Study of the effects of structure on soil aggregate stability using a 3D network model

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Abstract
Aggregate stability strongly influences soil structure and has relevant implications to soil organic carbon protection. We studied the physico-chemical and physical mechanisms of soil structural stability in a long-term experiment in north-eastern Italy. A 3D void network model was used to investigate subtle structural changes in aggregates and their hydraulic properties (intrinsic permeability). The study demonstrated the central role of organic carbon on aggregate stabilization, partly by reducing the intrinsic aggregate permeability and soil wettability.

Key Words
Soil structure, aggregate stability, SOC, Pore-Cor, long-term experiment, organic fertilizers

Introduction
Aggregate stability is an important factor influencing soil fertility. Aggregate breakdown is strongly affected by physico-chemical and physical mechanisms. Recent studies showed the importance of soil organic carbon (SOC) and its humic compounds in aggregate stabilization by at least two different mechanisms: first by increasing soil hydrophobicity and then reducing its breakdown by slaking (Chenu, 2000). Secondly, organic carbon increases the aggregates' inter-particle cohesion. Effects of SOC on porosity and indirectly aggregate stability have recently been suggested (e.g. Lugato *et al*., 2009; Papadopoulos, 2009). Fertilizers with a high organic carbon content, such as manure, would therefore be expected to increase aggregate stabilization. However, little is known about the relative importance of chemical and physical soil stability mechanisms. Organic carbon can maximize the effect of stability indices with different pre-treatments. In addition, a 3D void network model can be used to investigate subtle structural changes in soils based on intrusion curves (e.g. Holtham *et al*., 2007). In this work we used a 3D void network model combined with physico-chemical and physical measurements to investigate the factors affecting soil aggregate stability in a long-term experiment.

Methods
The long-term experiment is located in north-eastern Italy at the Experimental Farm of the University of Padua. It has been underway since 1962, comparing organic (farmyard manure and slurry), mineral and mixed (organic and mineral) fertilizers. The experimental layout is a split-plot with three replications. This work considers 8 treatments with maize as main crop. Half of the treatments also include crop residue incorporation. Wet sieve analyses were carried out on 1-2 mm aggregates after pre-treatments with ethanol (ETOH), benzene (BENZ), fast and slow wetting with water (FW and SW). The aggregate stability index was calculated according to Diaz-Zorita *et al.* (2002). Soil organic carbon characterization included humic fractions (nominal molecular weight: >100 kDa, 100-10 kDa and <10 kDa) and functional group analysis. Wettability was measured by the capillary rise method (Siebold 1997). Aggregate pore distribution in the range 0.0037-58 µm was analyzed by mercury porosimetry with Thermo Finnigan Pascal 140 and Thermo Finnigan Pascal 240. To evaluate the effect of soil structure on aggregate stability, pore distribution curves were analyzed with Pore-Cor (Price *et al.* 2009), a network void model that can generate a simple 3D stochastic representation of soil structure and then quantify its features. The model approximates the geometry of a void unit cell containing 1000 cubic pores connected by up to 3000 cylindrical throats.

Pore-Cor's uniqueness over other modeling approaches is that it creates a physically realizable geometry and generates five parameters that are real properties resulting from the closeness between simulated and experimental curves. Intrinsic hydraulic conductivity (Perm) was estimated from primary parameters. At least ten fits were conducted per replication, corresponding to different stochastic generation numbers. To emphasize the effect of soil structure on wetting and consequently on aggregate stability, fast dynamic wetting with water was modeled on the basis of previously generated unit cells.

Results

The aggregate stability index varied according to treatments and soil characteristics. Aggregates pre-treated with benzene maximized the effect of organic matter, increasing hydrophobicity. Indeed, contact angle measurements were correlated to SOC, high-weight humic fraction (HF1) and stability structure index (pre-treated with benzene). On the contrary, the stability index with fast and slow wetting pre-treatments was influenced by porosity, especially in the 5-0.1 μm range (ultramicropores). Pore-Cor parameters showed high variability among replicates and no significant differences were observed among treatments. However, connectivity (Conn, i.e. the average number of connected throats per pore) and correlation level (CorLevel, i.e. the local degree of clustering within the unit cell) had higher variability in mineral treatments than organic ones. All modeled samples showed a bimodal throat size distribution (throat spread greater than 0.55), with higher values in mineral treatments (0.83) than in organic ones (e.g. 0.60 in farmyard manure). Even if the differences were not significant, the trend distinctly underlined a smaller throat spread at increasing levels of organic input. According to Lugato *et al.* (2009), organic carbon positively affects soil microporosity, reducing the widening effect towards small pores. This is also confirmed by the positive relationship ($p<0.05$) between SOC and ultramicropores (5-0.1μm). The effect of the different pore sizes on fast wetting is shown in Figure 1.

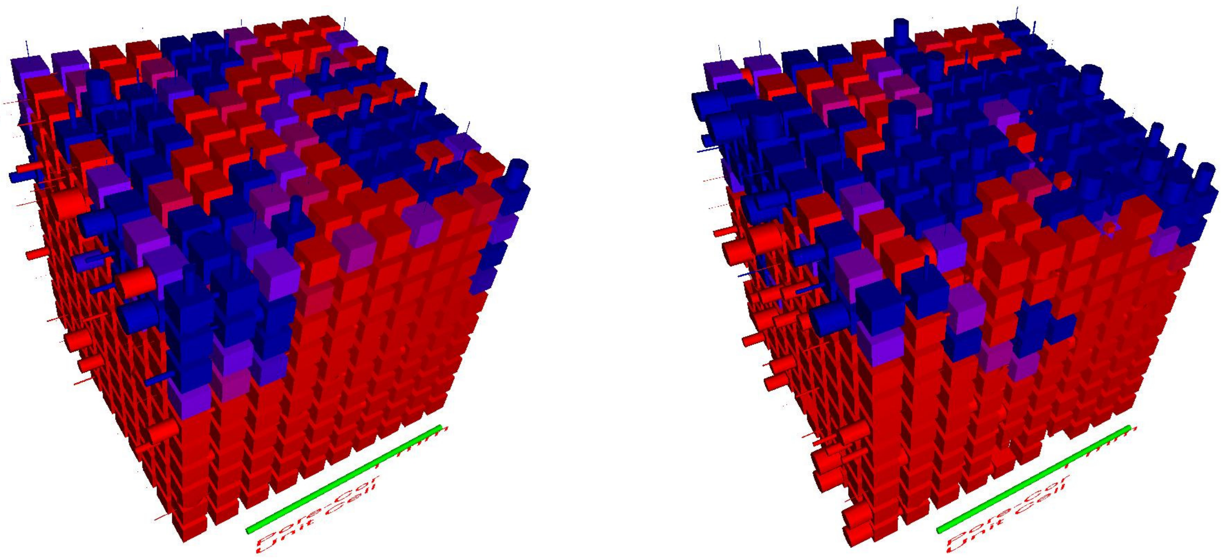

Figure 1. 3D modeled structures (unit cell) after 10 minutes of simulated fast wetting at unit pressure. Wetting rate is visibly lower with farmyard manure which has high microporosity (left) than in mineral fertilization + residues, with low microporosity (right). Colors of throats and pores vary from blue (completely full, 100%), to purple, to red (completely empty, 0%).

Principal Component Analysis (PCA) performed on 18 variables (aggregate stability indexes, SOC and humic fractions, porosity classes, Pore-Cor parameters) emphasized the essential role of water repellency on aggregate stabilization, clustering organic carbon content (OC), contact angle (WET) and high weight humic fraction with wet sieve analysis pre-treated with benzene (Figure 2). PCA also highlighted the positive effect of intrinsic permeability on breakdown mechanisms (higher slaking) due to the faster water infiltration in the aggregates (Figure 2). Correlation level seems to be the only Pore-Cor parameter affecting permeability (see cluster in Figure 2), most likely because it reduces the shielding effect of small throats around large pores.

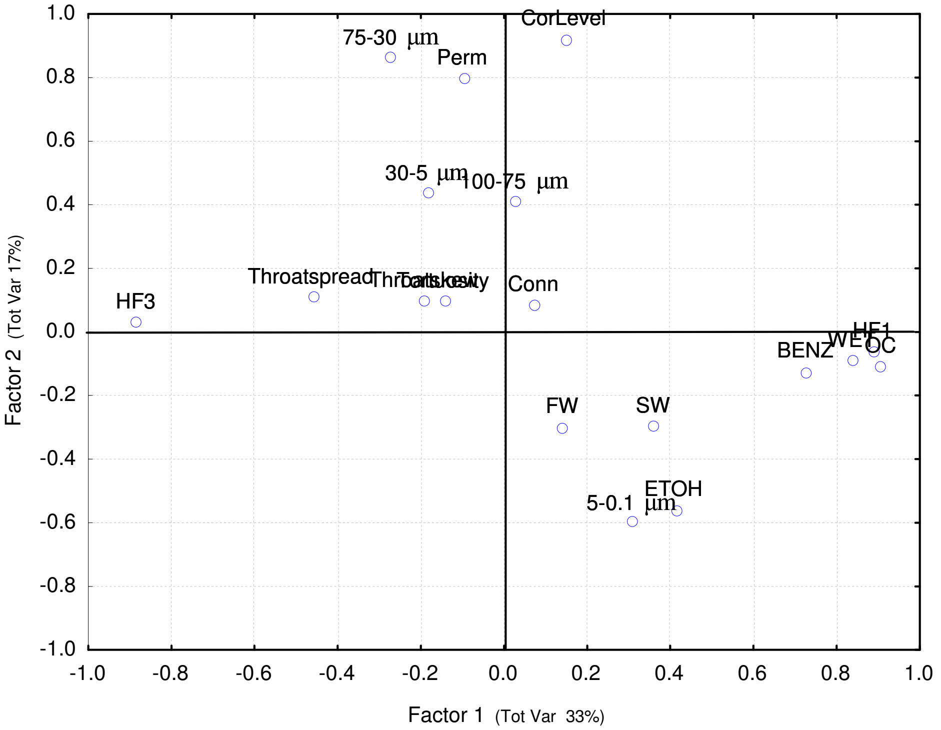

Figure 2. Factor loadings for 18 parameters selected for principal component analysis.

Conclusion

Physico-chemical and physical mechanisms affected aggregated stability in the experiments. The former were mainly due to the influence of organic carbon on soil wettability. Organic carbon also had a partial effect on the physical protection mechanisms influencing void size distribution. In this case ultramicropores were decisive in reducing fast wetting and therefore aggregate stability.

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