachepsky et al. (1996) reported that if the outlines are not fractal, D is equal to 1, and fractal if $D>1$. Kampichler and Hauser (1993) stated that the rougher the pore walls in a given soil, the higher their D values. While several studies have utilized fractal concepts to describe many pedological features (Ahl and Niemeyer, 1989; Tyler and Wheatcraft, 1989; Toledo et al., 1990; Bartoli et al., 1991; Young and Crawford, 1991), Pachepsky et al. (1995) state that fractal dimensions or parameters of soil pore surfaces are important in understanding soil degradation and dynamics.

The objectives of this study were to: (i) quantify changes in soil structural quality resulting from oil contamination and oil-contaminated soil remediated with organic wastes using image analysis of soil pores and (ii) assess the applicability of fractal scaling of pore surfaces to evaluate soil degradation following oil pollution and remediation option.

2. Materials and methods

2.1. Site description

The experiment was located at the University of Agriculture, Teaching and Research Farm, Abeokuta, southwestern Nigeria (Lat. 7.12° N and Long. 3.23° E), within the transition zone of the sub-humid forest to the south and derived savannah to the northwest (Keay, 1959). The soil at this site, an Oxic Paleustalf (FDALR, 1990), is a well-drained sandy loam in the surface and gravelly sandy clay loam in the sub-surface horizons, derived from the basement complex. Selected physical and chemical properties of this site are presented in Table 1. The area has a bimodal rainfall pattern with rainfall usually commencing in late March or early April and ending in late October or early November with a short dry spell in August. The mean annual rainfall is about 1470 mm with the maximum rainfall in July and September, while the mean monthly temperature ranges between 28 °C and 32 °C.

2.2. Experimental layout

An area of 0.0289 ha was used for this study. The experiment was a split plot in randomized complete block design (RCBD). The field layout consisted of four treatments in each main and sub-plots. The main treatment plots were 3.5 m × 3.5 m while the sub-plots were 1.5 m × 1.5 m with four replicates, making a total of 64 plots. They were raised beds with edges to prevent exchange between the plots, and were separated by 50 cm border rows. Organic waste treatments included control (C), cow dung (CD), poultry manure (PM), and pig waste (PW) at 10 Mg/ha each. The waste lubricating oil (Rubia S SAE 40), also called spent oil (SP), treatments included control (0%), 0.5%, 2.5% and 5%) applied at 0, 10, 50 and 100 Mg/ha respectively. This spent oil was sourced from heavy machines and each concentration

Table 1
Selected properties of the experimental site, and organic wastes and spent oil applied

Parameter	Units	Soil	CD	PM	PW	SP
Sand (2000–50 μm)	g/kg	836	–	–	–	–
Silt (50–2 μm)	g/kg	48	–	–	–	–
Clay (<2 μm)	g/kg	116	–	–	–	–
Texture	–	Sandy loam	–	–	–	–
pH (H_2O)		5.8	6.4	6.7	7.5	–
OC	g/kg	8.3	2.4	39.5	13.2	30.7
Total N	g/kg	0.71	0.97	4.0	1.30	2.66
C:N	–	11.7	12	9.9	10.2	11.5
Ave. P	mg/kg	7.4	126.5	143.6	74.8	0.1
Ca	Cmol/kg	6.09	103.4	116.8	75.0	
Mg	Cmol/kg	2.21	105.8	129.4	75.8	
K	Cmol/kg	1.24	0.9	1.1	0.9	
Na	Cmol/kg	1.13	10.5	3.6	3.0	
Exch. Acidity	Cmol/kg	0.6	0.2	0.1	1.2	
ECEC	Cmol/kg	11.27	–	–	–	