Korean J. Soil Sci. Fert. 44(3), 517-526 (2011)

Article

Review of Soil Structure Quantification from Soil Images

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Soil structure plays an important role in ecological system, since it controls transport and storage of air, gas, nutrients and solutions. The study of soil structure requires an understanding of the interrelations and interactions between the diverse soil components at various levels of organization. Investigations of the spatial distribution of pore/particle arrangements and the geometry of soil pore space can provide important information regarding ecological or crop system. Because of conveniences in image analyses and accuracy, these investigations have been thrived for a long time. Image analyses from soil sections through impregnated blocks of undisturbed soil (2 dimensional image analyses) or from 3 dimensional scanned soils by computer tomography allow quantitative assessment of the pore space. Image analysis techniques can be used to classify pore types and quantify pore structure without inaccurate or hard labor in laboratory. In this paper, the last 50 years of the soil image analyses have been presented and measurements on various soil scales were introduced, as well. In addition to history of image analyses, a couple of examples for soil image analyses were displayed. The discussion was made on the applications of image analyses and techniques to quantify pore/soil structure.

Key words: Soil structure, Pore geometry, Computer tomography, Image analysis, Fractal, Entropy

Introduction

The roles of soil structure in nature are numerous, including the transmission and storage of matter and energy and the support of plant growth and microbial activity (Dexter, 2002; Karlen, 2002; Young et al., 2001). The aspects of soil structure typically studied include structural form, structural stability, and structural resiliency (Kay et al., 1997). Structural form can be defined as the heterogeneity in the arrangement of solid and void phases, or in general as the heterogeneity of the different components or properties of soil (Dexter, 1988). Structural stability refers to the degree to which the structural form is maintained when external forces are applied. Two types of soil stabilities have been defined in relation to how well a soil retains its structure under: 1) the stress of water, and 2) external stress in the absence of water (Dexter, 1988). Structural resiliency is defined as the ability to recover the structural form when the stress is removed or reduced. Soil structure exhibits a hierarchical organization, with structural units or aggregates at one level formed by structural units of a lower organization (Dexter and Hakansson, 1989). The lowest level of organization is the combination of soil particles. The next level of organization is the clustering of soil particles into microaggregates with diameters between 20 and 250 μm, bounded by polysaccharides and other organic materials produced by soil organisms (Young et al., 2002) (Fig. 1). The next level of organization is the grouping of soil microaggregates to form soil macroaggregates (aggregates larger than 250 μm in diameter). Forces within structural units are stronger than forces between structural units tending to keep the integrity of soil aggregates (Boix-Fayos et al., 2001; Dexter, 2002).

The hierarchical organization of soil structure leads to a dual system of soil pores (Young et al., 2001). Pores located between macroaggregates are called macropores, whereas pores within soil aggregates are known as

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Received : March 18. 2011 Accepted : June 22. 2011
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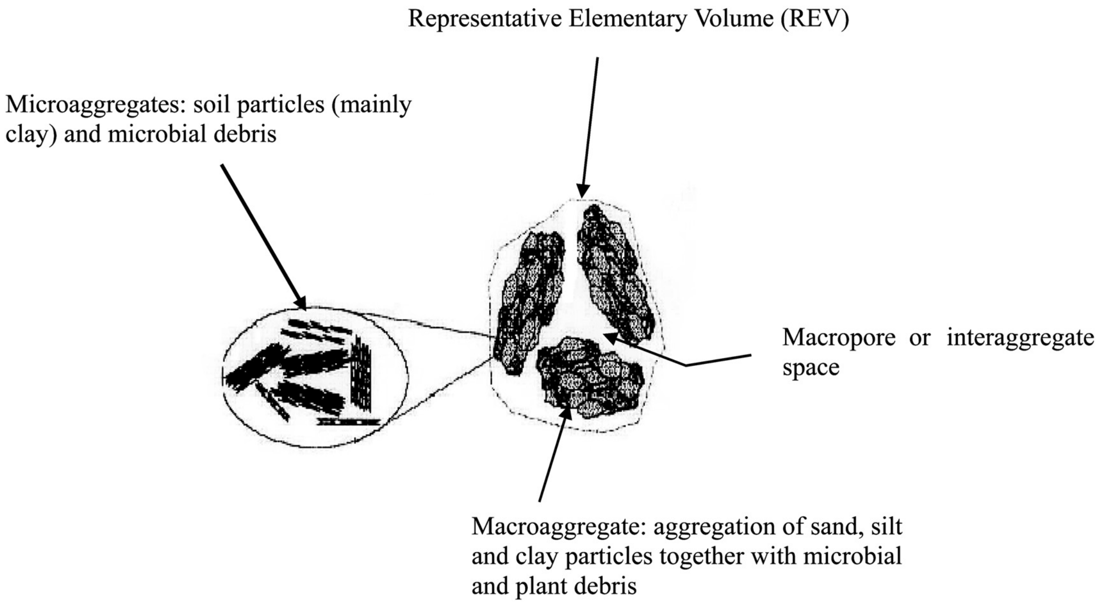


Fig. 1. Hierarchy of soil structure (adapted from Young et al., 2001).

micropores (Fig. 1). Macropores are produced by plant roots, shrinking of soil due to drying, and by soil fauna (Giménez et al., 2002). Macropores provide room for plant roots and constitute the fastest pathways of water and gases, thus reducing the buffering and filtering functions of soils (Dexter, 2002; Keith and Buchan, 2002). In contrast, water flow is slower in micropores, sometimes preventing or slowing down the growth of plant roots and aerobic microorganisms (Brady and Weil, 2000).

All these components create different types and shapes of soil pores and soil structure. These differences make soil characteristics more complicated and complex, therefore there is a need to understand various soil scales and its measurements at each scale.

Scales of Soil Measurements

Soil system has extreme complexity on various scales. There have been many definitions and explanations on different scales. In this paper, scales related to more on soil image analyses were listed and interpreted. The first attempts to characterize soil structure were made through measurements of pore- (Russell, 1941) and particle- size distributions (Wittmuss and Mazurak, 1958). These are considered indirect measurements of soil structure aimed at inferring soil behavior from properties known to reflect pore-solid arrangement. Direct measurements of pore-solid arrangement are made on resin-impregnated soil samples (Oleschko et al., 2002; Ringrose-Voase and Nys, 1990) and more recently on 3 dimensional images obtained from computer tomography (Wong and Wibowo, 2000).

Soil structure is heterogeneous across a wide range of size scales (Dexter, 2002). Therefore, any measurement of soil structure requires considering sample size. The Representative Elementary Volume (REV) is defined as the smallest volume at which the variance of the measurements becomes independent of sample size (Bear, 1972). In soils, as soil structure changes from a single grain to large aggregates, the size of REV increases 3 orders of magnitude (Fig. 1 and Table 1). The REV concept can be translated to a 2 dimensional plane by defining the Representative Elementary Area (REA). VandenBygaart and Protz (1999) found the REA of samples containing pores with diameters ranging from 50 to 500 μm in diameter was 5.1 cm^2 and the average REA for pore sizes between 500 and 2,000 μm in diameter was 6.73 cm^2. Based on the size of REV (or REA) and the objectives of a research, sample scale is classified as: 1) macro or field scale, 2) meso or laboratory scale, and 3) micro or pore scale (Kutilek and Nielsen, 1994).

Measurement of soil structure at the macro-scale is important to understand water movement, contaminant transport and biodegradation at the field scale (Kaluarachchi et al., 2000; Oleschko et al., 2002; Pohlmann et al., 2000). Photographic techniques have been used at the m^2 scale with the objective of quantifying size and spatial distribution of macropore (Edwards et al., 1988, 1990; Oleschko et al., 2002; Smetten and Collis- George, 1985). This

Table 1. Sizes of REV in different types of soil structure (Bouma, 1985).

Texture	Soil Structure	Hypothetical REV (cm^3)
Sandy	No aggregates	10^2
Loamy	Small aggregates	10^3
Clayey	Medium aggregates, continuous macropores	10^4
Clayey	Large aggregates, continuous macropores	10^5

technique is invasive and can only provide two dimensional information. Lately, non-invasive techniques such as ground-penetrating radar have been used to provide information on subsurface heterogeneity (Huisman et al., 2002; Oleschko et al., 2002; Splajt et al., 2003).

Measurements at the meso-scale are generally less costly and allow for more control during experiments. At this scale, soil properties are measured on individual aggregates or on soil columns involving disturbed or undisturbed soil. Investigation at the aggregate scale provides information on the formation of soil structure, on the distribution of pore sizes within aggregates, and on micro heterogeneity of chemical and microbial distribution in soil (Dexter, 1988; Dexter and Hakansson, 1989; Kirchhof and Daniel, 2003). The disadvantage of characterizing soil structure through aggregate properties is that interaggregate space defined by the natural arrangement of aggregates is neglected. Aggregates properties typically studied include aggregate shape (Dexter, 1985; Holden, 1993), aggregate roughness (Dexter, 1985; Holden, 1995; Young and Crawford, 1992), and chemical gradient between the surface and cores of soil aggregate (Kirchhof and Daniel, 2003). Dexter (1985) found that the shape of aggregates from tilled soil was influenced by the contents of clay and organic matter. In turn, the shape and surface roughness of aggregates influence the size and spacing of structural features and the degree of structural development in a soil. Holden (1995) found a significant correlation between roughness of aggregate surfaces and water retention at -10 kPa.

A complete measurement or characterization of soil pore structure can be challenging at any scale. There have been many attempts to characterize REV or proper scales for soil structure analyses, however there was no absolute answer for the proper scale for the analyses. There should be more research to find the proper scale of soil samples for reliable measurements and representative results for the real world.

Image Analyses in Soil

Two dimensional soil images analyses There are at least three ways to measure structure from soil images. The first method characterizes sequences of pores and solids measured along lines (1 dimensional analysis), while the remaining two techniques use 2 dimensional information. Fara and Scheidegger (1961) were the first researchers to characterize the statistical properties of natural porous media by using a binary image in which solids and pores were assigned values of 1 and -1, respectively. They measured sequences of solids and pores along a line and used it to calculate autocorrelation and a random function based on a wave function. This theory influenced Dexter (1976) who used thin sections of tilled soil to estimate probabilities of occurrence of different linear combinations of solid-pore strings. Probabilities were calculated by manually counting solids and pores at intervals of 1 mm along lines drawn on thin sections. The results were considered as binary signals and used to calculate the Shannon (1948) entropy and to simulate soil structure with a Markov process. The development of image analyzers and faster computers allowed measuring pore-solid arrangements defined as pixel values (Oleschko et al., 1997; Ringrose－Voase and Nys, 1990). Ringrose－Voase and Nys (1990) proposed determining pore size and mean solid intercept length from thin soil sections. They concluded that mean solid intercept length is inversely proportional to pore size. Oleschko et al. (1997) proposed determining linear fractal dimensions of pores and solids as a way to specify soil structure. Irregularity of fracture and pore surfaces measured on images of soil sections have been also used to characterize soil management (Young and Crawford, 1992).

Another way to characterize soil structure from one dimensional information is to measure the autocorrelation function along lines arranged radially to cover a circle. Results are used as either individual lines (Masad and Muhunthan, 1997) or averaged across lines (Bentz and Martys, 1994). Talukdar et al. (2002) used autocorrelation to reconstruct 3 dimensional images from 2 dimensional information and concluded that 3 dimensional reconst-

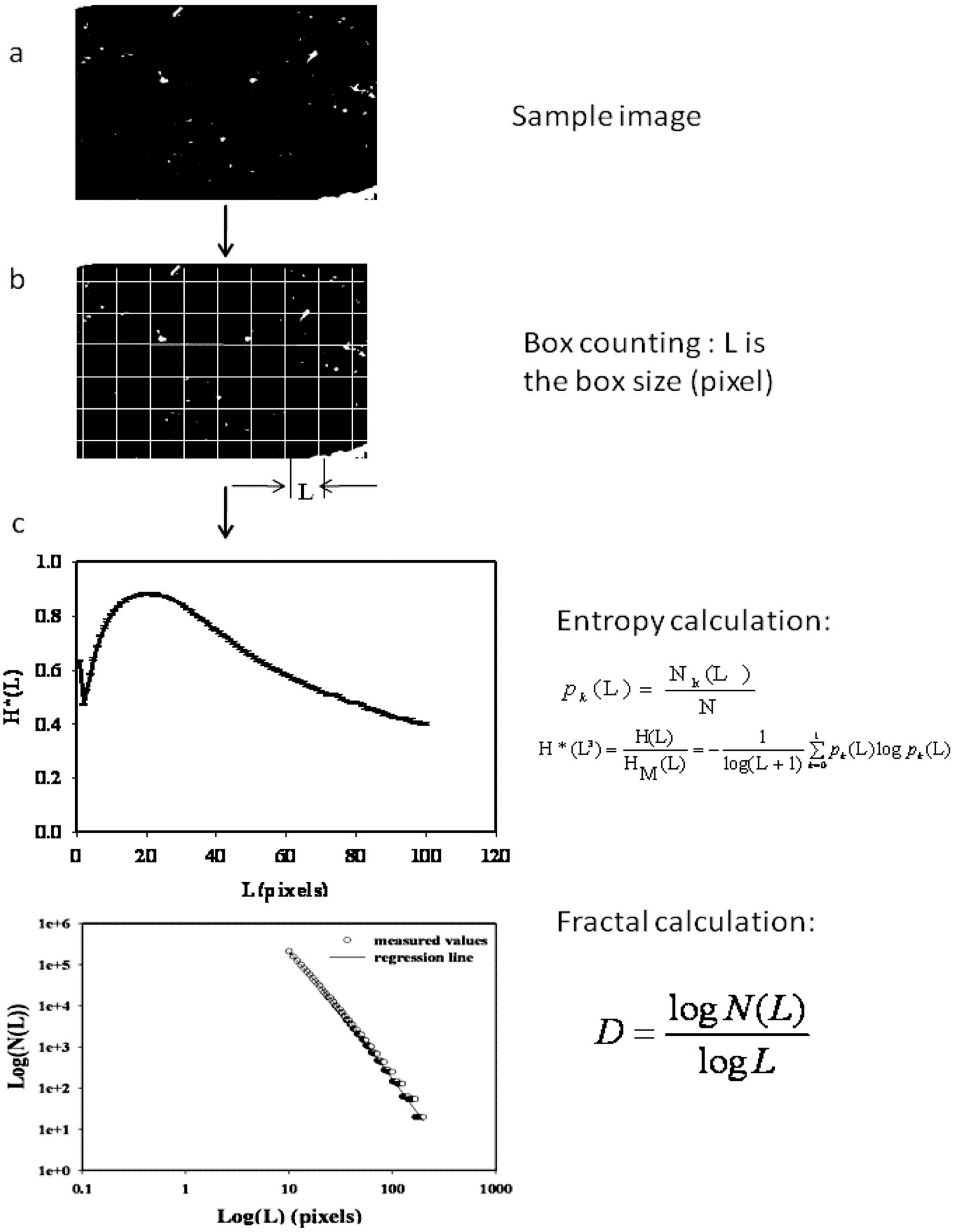


Fig. 2. Diagram of image analyses; a. sample image, b. box counting with box size of L (pixel), and c. image analyses- entropy and fractal. $N_k(L)$ represents the number of boxes with same porosity, where k means the possible porosity of each box.

ruction from 2 dimensional autocorrelation calculations produces reasonable results. On the other hand, Masad and Muhunthan (1997) developed a directional autocorrelation function to improve the simulation of 3 dimensional image from information on 2 dimensional images. Their method measures autocorrelation along lines organized radially from the center of the sample without averaging the function.

The remaining two methods of characterization of soil structure from soil images are based on characterizing pixels or groups of neighboring pixels defining either an irregular object or contained in cells of regular sizes (Fig. 2). Mathematical morphology is based on measuring pore surface area and length of the intricate solid-pore structure, which are used to characterize three properties of soil structure: 1) the amount of pore space and solid space, 2) coarseness/ fineness of solid space, and 3) size of pore space (Horgan, 1998; McBratney et al., 1992; Moran and McBratney, 1992; Serra, 1988). The third technique measures the properties of pixels in units (cells) of regular shape. Typically, images are covered with square grid of variable size and the property(ies) of the solid-pore arrangements of interest are measured inside each cell (Fig. 2b). These results have been analyzed with fractal and entropy methods (Andraud et al., 1994; Andraud et al., 1997; Crawford et al., 1993; Oleschko et al., 2002; Yelshin, 1996) (Fig. 2c). These types of techniques are called pore spatial distribution analyses.

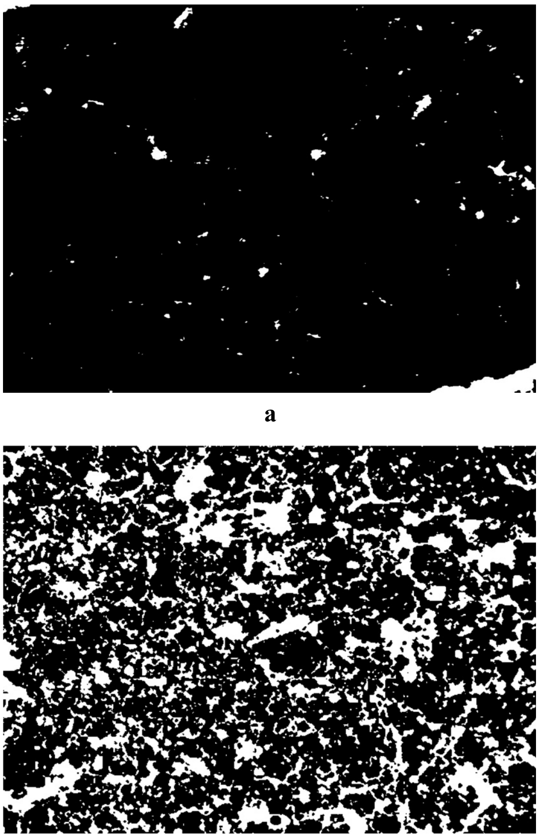
Fractal analysis is transforming measured properties into a single scaling dimension and finding repeated patterns or relations (Perfect and Kay, 1995). Fractal analysis from soil images has characterized heterogeneity of pore structure (Gibson et al., 2006; Perret et al., 2003; Rachman et al., 2005), pore surface geometry (Dathe et al., 2001) and pore size distribution (Bartoli et al., 2005). Generally, fractal analysis provides fractal dimension (D) values and trend of distributions in log formation. Based on these values, researchers can understand complexity of pore structure or a matter of interest.

Fractal analysis determines scaling behavior with a single power law and this method has been questioned (Gouyet, 1996; Posadas et al., 2003). Because a single fractal dimension may be not enough to characterize complex system, there is a trend to assess soil physical properties by multifractal measures, which is a series of fractal dimensions at various exponents (moments). Multifractals can separate complex soil structure types but the interpretation of the results is complicated (Posadas et al., 2003). To compensate for this problem, the universal multifractals were introduced (Liu and Molz, 1997). This analysis measures spatial dependence in a range of moments and provides parameters which characterize scaling behavior (Tennekoon et al., 2003). This method has been applied to a spatial distribution of soil hydraulic conductivity (Tennekoon et al., 2003) and spatial distribution of crop yields (Kravchenko, 2008; Pozdnyakova et al., 2005), but not soil structure from images.

Local porosity distribution analysis is a calculation of porosity at various cell sizes from porous images (Lin and Hourng, 2005). Applying statistical analyses to the local porosity distribution provided spatial distributions of pores and general geometric characteristics; variogram (Cislerova and Votrabova, 2002), percolation (Biswal et al., 1998; Boger et al., 1992), and entropy (Beghdadi et al. 1993). This analysis has been applied to characterize spatial distribution of intra-aggregate pores (Cislerova and Votrabova, 2002; Wong and Wibow, 2000) or simulation of soil (Masad and Muhunthan, 1997). Previous studies found that local porosity distribution can provide accurate description of three dimensional pore space from microstructure images (Biswal et al., 1998), however this analysis has not been applied to morphological analysis for pores.

Entropy analysis is a log transform of local porosity distribution at different cell units. Entropy analysis is counting numbers of cells with same porosity and added log transform to distinguish clearly in porosity distributions. Beghdadi et al. (1993) showed that the configuration entropy or normalized entropy could be more sensitive to separate structural differences than other methods, such as multifractal analysis. By this process, a well defined peak relation across cell size can be found (Chun et al., 2008). The normalized entropy has been applied to two dimensional soil images by Tarquis et al. (2006) and Chun et al. (2008). Both studies showed that entropy analysis was able to characterize complexity of pore structure in macro scale (Tarquis et al., 2006) and micro scale (Chun et al., 2008). However, there has been no application of configuration entropy analysis on three dimensional soil images.

Examples of two dimensional image analyses; fractal and entropy analyses In Fig. 3, two images with different pore structures are shown. Both soils were aggregates taken from New Jersey, USA in 2002 (adapted from Chun et al., 2008). Images were taken from blocked soil section at the resolution of resolution of 2048 x 1536 pixels. The soil 1 was the aggregate from cultivated soil and the soil 2 was from forest soil. Fractal and entropy analysis were calculated from these two images. Both calculations resulted in distinguishably different fractal dimension (D) values and trends from two images. As they showed, these analyses can characterized different pore structure and provide quantitative values to represent pore structures (Fig. 4 & 5). All these spatial distribution analyses measured porosity or existence of pore pixels from cell units and they do not provide quantitative description of pore properties. Spatial analyses are relatively simple to calculate and provide fast results of pore characteristics. However, these analyses have limitations to characterize accurate picture of soil structure. To understand soil function fully, such as hydraulic conductivity or water retention, spatial analyses of pore structure are not enough, because these properties are more related


a

b

Fig. 3. Example of soil aggregate images with different pore structure (adapted from Chun et al., 2008); a, cultivated soil with less and isolated pores; b, forest soil with greater porosity and more large size pores.

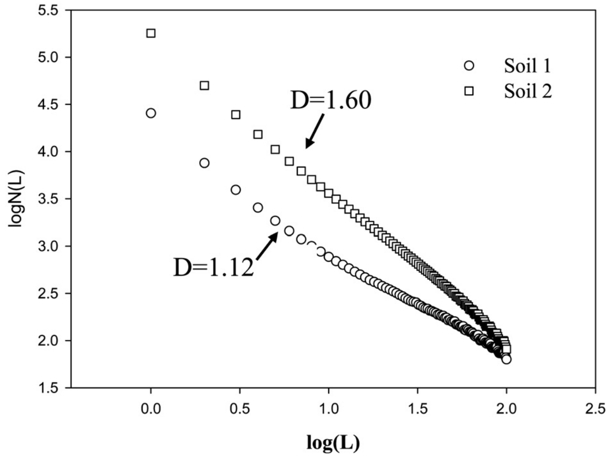


Fig. 4. Fractal calculation results from Fig.3 images (Soil 1 & 2). Fractal dimension (D) values were calculated from the fractal equation in Fig. 3.

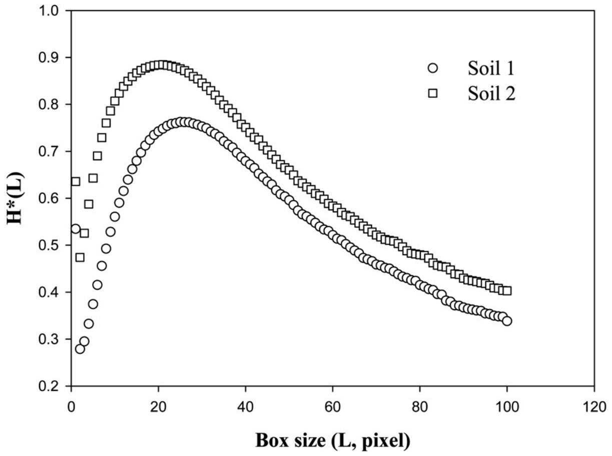


Fig. 5. Entropy calculation results from Fig. 3 images (Soil 1 & 2). H*(L) values were calculated from the entropy equation in Fig. 3.

to pore morphological properties. It requires quantitative knowledge of pore morphological properties to overcome the limitations of spatial analyses.

Three dimensional soil images analyses In the last decade, research has been performed to characterize quantitative analyses of pore structure from soil images (Peth et al., 2008). First attempts to characterize pore structure from two dimensional soil images, found that it was difficult to understand the physical properties of soils without the knowledge of the three dimensional distributions of pores (Chatzis and Dullien, 1975; Gibson et al., 2006). Therefore, three dimensional characterization is of interest not only to improve quantification of soil pore structure but also to improve understanding of structure changes of pore properties across scales or when different treatments apply to soil.

A complete measurement or characterization of soil pore structure can be challenging at any scale. Recent development of computer tomography (CT) technique made possible to observe intact internal structure of soil. A computer tomography can provide a non-invasive three dimensional images by mapping x-ray absorption through a sample. Each scan provides a series of cross section from a sample and these cross sectional images are reconstructed as three dimensional image. Soil structure has been analyzed from computer tomography images since 1960's and interest of this analysis has been increased rapidly; measuring pore pattern (Taina et al., 2008), transport through pore structure (Olson et al., 1999) and quantify soil biota or microbe (Capowiez et al., 2001; Nunan et al., 2006). The methods of pore property measurements are separated in two part; pore spatial distribution analyses and morphological analyses.

Pore network models have been developed as three dimensional images become more available and computer capacity increased (Taina et al., 2008). Pore network models were introduced by Fatt (1956) who considered pore-body objects and linking channels (throats) between those pores to describe connectivity. Each pore-body object was considered as spheres and throats as cylinders to calculate length and diameter. Although network models can be two- or three- dimensional, two dimensional networks cannot provide a good representation of three-dimensional systems because of their inability to provide a complete representation of the interconnectivity (Chatzis and Dullien, 1975).

Example of three dimensional image analysis

The core of pore network is skeletonization models (Luo et al., 2008). Skeletonization is a process for reducing foreground regions in an image to a skeletal remnant that largely preserves the extent and connectivity of the original region while ignoring most of the original foreground pixels. There are two ways to produce skeleton structure in an object. Figure 6a displays an example of 3d soil pore structure. The intact soil was scanned with x-ray micro computer tomography (model MS, General Electric Medical Systems, ON, Canada) at the resolution of 21 μm. Based on this image, pores in the soil sample were selected by thresholding program (Fig. 6b). The quantification of the pores can be done by construction of pore skeletonization (Fig. 6c), which represents the pore distribution of the soil sample and colors represent sizes of each pore or channel. The volume, length, tortuosity and connectivity of pore or channel can be calculated from the skeletonized image.

Morphological analyses from CT images have disadvantages when applied for large data sets or samples, since they require large computer capacity and time to get results. Tania et al. (2008) stated that major studies of pore morphological studies from CT images focused on intra-aggregate pore properties, such as, pores created by roots (Pierret et al, 1999), pores affected by earthworm or earthworm burrows (Bastardie et al., 2003; Capowiez et al, 2001, 2003), and hydraulic processes (Monga et al., 2008). As Perret et al. (2003) suggested, obtaining realistic properties of macropores created by roots, they needed images as large as at least one magnitude of root length. In thorough literature review, soil image sizes, especially three dimensional image sizes were less than 500×500×500 voxels in any resolution (except simulated images) and large sample sizes had lower resolution than 1 cm. Image sizes and resolutions were compromised by computer capacity to calculate morphological properties of pores. It is doubtful that low resolutions and small image sizes would fully characterize inter- and intra-aggregate pores in soil.

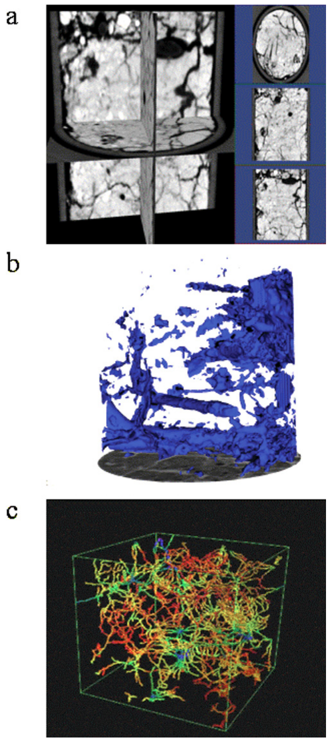


Fig. 6. Examples of 3D raw soil image and image processing: a. Example of real soil scanned with CT at resolution of 21 μm (provided from T. Elliot, University of Guelph) and b. volumetric image of pores and c. skeletonzation of the partial example soil by pore network model. Different colors represent sizes of pores and channels between pores.

Conclusion and Future expectations

From what was discussed in this review it can be observed that the image analysis techniques have been applied with success in the analysis of physical properties of soils during the last decades. With the investments that have been made in equipment exclusively projected for this purpose, it is expected that image analyses, especially CT will gradually be able to yield more representative results of these properties. New tomographic models based on the use of radiation from synchrotron light, positrons and neutrons may become interesting alternatives for the study of soil physical characteristics, opening the possibility of obtaining images of greater resolution and also presenting a greater sensitivity to monitor soil water content changes. Studies of the dynamics of fluid transport and root growth can also be carried out in a non-invasive way using microtomographs. Systems that make use of X-ray or synchrotron light beams can be used with success in this type of investigation since they allow the analysis of samples of very large size such as 20 cm or more. The improvement of the method has allowed, for instance, the rapid evaluation of the impacts of different management systems on soil physical properties. With an anticipated monitoring of some physical properties it is possible to measure and evaluate the impact of each soil management practice on soil structure, this being an important aspect from the environmental and agricultural points of view. This equipment opens the possibility of performing more detailed studies on soil properties and is available to help researchers to understand phenomenon in ecological systems.

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