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Fractal distribution of mass from the millimeter- to decimeter-scale in two soils under native and restored tallgrass prairie

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ABSTRACT

Fractal models that describe the distribution of aggregate mass and the hierarchical organization of soil structure at scales relevant to hydrological processes have been tested only over a small range of aggregate sizes. The objectives of this work were to extend to the decimeter-scale the range of aggregate diameters used in mass–volume investigations, to examine the ability of a fractal model to describe the mass–volume relationship, and to assess the variability of fractal parameters obtained from individual clods sampled within the same horizon. Soils at a native prairie (NP) and a restored prairie (RP) at a formerly cultivated field site in northeastern Kansas were studied. Six clods (500–1000 cm^3) sampled from each of two soil horizons at the NP (A and Btss1) and RP sites (Ap and Btss1) were sequentially broken and volume measured with a combination of a multistripe laser triangulation scanner and a displacement technique using two immiscible liquids. Volumes were converted to diameters and normalized by individual aggregate/ped roundness, paired with their respective masses and fit with a power law expression to obtain D_m (fractal dimension of mass) and k_m (the mass of an aggregate of unit diameter). Except for the RP Btss1 horizon, the fits demonstrated two domains separated at a breakpoint, d_b, with values between 0.8 and 1.1 cm. We found a strong relationship between d_b and the combination of organic carbon and silt + clay content ($R^2 = 0.95$, $P < 0.01$) suggesting that these properties interact to control aggregation in aggregates with diameters smaller than d_b. D_m-values for the Btss1 and A horizons were not fractal ($D_m = 3$) for small aggregates and fractal with values between 2.79 and 2.89 for large aggregates. For the RP Ap horizon, D_m was 2.51 for the small and ~3 for the large aggregates, likely due to high concentrations of roots and organic carbon observed in this horizon. Variation of D_m and k_m within any given horizon was large and comparable to the variation of similar values obtained from water retention from a variety of soils of contrasting textures found in other studies, suggesting that a more thorough understanding of the horizon-scale variability of these parameters is needed in order to appropriately apply fractal models of water retention. Our results confirm that fractal models provide a theoretical framework to describe soil structure, but they should be developed from data spanning several orders of magnitude and tested critically.

1. Introduction

Soil structure – the arrangement, shape, and size of soil aggregates – and the related pore networks are fundamental to processes that drive and/or influence soil ecology (Wu et al., 2004), nutrient availability and transport through the environment (Ersahin et al., 2002), heat and water flux (Lehmann et al., 2003; Lin, 2003), aeration (Moldrup et al., 2003), landform and surface stability (Zhang et al., 2007), mineralogy (Falsone et al., 2007), seedling germination and root development (Kay and Angers, 2002; Vocanson et al., 2006), faunal locomotion (Striganova, 2000), organic matter transformations (Kristensen et al., 2000), and pedogenesis (Chadwick and Graham, 2000). Understanding the relationship between the physical architecture of the soil and these processes, therefore, depends upon our ability to accurately describe soil structure.

Fractal models characterize soil structure by quantifying the relationship between soil mass and soil volume (Giménez et al., 2002; Guber et al., 2005; Young and Crawford, 1991). A distinctive feature of the fractal model of soil structure is that power laws of aggregate mass vs. aggregate diameter should have an exponent (fractal dimension of mass, D_m) smaller than 3; this, in turn, results in aggregate densities decreasing with aggregate size. A dimension with a value of 3 describes a non-fractal pattern of aggregation such that the density of the soil aggregates does not change with aggregate size (Rieu and Sposito, 1991a). One of the perceived advantages of these models is that they integrate the morphology of soil structure with soil function. Mass scaling of aggregates can potentially be linked to soil

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properties such as the abundance and proportion of soil organic molecules and the concentrations of soil fines as well as the binding actions of biological agents such as roots, fungi, and macroorganisms (Jastrow et al., 1998; Martens et al., 2003; Schulten and Leinweber, 2000). Most notably, fractal models of hydraulic properties provide a morphological interpretation of the parameters used in mathematical descriptions of water retention and hydraulic conductivity. Furthermore, the distribution of soil mass represented by fractal models agrees with the accepted concept of hierarchical organization of soil aggregates and the related 'porosity exclusion principle' by which larger aggregates are formed from smaller and denser aggregates. At low levels of organization, soil organic matter acts as the primary binding agent of clay- and silt-size particles (Dexter, 1988; Oades and Waters, 1991; Schulten and Leinweber, 2000).

Data on mass scaling of aggregates spanning several orders of magnitude are needed to guide the development of theories of soil aggregation. Few datasets available in the literature confirm a fractal distribution of mass, particularly in soils not disturbed by tillage (Giménez et al., 2002; Young and Crawford, 1991). However, measurements on those datasets have only been done on aggregates with volumes smaller than about 4 cm^3 because of the difficulty in obtaining accurate, non-destructive volume measurements of larger, irregularly-shaped intact samples. The hierarchical organization of soil structure is not directly tested with mass–volume data because the physical location of smaller aggregates within the larger ones is typically not considered (Eghball et al., 1993; Filgueira et al., 1999; Giménez et al., 2002; Guber et al., 2005; Young and Crawford, 1991).

Recent applications of multistripe laser triangulation (MLT) technology, which yield high-resolution (120 μm), three-dimensional digital models, show that the volume and thus density of relatively large peds and clods can now be accurately measured (Rossi et al., 2008). This technique combined with more traditional methods to measure soil volume of smaller aggregates (e.g., Subroy et al., 2012), could provide the necessary range of sizes needed to investigate mass scaling in aggregates and peds. Furthermore, fragmentation of large intact soil samples and sequential measurement of the resulting fragments/aggregates would provide a unique opportunity to study mass–volume relationships within relatively small soil volumes.

We investigated the relationship between the masses and volumes of soil aggregates and structural peds across a range of scales (millimeters to decimeters) using soils from an unplowed native prairie and a historically cultivated site nearby, each sampled at two depths. In addition, individual intact samples (clods) were sequentially broken and mass–volume relationships of the resulting peds and aggregates were analyzed as well as aggregation agents investigated using particle-size analyses by laser diffraction on both untreated and pretreated samples. Objectives for this study were to: (1) extend the range of mass–volume investigations through MLT scanning; (2) examine the range at which fractals describe the aggregate mass–volume relationship in individual peds; and (3) analyze the variability of fractal dimensions of mass determined on multiple large clods sampled from surface and subsurface horizons of two soil profiles.

2. Materials and methods

2.1. Study site

This study was conducted in the Rockefeller Experimental Tract (RET) at the University of Kansas Field Station located in Jefferson County, Kansas. The RET is a long-term prairie restoration experiment initiated by the University of Kansas in 1956 (Fitch and Hall, 1978) and is representative of the tallgrass prairie and oak–hickory forest ecotone of northeastern Kansas (Kettle et al., 2000). The land-use history of the RET has been reconstructed since presettlement of the area (~1860) using General Land Office survey records, ownership records, agricultural censuses, interviews, and aerial photographs (Kettle et al., 2000). In addition, the RET contains an extensively-studied native prairie (Kettle et al., 2000; Kindscher and Tieszen, 1998). Between the 1870s and 1956, this 4-ha native prairie was maintained as a hay meadow and located immediately adjacent to a larger, 40-ha area that was cultivated prior to 1957 (Kettle et al., 2000). In 1957, this cultivated field was disked and reseeded with a commercial native warm-season grass mixture and has been unmanaged (i.e., no grazing or prescribed fire) since that time (Fitch and Hall, 1978; Kindscher and Tieszen, 1998). The native prairie has been managed by spring burns every 1–3 years (Kindscher and Tieszen, 1998), is occasionally spot mowed, and was hayed in 2007 and 2008 to control woody encroachment (D. Kettle, personal communication).

2.2. Field sampling

We excavated and exposed a >1.2 m deep soil profile in the native prairie area (NP) and 44 m away in the adjacent cultivated field (RP). Both pedons had similar surface slopes, were located on summit positions of the cuesta topography, and mapped as the Pawnee series (fine, smectitic, mesic Oxyaquic Vertic Argiudolls which correlates to Luvic Vertic Phaeozems in the World Reference Base) (Krasilnikov and Arnold, 2009; Soil Survey Staff, 2012). Soil profiles were described following Schoeneberger et al. (2002) and classified according to US Soil Taxonomy (USST; Soil Survey Staff, 2010) and the World Reference Base (WRB; IUSS Working Group WRB, 2006). Two representative morphological horizons from the surface (NP pedon—A horizon; RP pedon—Ap horizon) and subsurface (Btss1 horizons) of each pedon were sampled to examine mass–volume scaling relationships.

Six large (500–1000 cm^3) intact aggregates were sampled from each of these horizons, wrapped in aluminum foil and plastic sampling bags to prevent significant moisture loss, and placed in a partitioned cardboard carrier to minimize disturbance during transport from the field. Bulk samples were collected from each horizon for determination of particle-size distribution, organic carbon (OC) content, and cation exchange capacity (CEC). In addition, bulk density was assessed in triplicate following the core method (Grossman and Reinsch, 2002) using a soil sampler (SoilMoisture Equipment Corp, Santa Barbara, CA) equipped with 3 cm × 5.4 cm i.d. brass rings.

2.3. Laboratory analyses

In the laboratory, each aggregate was carefully unwrapped, subsampled for gravimetric moisture determination in triplicate, and volume was determined by 3-D laser scanning following Rossi et al. (2008). We used a MLT scanner (3D Scanner HD, NextEngine, Santa Monica, CA) to characterize volumes down to approximately 2 cm^3 by progressively and gently breaking smaller pieces from the clod by hand and rescanning. For each break, the aggregate was subsampled for gravimetric moisture and weighed. Aggregate volumes were determined by processing the scans with the ScanStudio software (NextEngine, Santa Monica, CA) following procedures outlined by Platt et al. (2010). Several multi-colored ball-head pins were placed around a clod before scanning to serve as reference points for aligning individual scans (Eck et al., 2013).

Volumes of the aggregates, when broken down to less than ~2 cm^3, were determined following Subroy et al. (2012). Briefly, these small air-dried aggregates were saturated by capillarity with a glycerin–ethanol mixture (1:1, v/v) and weighed in air. The aggregates were then submerged in kerosene and their weights recorded. Aggregate volumes were determined from the density of kerosene and the difference between the weights in air and in the displacing liquid. In addition, a subset of nine aggregates with volumes between 2 and 5 cm^3 was chosen to assess the accuracy of the 3-D scanning method for small volumes and to ensure that the volumes obtained from the scanner were comparable to the displacement method.