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Are power laws that estimate fractal dimension a good descriptor of soil structure and its link to soil biological properties?

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ABSTRACT

The study of interrelationships between soil structure and its functional properties is complicated by the fact that the quantitative description of soil structure is challenging. Soil scientists have tackled this challenge by taking advantage of approaches such as fractal geometry, which describes soil architectural complexity through a scaling exponent (*D*) relating mass and numbers of particles/aggregates to particle/aggregate size. Typically, soil biologists use empirical indices such as mean weight diameters (MWD) and percent of water stable aggregates (WSA), or the entire size distribution, and they have successfully related these indices to key soil features such as C and N dynamics and biological promoters of soil structure. Here, we focused on *D*, WSA and MWD and we tested whether: *D* estimated by the exponent of the power law of number-size distributions is a good and consistent correlate of MWD and WSA; *D* carries information that differs from MWD and WSA; the fraction of variation in *D* that is uncorrelated with MWD and WSA is related to soil chemical and biological properties that are thought to establish interdependence with soil structure (e.g., organic C, N, arbuscular mycorrhizal fungi). We analysed observational data from a broad scale field study and results from a greenhouse experiment where arbuscular mycorrhizal fungi (AMF) and collembola altered soil structure. We were able to develop empirical models that account for a highly significant and large portion of the correlation observed between WSA and MWD but we did not uncover the mechanisms that underlie this correlation. We conclude that most of the covariance between *D* and soil biotic (AMF, plant roots) and abiotic (C, N) properties can be accounted for by WSA and MWD. This result implies that the ecological effects of the fragmentation properties described by *D* and generally discussed under the framework of fractal models can be interpreted under the intuitive perspective of simpler indices and we suggest that the biotic components mostly impacted the largest size fractions, which dominate MWD, WSA and the scaling exponent ruling number-size distributions.

1. Introduction

Soil architectural characteristics depend on the size and arrangement of particles and pores, which depend on the dynamics of the chemical and physical processes driving the formation of micro and macroaggregates (Hartge and Stewart, 1995). Overall, these features are conceptualised as “soil structure” and, from an ecological point of view, they are known to regulate several functions such as soil gas and solution exchange that are of fundamental importance for the growth of plants and the maintenance of soil biota (e.g., Coleman and Crossley, 1996; Elliott and Coleman, 1988; Paul and Clark, 1989). The converse is also true: soil organisms positively feed back to the formation and maintenance of soil structure. This is particularly true for organisms such as arbuscular mycorrhizal fungi (AMF), which are known to be among the most important biological promoters of soil aggregate stabilization under given abiotic conditions, especially when measured as water stable aggregates (Harris et al., 1964; Tisdall and Oades, 1982; Jastrow et al., 1998; Rillig, 2004). In fact, the extraradical hyphae of AMF enmesh particles and produce compounds (e.g., proteins) that may stabilize aggregates (Rillig et al., 2007). Of course, plants are the other main biological driver of soil structure owing to their root system and the release of exudates (Thomas et al., 1993; Angers and Caron, 1998; Hallett et al., 2009). Finally, biological drivers interact with physical processes. The latter initially provide the background for the formation of soil structure and finally feed back to the biotic component. In this paper, we focused on the biotic component and on synthetic indices for describing some features of

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soil structure. In fact, the study of the interrelationships between organisms, soil structure and its functional properties is complicated by the fact that the quantification of soil structure is challenging, since structure cannot be easily reduced to a few numbers without losing information. Given our first definitions, an important feature of soil structure lies in the size distribution (SD) of soil particles, especially aggregates (SDA). Classically, a synthetic descriptor of SDA is the Mean Weight Diameter (MWD; Kemper and Rosenau, 1986)

$$\mathrm{MWD} = \sum_{R=r\,\max}^{r\,\min} W_R R \quad (1)$$

where R is the sieve size and W_R is the weight ratio of the material retained on the sieve of size R. Therefore, the MWD reflects the relative proportions of aggregates having a mean diameter of the size fractions defined by the upper and lower bounds of the sieves used. Of course, this index is biased towards the largest abundant fractions. This index should capture a small fraction of the complexity of soil structure, or at least the concept soil biologists have of it. For this reason, soil ecologists have analysed the various size classes in order to describe the entire distribution (e.g., Six et al., 2000a; Wilson et al., 2009). Alternatively or complementarily, they have focused on the total percentage of water stable aggregates >250 μm (macroaggregates), where the resistance to the disintegrating force of water is intended to be a reverse proxy to the aggregation processes. Macroaggregates are of special interest, since they are a major player in the complex interrelationships that determine fluxes of nutrients (especially C and N) between the abiotic and biotic components of soil (Six et al., 1998, 2000b; Rillig, 2004). Other authors, more oriented towards pedological and/or modelling approaches, have used different synthetic descriptors of architectural complexity taking advantage of fractal geometry (Mandelbrot, 1983). The main reason for using fractal indices is that the probability of failure of aggregates is not scale-invariant. Instead, larger particles are more easily fragmented than smaller ones (Tyler and Wheatcraft, 1992; Rasiah et al., 1997; Martínez-Mena et al., 1999; Gülser, 2006). Of course, this is also true for the reverse (aggregation). Thus, independently of the direction of the processes creating aggregates and particles (aggregation *vs.* fragmentation), the main idea of the fractal approach is to describe the scaling between the size of a particle and the number of particles of that size or, more appropriately, between the size of a particle and the cumulative number of particles of that size. Then, the exponent ruling this scaling can be used as a structural (i.e. architectural) variable, which can be related to other soil properties. However, from a theoretical and practical point of view, the geometric approach proposed by theorists of fractals is challenging when researchers have to shift from a mathematical description to a physical interpretation, and soil scientists have debated about the fractality of soil and methods for estimating it. For example, regardless of the object under investigation there are many quantitative definitions of a fractal object, depending on the physical nature of the process to be described for the object (Mandelbrot, 1983). Also, the same process can be described by different fractal models depending on the assumptions made and experimental responses obtained (e.g., Perfect and Kay, 1991; Tyler and Wheatcraft, 1992; Crawford et al., 1993; Rasiah et al., 1993, 1995, 1997). For example, there is a fundamental difference between mass and boundary fractal dimension: according to Crawford et al. (1993) and Perrier and Bird (2002), the exponent of the power law of a fragmentation process can be directly related to the fractal dimension *sensu* Mandelbrot (1983) only when the analysed object is self-similar, which implies that the dimension of its boundary equals its mass fractal dimension. In principle, in the case of a truly fractal soil material, the scaling exponent of the power law that describes the fragmentation process should be between 2 and 3, since soil surface can neither be more than three-dimensional nor less then two-dimensional. If, as often occurs (e.g., the review by Perfect and Kay, 1995), values lower than 2 and higher than 3 are observed, the explanation can be theoretical and/or physical (e.g., the object is not a fractal: Crawford et al., 1993) or methodological (e.g., analytical and statistical tools used for estimating fractal dimension are biased: Rasiah et al., 1995). Besides the interpretation given to indices derived from power laws (e.g., are they an estimate of fractal dimensions?) that summarize the distributions obtained by fragmentation and/or aggregation processes, there have been several successful attempts to link these indices which are often assumed to estimate fractal dimension of soil aggregates, to biological or ecological descriptors such as biomass and diversity of earthworms or plants (e.g., Duhour et al., 2009; Liu et al., 2009). In the last 20 years, studies that addressed the use of fractal dimension as a descriptor of soil structure have been focusing on the following issues: 1) different methods for estimating fractal dimension using power laws for number-size distributions and their consistency and/or theoretical foundation (e.g., Perfect and Kay, 1991; Crawford et al., 1993; Perfect et al., 1994; Rasiah et al., 1993, 1995, 1997); 2) the reliability of fractal dimension in measuring structural properties that are relevant to soil physics (Young and Crawford, 1991; Martínez-Mena et al., 1999); 3) the capability of fractal dimension to detect the effects of disturbances such as tillage (e.g., Perfect and Kay, 1995; Perfect and Blevins, 1997). Here, we aimed at testing whether: 1) over a wide range of environmental conditions and land use, which should cause changes in soil structure, the scaling exponent of power laws summarising the number-size distribution of aggregates (below called for brevity "D", which does not necessarily have to be understood as an estimate of fractal dimension) is a good and consistent correlate of MWD and WSA; 2) D carries information that differs from MWD and WSA; 3) the portion of the information of D which is uncorrelated with the information carried by MWD and WSA is related to ecological soil properties that are known to have a high interdependence with soil structure (e.g., organic C, N, AMF). Certainly, there remains structural information that is not described by the above synthetic indices, but which is tightly related to key soil processes (e.g., C dynamics), and which can probably be captured by a simultaneous analysis of all class sizes (e.g., Six et al., 2000a). However, we are not addressing that aspect in this paper (i.e. comparing synthetic indices to other methods for describing size distribution). Further, we focused on the relationship between the biotic components and soil structure and we did not address abiotic drivers of soil structure. In order to test these three hypotheses, we analysed a subset of a large data set gathered from a broad scale field study in the framework of the German Biodiversity Exploratories, a suite of large scale field studies. Further, in order to have higher control in terms of environmental variability and the heterogeneity of processes that may affect soil structure, we analysed data from a greenhouse experiment, in which the differential roles of different soil organisms in promoting soil aggregation were examined.

2. Methods

2.1. Data set I – German Biodiversity Exploratories

The study sites were located in the German Biodiversity Exploratories, with sites in Schorfheide Chorin (SC), Hainich Dün (HA), and the Schwäbische Alb (AL) (Fischer et al., 2010). Sites in all Exploratories are managed with a range of grazing, mowing, and fertilization intensities. In SC soils are primarily glacially formed