Eurasian Journal of Soil Science

Relationship between soil water retention model parameters and structure stability

Amrakh I. Mamedov [a], Imanverdi Ekberli [b,*], Coşkun Gülser [b], Ilknur Gümüş [c], Ummuhan Çetin[c], Guy J. Levy [d]

[a] Institute of Soil Science and Agrochemistry and Institute of Botany, ANAS, Baku, Azerbaijan
[b] Ondokuz Mayis University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Turkey
[c] Selcuk University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Konya, Turkey
[d] Institute of Soil, Water and Environmental Sciences, ARO, The Volcani center, Bet Dagan, Israel

Abstract

Studying and modeling the effects of soil properties and management on soil structure and near saturation water retention is vital for the development of effective soil and water conservation practices. The contribution of soil intrinsic properties and extrinsic conditions to structure stability was inferred, in quantitative terms, from changes in water retention curves near saturation (low matric potential, 0-50 cm, macropores > 60 μm) that were obtained by the high energy moisture characteristic (HEMC) method. The S-shaped water retention curves were characterized by the modified van Genuchten model that provided: (i) the model parameters α and n, which represent the location of the inflection point and the steepness of the water retention curve, respectively; and (ii) the soil structure index, SI=VDP/MS, where VDP is the volume of drainable pores, and MS is the modal suction. Model parameters, claculated by the soil-HEMC model, were related to soil properties and hence soil water retention properties were linked to measured characteristics in several field and laboratory experiments. Soil SI increased exponentially with the increase in α and the decrease in n, while the relationship between SI and α/n was linear. An improved description of the water retention and its link to pore and apparent aggregate size distribution, by using the model parameters α and $n,$ could potentially assist in the selection of management practices for obtaining the most suitable type of soil structure depending on the desired soil function.

Keywords: Structure stability, water retention, pore size, stability index, model.

Article Info

Introduction

Soil structural stability is a basic property of soil health, affecting many soil properties including soil hydraulic properties, surface runoff generation and soil erosion. The formation of soil aggregates and structure is the result of biotic and abiotic factors and their interaction. The ability of aggregates to resist the dispersive and slaking processes of water is a vital property in relation to the preservation of a porous soil structure (Haynes, 2000; Levy and Mamedov, 2002; Rillig and Mummey, 2006). Incorporating organic matter (biosolids, crop residues and plants) and soil amendments in the soil favors the increase of substances (aggregation agents) involved in aggregate stability and decreases slaking and mechanical breakdown. Therefore, studying the effects of soil properties and management practices on soil structure is

important for the development of effective soil and water conservation, and predictive soil-crop modeling tools in order to avoid risks of soil deterioration (Roger-Estrade et al., 2009).

Tillage, soil compaction, crop rotation, irrigation and amendment application can alter pore size distribution (PSD), and subsequently affect physical and chemical properties of soils, and nutrients availability. Furthermore, plant growth associated with activities of soil biota interacts with environmental variables such as dry-wet and freeze-thaw cycles to modify soil structure (Haynes 2000; Lipiec et al., 2007; Mamedov and Levy, 2013). The ability to study soil structure dynamics and affecting mechanisms are complicated by the (i) magnitude of temporal variability which in itself is affected considerably by the spatial location and growing season, (ii) effects of management practices, and (iii) difficulties involved in relating results from laboratory measurements to real field behavior (Strudley et al., 2008; Mamedov and Levy, 2013).

Structure and aggregate stability can be inferred from changes in the soil water retention curve even at the low end of the matric potential. The PSD can be derived from the water retention characteristics and is considered as a basic index for soil physical quality (Dexter and Czyz, 2007; Mamedov et al., 2010). The contribution of agricultural management to soil water retention could also be quantitatively characterized by the parameters derived from the modified van Genuchten (1980) model (e.g., α and n, the location of the inflection point and the steepness of its slope), because changes in α and n are considered to be closely related to PSD and therefore to aggregate and particle size distribution (Lipiec et al., 2006; Porebska et al., 2006). In the case of smectitic soils the α and n parameters were found useful in characterizing the contribution of both large aggregate size (> 0.25-0.5 mm, $\psi \sim 0$ to 12 cm) and small (< 0.25-0.5 mm, $\psi \sim 12$ to 50 cm) aggregates/particles, respectively, to soil structure condition (Mamedov and Levy, 2013).

The near saturation PSD and fractionation of water stable aggregates could be helpful for the better understanding of soil quality/health dynamics affected by soil management, since aggregate size distribution is more sensitive to changes in soil management than for instance organic C (Pikul et al., 2007). Soil pores affected by the suction at the range of 0–50 cm are associated with soil structural porosity (i.e. inter-particle pores, > 60 μm). These pores can be divided broadly into three subclasses (Mamedov et al., 2010) within the very fine macro-pore equivalent diameter class (75–1000 μm) with matric potential range of: (i) 0-12 cm (corresponding to pores >250 μm, herein referred to as macropores); (ii) 12–24 cm (125–250 μm, mesopores); and (iii) 24–50 cm (60-125 μm, micropores). These size-ranges of the drainable pores are accompanied by soil aggregates of comporable sizes. Hence, three apparent size classes of aggregates (e.g. apparent macro-, meso- and micro-aggregates), which correspond to the aforementioned macro-, meso- and micro-pores, respectively are defined (Mamedov and Levy, 2013).

Characterization of soil aggregate stability has commonly been used to portray structure stability, although aggregates are not necessarily a suitable proxy of soil structure. Several aggregate stability methods, utilizing diverse primary breakdown mechanisms (e.g. wet sieving, drop test, application of ultrasonic energy, etc.), are used for establishing an index of soil structure, which makes comparison between treatments difficult (Pulido Moncada et al., 2015). The recently modified high energy moisture characteristic (HEMC) method (Pierson and Mulla, 1989; Levy and Mamedov, 2002) having high reproducibility was found to be sensitive and capable of detecting even small changes in aggregate and structure stability of a range of soils from arid and humid zones (Mamedov and Levy, 2013).

The objective of this study was to examine the relationship between the soil structure stability indices and the van Genuchten model parameters (α and n) for the studied water retention curves based on already published and unpublished data of water retention curves obtained by the HEMC method.

Material and Methods

Soils

An array of samples from semi-arid cultivated soils varying in intristic soil properties and studied under differing extrinsic conditions were examined in our study: (i) effects of wetting rates (2, 8, 32, 100 and 200 mm h^{-1}) using six soils (from loamy sand to clay) (Mamedov and Levy, 2013); (ii) three soils varying in texture (loamy sand, loam and clay) treated with two biosolid amanedments (composted manure and sweage sludge, at a rate of 50 t ha^{-1} and thier components [orthophosphate, phytic acid and humic acid]) and exposed to six consequative rainfall (Mamedov et al., 2014); (iii) clay loam soil (control, rhizosphere and bulk) used under 10 various wheat types (Uyanoz et al., 2012); (iv) clay soil treated with fresh or composted poultry litter (10 t ha^{-1}), and zeolite (1.5 t ha^{-1}) under corn and wheat production (Gumus and Seker 2014). In all cases the soil samples studied were taken from the cultivated soil layer.

Water retention

We used soil samples (from various studies) water retention curves that were obtained at high energies of matric potential (HEMC, 0 to 50 cm H_2O), corresponding to drainable pores (> 60 μm). In these studies, the Soil-HEMC model (e.g., Mamedov and Levy, 2013), which enables an accurate fit of the measured water retention curves (ψ, 0 to 50 cm) was used to calculate model parameters (α and *n*) and structural index (SI=VDP/MS; VDP-volume of drainable pores, MS-modal suction) by the following equations (Pierson and Mulla, 1989; Mamedov and Levy, 2013):

$$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha\,\psi)^n\right]^{(1/n-1)} + A\psi^2 + B\psi + C \qquad [1]$$

$$d\theta/d\psi = (\theta_s - \theta_r)\left[1 + (\alpha\,\psi)^n\right]^{(1/n-1)}(1/n-1)(\alpha\,\psi)^n\,n/\left[\psi(1+(\alpha\,\psi)^n)\right] + 2A\psi + B \qquad [2]$$

where, θ_r and θ_s are the residual and saturated water content, respectively; α (cm^{-1}) and *n* represent the location of the inflection point and the steepness of the S-shaped water retention curve; A, B and C are coefficients.

Results and Discussion

Water retentions

The various attributes that were examined (contribution of soil texture, wetting rate, biosolid and its components, zeolit and poultry litter application and rhizosphere zone processes under the crops) all had considerable effects on the shape of the HEMC water retentions curves (Figures. 1-4). Increasing the wetting rate shifted the location of water retention curve (Figure 1) up-right (Mamedov and Levy, 2013). Most of the changes in pore size distribution occurred in a wide range of matric potential 0-50 cm (pore size > 60 μm). The water-retention curves of manure (and orthophosphate and phytic acid) and sludge (and humic acid) amended soil aggregates differed from the control generally in the matric potential range of 0-12 cm and 0–24 cm, corresponding to changes in macro- and mesopores (>125-250 μm) respectively (Mamedov et al., 2014). The impact of cropping of 10 wheat variety with a different root characteristics, was considerable on soil biological and chemical properties in the rhizosphere zone and around (rhizosphere and bulk) (Uyanoz et al., 2012), and also notable modified soil water retention capability. The difference between control and bulk or rhizosphere soil samples were related to the meso-and micropores (<125-250 μm) or all studied pores (> 60 μm) accordingly (Figure 3). In the field condition application of poultry litter, zeolite and their combination boosted clay soil properties, and corn and wheat production (Gumus and Seker, 2014), and sizeable enhanced soil water retention at the range of 0-24 cm (> 125 μm) (Figure 4).
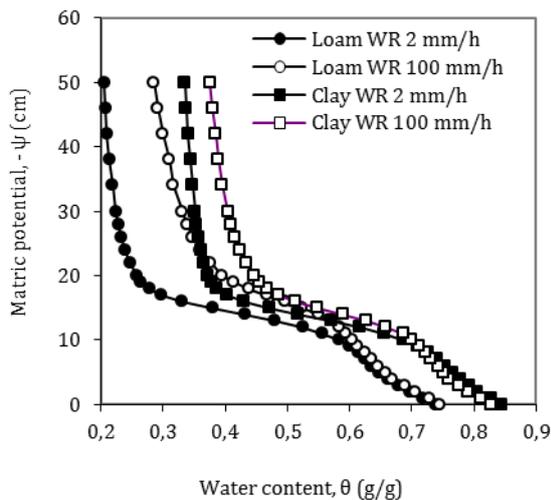

Figure 1. Soil water retention as affected by wetting rate (WR)
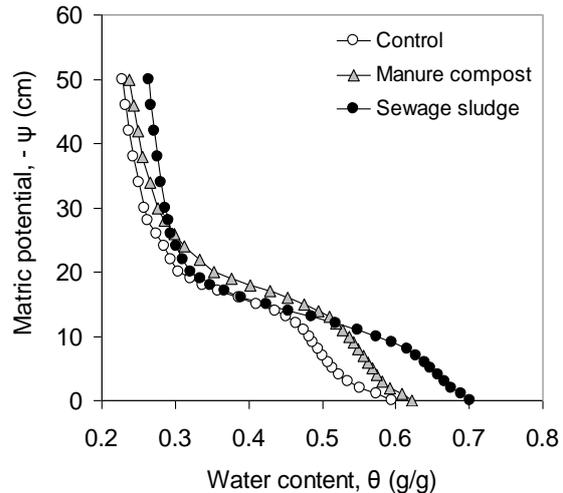

Figure 2. Loam soil water retention as affected by composted manure and sewage sludge application
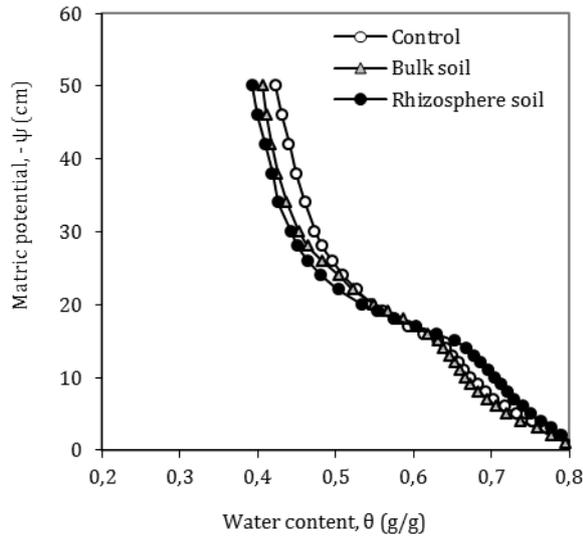
Figure 3. Clay loam soil water retention (control, bulk and rhizosphere) as affected by cropping under wheat
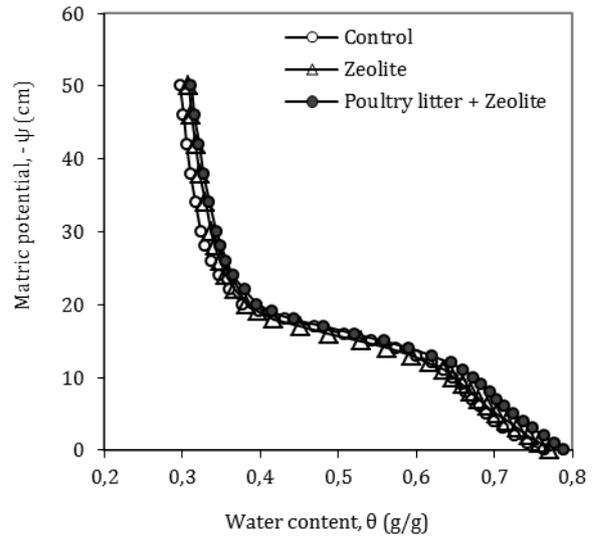

Figure 4. Clay soil water retention as affected by poultry litter and zeolite application under wheat

Wetting rate

Changes in soil structure following aggregate breakdown by fast wetting, generally resulting from formation of a larger number of aggregates or particles of smaller sizes than the original ones (leading to smaller inter-aggregate pores), affects the shape of water retentions, and hence model parameters (Mamedov and Levy, 2013). Used semi-arid soils, with low organic matter and plant residue material on soil surface, and long term cultivation history were found to be sensitive to various degree of aggregate breakdown by wetting with the effect being more pronounced in the soil with low clay content (Figure 1). Increasing the wetting rate from 2 to 200 mm h^{-1} for six soils varying in texture, increased n, and decreased α and hence led to wide variation in the SI (0.003-0.023). Generally the SI of soils were in the following order: loam < silty clay loam < clay. The relationship between SI and α or n is characterized by a strong (R^2>0.9) exponential type of relationship (Figure 5 and 6). Comparable examining the contribution of wetting rate and soil management (e.g. aggregate size distribution by tillage, irrigation, raindrop impact, crop residues) on soil PSD and structure stability could assist in simulation on surface deterioration, gas emission and N mineralization rate of semi-arid soils affected by agricultural practices (Shainberg et al., 2003; van Donk et al., 2010; Mamedov and Levy, 2013).
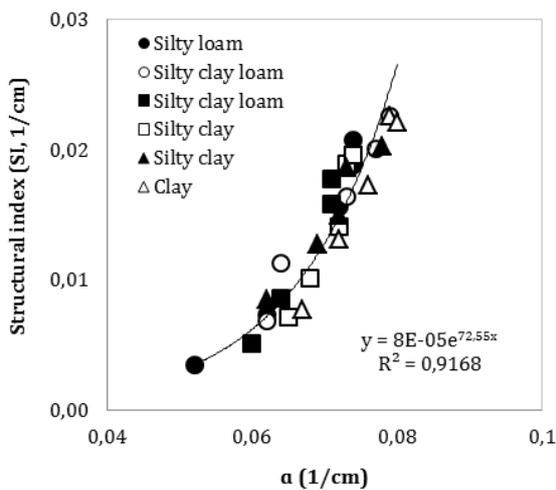

Figure 5. Soil structural index (SI) as a function of α for six soils (ranging from loamy sand to clay) saturated with five wetting rate (2, 8, 32, 100 and 200 mm h^{-1})
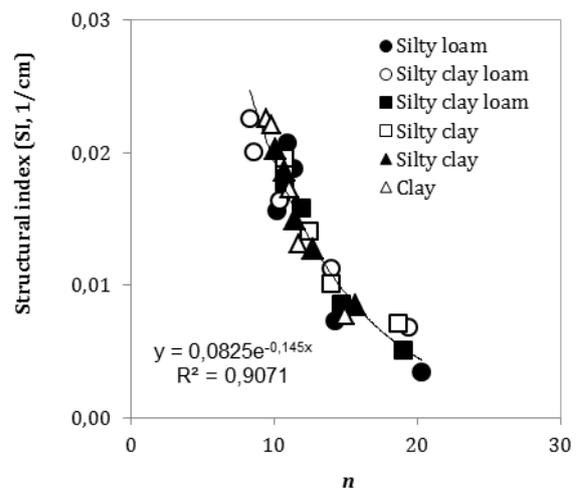

Figure 6. Soil structural index (SI) as a function of n for six soils (ranging from loamy sand to clay) saturated with five wetting rate (2, 8, 32, 100 and 200 mm h^{-1})

Amending with biosolids

The use of biosolids and organic wastes in agricultural soils as a nutrient resource and as a soil amendment is a common practice. The effects of the biosolid treatments on soil water retentions were soil-dependent (Figure 2) beeing in agreement with the results of previous studies that reported the effects of biosolids application on aggregate stability to be at times vague (Haynes, 2000; Mamedov et al., 2014). Amending soils with biosolids and exposing to six consecutive rainfall rates resulted in a wide range of values for the SI (0.0017-0.035), α (0.032-0.093) and *n* (6.48-21.32). The sludge and humic acid treatments contributed to an increase in macro and lesser degree on meso-pores, whereas other amendments contributed only to macro-pores, and hence the stability of apparent aggregate sizes. Amendments role was generally related to formation of adhesive films that form a bridge between soil clay platelets, and induced hydrophobic conditions, and thus increasing aggregate resistance to slaking (Haynes, 2000; Mamedov et al., 2014).

Treating soils with composted manure and sewage sludge, and their component were more notable in the coarse-textured loam and loamy sand soils than the clay soil (Mamedov et al., 2014), however the averaged SI (and α) of soils (slow and fast wetted) were in the following order: loamy sand < loam < clay (Figure 7 and 8). The exponential relationship between SI and α was much greater (R^2=0.8) than the relationship between SI and *n* (R^2=0.42), showing importance of treatments on enhancing macroaggregates. Separation of aggregates (pores), into macro- and micro-aggregates (pores), and relevant relationship between SI and model parameters, will be important for more precise evaluation and understanding of the effects organic amendments might have on aggregate stability and soil conservation planning.
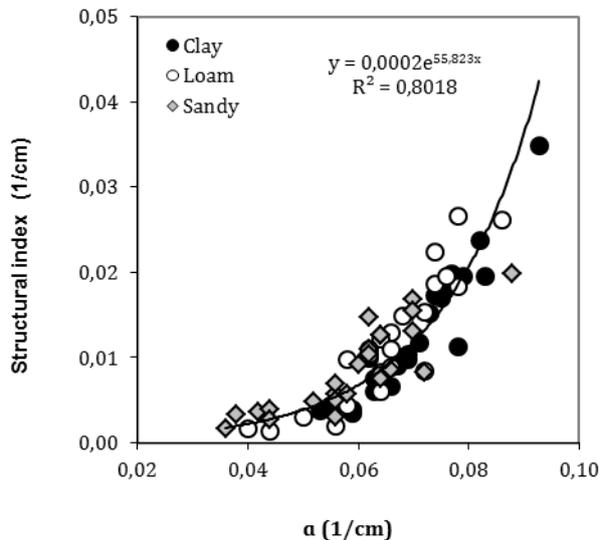

Figure 7. Soil structural index (SI) as a function of α for soils (clay, loam and loamy sand) treated with composted manure and sewage sludge and thier components (orthophosphate, phytic acid and humic acid)

Figure 8. Soil structural index (SI) as a function of *n* for soils (clay, loam and loamy sand) treated with composted manure and sewage sludge and thier components (orthophosphate, phytic acid and humic acid)
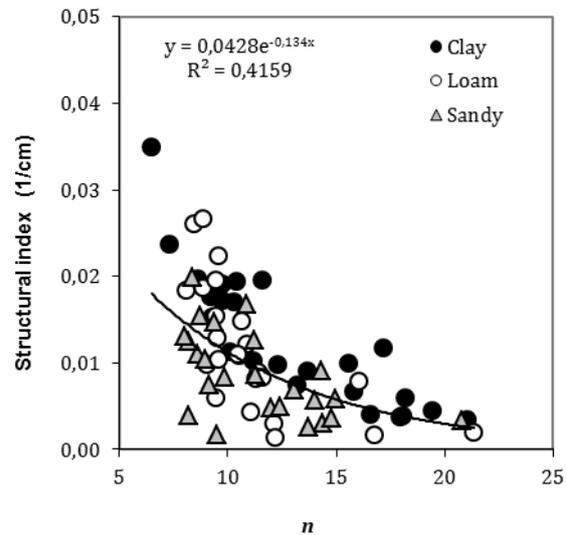
Rhizosphere and bulk soils

The rhizosphere soil is directly influenced by the root, plant residues, root secretions and symbiotic associated microorganisms (e.g. mycorrhizal fungi). Relative to control under cropping condition the high C content, enzyme or microbial activity in the rhizosphere and bulk soil significantly increased soil SI (0.041-0.052) and α and decreased *n* (Figure 9 and 10). The SI and α of soils were in the following well defined order: rhizosphere > bulk > control. The relationship between SI and α or *n* is characterized by a strong (R^2>0. 9) exponential type relationship. Since cropping was made in same clay loam soil with a weak structure and low organic matter, the variation in SI, α and *n* in rhizosphere and bulk soil were related to wheat varieties. Soil C accounted for up to 50 % of the change of biophysical soil properties (data are not shown).

Results show that crop variety may contribute to the short-term sustainability of the agroecosystem by improving physical soil characteristics under semi-arid conditions. Main effects of rhizosphere processes on

soil structure in moist conditions were orientation of clay particles around the cells, excretion of extracellular polysaccharides that induced local binding of clay particles, and a general packing effect by hyphae (Hinsinger et al, 2005). A major challenge for the future ecosystem will be to transfer new knowledge into actions that result in the beneficial management of the rhizosphere (Hinsinger et al, 2005 Rillig and Mummey, 2006). Therefore HEMC approach could be useful tool to introduce the effects of soil macroporosity on biological processes in agroecosystems models.
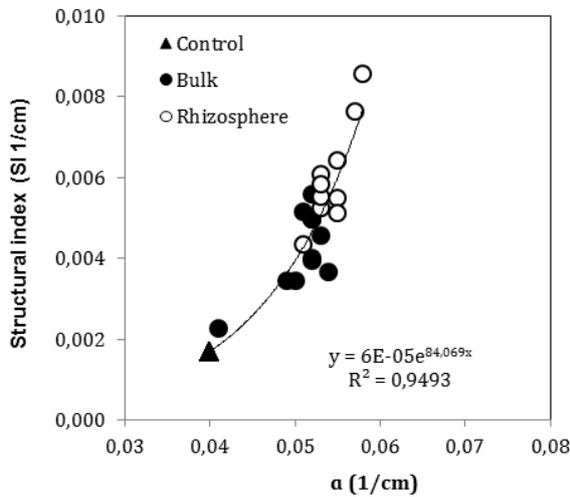

Figure 9. SI as a function of α for loam soil (control, bulk and rhizosphere soil) used under 10 varieties of wheat
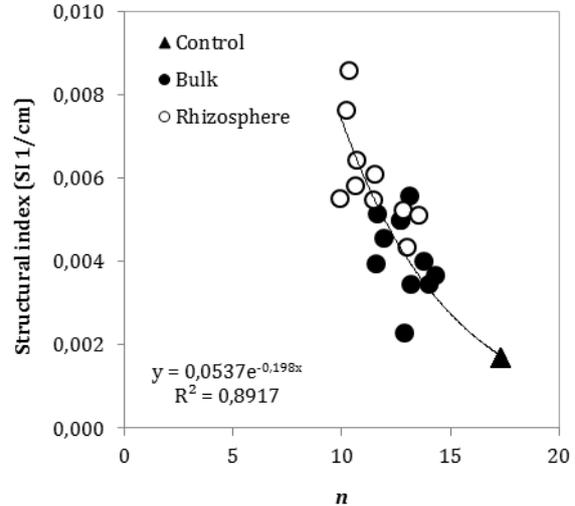

Figure 10. Soil SI as a function of *n* for loam soil (control, bulk and rhizosphere soil) used under 10 varieties of wheat

Poultry litter and zeolite application

The litter produced by the poultry industry is currently applied to agricultural land as a source of nutrients and soil amendment. However, following its application environmental pollution, resulting from nutrient and contaminant leaching may occur under certain condition (Bolan et al., 2010). Application of zeolite in combination with poultry litter may significantly improve soil physical and chemical environment, plant nutrition and yield (Gumus and Seker, 2014), and mitigate pollution issues. Contribution of poultry litter and zeolite and their combination on soil structural indices in clay soil under the wheat is characterised by a relative narrow range of SI (0.010-0.025), α (0.058-0.074) and *n* (7.6-12.2) compared with all above mentioned experiments. Yet a moderate exponential type relationships between SI and α and *n* were noted (Figure 11 and 12).
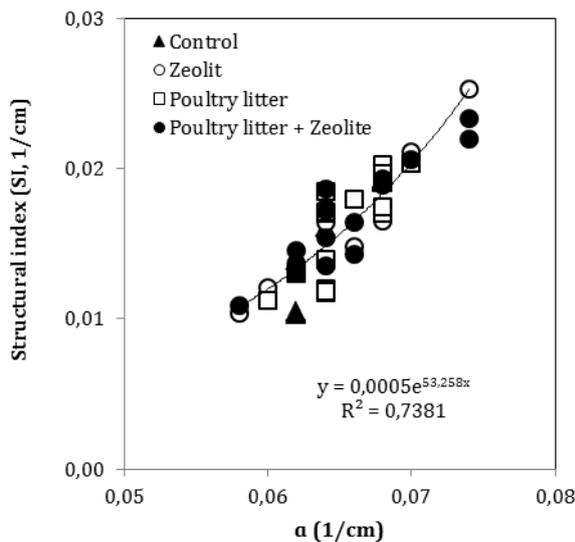

Figure 11. Soil SI as a function of α for clay soil treated with poultry litter and zeolite, and their combintion.
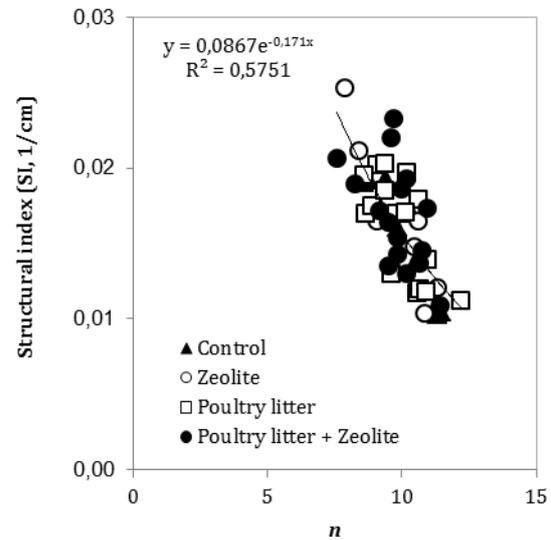

Figure 12. Soil SI as a function of *n* for clay soil treated with poultry litter and zeolite, and their combintion

In general the averaged SI and α of treatments were in the following order: Control < Poultry litter < Zeolite < Zeolite + Poultry litter; but for *n* the picture was not clear, since the value of *n* for treatments had a similar range. The results was in agreement with the results of previous studies showing that in the cultivated soil the addition of poultry manure may decrease the bulk density, and increase the organic matter content, water holding capacity, and the aggregate stability of the soils (Bolan et al., 2010).

The relationship between soil SI and model parameters (α and *n*) had, in general, a similar shape for the examined attributes. Soil SI increased exponentially with increase in α and decrease in *n*, while the parameters of the exponential equations were different (Figure 5-10). In all the above examined attributes the relationship between SI and a/n was linear (Table 1). Similar results was received by Mamedov and Levy (2013) where about 50 cultivated and irrigated semi-arid Israeli soil widely varying in texture were used (Table 1). It is suggested the exponential relationship, exponents and coefficient of the equations are related to soil texture and treatments contribution on PSD and aggregate size distribution that should be investigated in details in future studies (Mamedov and Levy, 2013).

Table 1. Relationship between soil structural index (SI) and the ratio of the water retention model parameters (α/n)

Treatments	Saoil texture	Equation SI = f (α/n)
Wetting rate	Six soil ranging from loam to clay	$y = 3.1677x - 0.0044$, $R^2 = 0.91$
Biosolid application	Loamy sand, loam, clay	$y = 2.6447x - 0.0049$, $R^2 = 0.80$
Rhizosphere and bulk soil	Clay loam	$y = 1.6022x - 0.002$, $R^2 = 0.87$
Poultry litter and zeolite	Clay	$y = 2.9267x - 0.0033$, $R^2 = 0.73$
Semi-arid soils-irrigated	50 soils ranging from loamy sand to clay	$y = 3.5325x - 0.0076$, $R^2 = 0.92$

Conclusion

Research data reporting a wide range of changes in pore size ditribution, and structure stability indices of semiarid soils widely varying in intrinsic properties and management histories were used to explore the relationships between SI and the water retention model parameters α and *n*. In all cases SI increased exponentially with an increase in α and a decrease in *n*, while the relationship between SI and α/n was linear. It is postulated that description of the water retention by soil-HEMC model and linking model parameters to soil structural index and thus pore- and aggregate size distribution, may help to select proper management practices for obtaining the most suitable type of aggregation depending on the desired soil function or soil type.

References

Bolan, N.S., Szogi, A.A., Chuasavathi, T., Seshadri, B., Rothrock M.J., Panneerselvam, P., 2010. Uses and management of poultry litter. *World's Poultry Science Journal* 66(4): 673-698.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. *Geoderma* 124(1-2): 3-22.

Gumus, I., Seker, C., 2014. Residual effect of different organic manure application on wheat yield in corn-wheat rotation. *Soil-Water Journal* 3(1): 1-5.

Haynes, R.J., 2000. Interactions between soil organic matter status, cropping history, method of quantification and sample pretreatment and their effects on measured aggregate stability. *Biology and Fertility of Soils* 30(4): 270–275.

Hinsinger, P., Gobran, G.R., Gregory, P.J., Wenzel, W.W., 2005. Rhizosphere geometry and heterogeneity arising from root-mediated physical and chemical processes (Review). *New Phytologist* 168, 293-303.

Levy, G.J., Mamedov, A.I. 2002. High-energy-moisture-characteristic aggregate stability as a predictor for seal. *Soil Science Society of America Journal* 66(5): 1603-1609.

Lipiec J., Walczak, R., Witkowska-Walczak, B., Nosalewicz, A., Słowinska-Jurkiewicz, A., Sławinski, C. 2007. The effect of aggregate size on water retention and pore structure of two silt loam soils of different genesis. *Soil and Tillage Research* 97(2): 239–246.

Mamedov A.I., Levy, G.J. 2013. High energy moisture characteristics: linking between some soil processes and structure stability. In: S. Logsdon, M. Berli, and R. Horn, (eds). *Quantifying and Modeling Soil Structure Dynamics: Advances in Agricultural Systems Modeling. Trans-disciplinary Research, Synthesis, Modeling and Applications,* vol. 3, SSSA, Inc. Madison, WI USA, pp.41-74.

Mamedov, A.I., Wagner, L.E., Huang, C., Norton, L.D., Levy, G.J., 2010. Polyacrylamide effects on aggregate and structure stability of soils with different cay mineralogy. *Soil Science Society of America Journal* 74(5): 1720-1732.

Mamedov, A.I., Bar-Yosef, B., Levkovich, I., Rosenberg, R., Silber, A., Fine, P., Levy, G.J., 2014. Amending soil with sludge, manure, humic acid, orthophosphate and phytic acid: Effects on aggregates stability. *Soil Research* 52(4): 317-326.

Pierson, F.B., Mulla, D.J., 1989. An improved method for measuring aggregate stability of a weakly aggregated loessial soil. *Soil Science Society of America Journal* 53(6): 1825-1831.

Pikul, J.J.L., Osborne, S., Ellsbury, M., Riedell, W., 2007. Particulate organic matter and water-stable aggregation of soil under contrasting management. *Soil Science Society of America Journal* 71(3): 766–776.

Porebska, D., Slawinski, C., Lamorski, K., Walczak, R.T., 2006. Relationship between van Genuchten's parameters of the retention curve equation and physical properties of soil solid phase. *International Agrophysics* 20(2): 153–159.

Pulido Moncada, M., Gabriels, D., Cornelis, W., Lobo, D., 2015. Comparing aggregate stability tests for soil physical quality indicators. *Land Degradation and Development* 26(8): 843–852.

Rillig, M.C., Mummey, D.L., 2006. Mycorrhizas and soil structure: *New Phytologist* 171(1): 41-53.

Roger-Estrade, J., Richard, G., Dexter, A.R., Boizard, H., de Tourdonnet, S., Bertrand, M., Caneill, J., 2009. Integration of soil structure variations with time and space into models for crop management. A review. *Agronomy for Sustainable Development* 29(1): 135–142.

Shainberg, I., Mamedov, A.I., Levy, G.J., 2003. The role of wetting rate and rain energy in seal formation and interrill erosion. *Soil Science* 168(1): 54-62.

Strudley, M.W., Green, T.R., Ascough, J.C., 2008. Tillage effects on soil hydraulic properties in space and time: state of the science. *Soil and Tillage Research* 99(1): 4-48.

Uyanoz, R., Karaca, U., Karaarslan, E. 2012. Effects of wheat (Triticum Aestivum L.) variaties on soil properties in the rizosphere. Selcuk University Project Report. Konya, Turkey.

van Donk, S. J., Martin, D. L., Irmak, S., Melvin, S. R., Petersen, J. L., Davison, D. R. 2010. Crop residue cover effects on evaporation, soil water content, and yield of deficit-irrigated corn in west-central Nebraska. *Transactions of the ASABE* 53 (6): 1787-1797.

van Genuchten, M.Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44(5): 892–898.