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Identifying Contrasting Pore Size Distributions within the Concentric Layers of Soil Aggregates Subjected to Different Management Practices

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Abstract

Soil water retention is an extremely relevant topic in today's society, in which only a minute amount, 1%, of total surface water on Earth is fresh. Sixty percent of this small quantity is expended for agricultural purposes i.e. supplemental irrigation. To reduce the necessary amount of water needed, the soil's water retention properties require further investigation. One investigation is at the micro-level. Soil aggregates, which are made up of physically and chemically bonded minerals, must be shaved to various sizes and exposed to different management practices in order to test for differing levels of water retention. Tillage modification of soil aggregate size indirectly affects water retention due to deterioration of pore geometries. Aggregates, in this study were collected from Wooster, Ohio, from both tilled and non-tilled research treatments. Soil aggregate surfaces were removed by abrasion, using Soil Aggregate Erosion (SAE) chambers, until three different sizes: exterior (original), transitional (33% removed) and interior (66% removed). Various characteristics of these aggregates were compared including bulk density, porosity, and water seepage under various matric potentials. It was found that non-tilled (forest) interior aggregates had the greatest bulk density, smallest porosity, and least water seepage when compared with their counterparts. This led to inferences among pore connectivities within aggregate interiors resulting in superior water retention and that tillage decreases these levels of retention. If these aggregates are implicated in newer land plots for agriculture, there will be lesser groundwater seepage, requiring much less supplemental irrigation water, allowing this precious resource to be utilized for other purposes including improving the lives of developing-nations' residents.

Keywords: Water-retention, Soil, Porosity

1. Introduction

The qualities of various soil types are directly impacted by its aggregates, conglomerates of soil held together by soil organic matter (SOM) and calcium bonding to the cationic charges among clay mineral surfaces. There are numerous characteristics of these aggregates that are yet to be discovered to further understand the composition of the entire earth's crust. One such topic investigates the effect of drying-rewetting cycles on the bacterial community in soil. It was found that the "drying-wetting regimes can influence bacterial community composition in oak but not in grass soils" (Fierer et al., 2002). Furthermore, other investigations involve such topics as the distribution of organic carbon, $C_{org},$which is "rather randomly distributed within the aggregates" and has no specific "enhancement in any of the aggregate regions"(Urbanek et al., 2011).

This research explores the mean pore size distributions within individual concentric layers of surface-eroded soil aggregates, which is responsible for different water retention capacities. Water retention is an extremely relevant topic in today's society. Usable fresh water is less than 1% of total water on the Earth's surface and this water is distributed for many uses, with more than 60% used by irrigation of agricultural crops (How Much). If the amount of water needed to keep these plants healthy can be significantly retained in the root zones and not drained deeply into the groundwater, then irrigation cycles could be reduced and large amounts of water needed for supplemental irrigation would be greatly conserved. This can effectively reduce the amount and frequency of irrigation cycles, allowing water consumption for humans to increase in underdeveloped areas of the world.

Soil pores are the predominant reservoirs of water in the root zones of soils. Information about the geometries and connectivities of these pores, responsible for soil water retention, can be investigated by removing concentric layers from surfaces of individual soil aggregates (Park and Smucker,2005). This can be done by exposing individual soil aggregates to the soil aggregate erosion (SAE) method of shaving surface layers from different aggregates. The shaved aggregates include exterior aggregates (original size), transitional aggregates (33% shaved), and interior aggregates (66% removed). By comparing water retention based on percent shaved and place of origination, the ability of specific soil as a whole to retain water can be predicted from a single aggregate and the larger pores located among communities of these soil aggregates.

2. Hypothesis

If the aggregates are shaved to a smaller layer (from exterior, to transitional then interior) their total volumetric water capacity will decrease because the total porosity declines and most probably their pore size distribution decreases.

3. Methodology

This project focuses on aggregate regions, which retain more water with fewer and smaller pores. These experiments use180 samples of aggregates collected from both conventionally tilled and natural ecosystems (without tillage) of a silt loam soil from Wooster, Ohio**.** Close evaluations of these aggregates will be made in a manner that compares the effects of these two types of tillage on the pore size and distribution in aggregates. These seemingly small portions of soil function as building blocks for the entire soil system, including the plethora of organisms that inhabit this soil domain (Smucker & Park, 2005).

These organisms depend on the water distribution provided by soil aggregates. In order to study optimal aggregates layer for best water distribution, we can compare pore distributions among soil aggregates of different layers using the SAE approach (Santos, 1997).

The Soil Aggregate Erosion process was made much simpler by the Soil Aggregate Erosion Chamber, patented by Dr. Alvin Smucker. This instrument contains a knurling in the inside wall of the top chamber which creates abrasive effective frictional causing the aggregate to be shaved uniformly into desired sizes of global spheres. The resulting debris is filtered through the 350 µm sieve and collected in the secondary retainer base chamber.

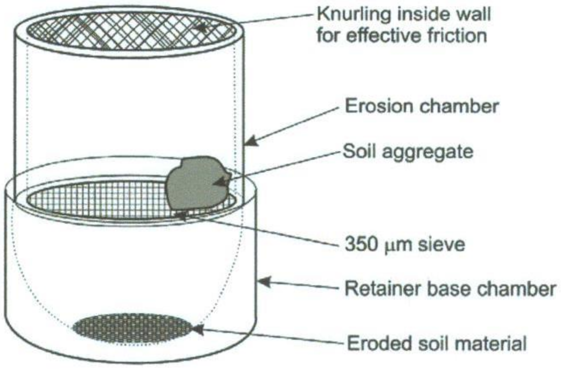

Figure 1: Soil Aggregate Erosion Chamber (SAE) Assembled and Detailed (Urbanek et. al., 2011)

The erosion process is catalyzed by placing the assembled erosion chamber on a platform shaker at 235 RPM. To prevent glass breakage, the instrument is placed in a 350 mL beaker within a protective shield, in the form of a sponge. It is also covered with a small sheet of aluminum foil to prevent spillage of the eroded aggregate dust and coarser materials during the rotational abrasive forces. In order to shave aggregates to specific sizes, they are weighed and placed onto the platform shaker for a specific time, in this case 0.25 hours or 2.2 hours to make the aggregate 2/3rd or 1/3rd of original size respectively (Smucker et al., 1998).

Once the aggregates are shaved to three layers: original size minus exterior layer, two-thirds size of original size (transitional aggregates) and one-thirds of original size (interior aggregates) we can study the average pore size differences and gradients across the interior of each aggregate. This knowledge will provide additional information that leads to better modeling of water passage and retention by different layers within individual aggregates. In order to determine pore diameter control of water absorption and retention, the mean pore size radius will be identified by employing the capillary rise equation (Smucker, 2011):

$$h_c = (2\gamma cos\alpha)/g(p_1 - p_g)r \qquad (1)$$

in which: hc= height of capillary column; γ = surface tension of water; α =contact angle of water; g=acceleration due to granity; p_1= density of liquid; p_g= density of gas; r=radius of capillary column.

Using equation 1, we can identify height of the capillary column, based upon the specific negative or vacuum energy required to extract specific soil water volumes from each layer within the aggregate. It will be assumed the contact angle, density, and radius of capillary column will be the same with only the pore size diameters changing. Once the radius of each pore is calculated, it will be compared among exterior, transitional, and interior aggregates. This will indicate specific water passageways through aggregates. Our premise for this conclusion is that water drained during lower negative vacuum pressures will decrease when smaller pore sizes are present and increase when larger pores are present. This will show that larger aggregates (exterior) are more favorable for the most rapid water distribution throughout the soil. Also, by difference, the gradients of pores among the three different layers of each soil aggregate can be identified.

The Water Retention Capacitor (WRC) was designed for the sole purpose of holding aggregates of different layers in a vacuum for a future experiment. This was specifically designed for this research experiment and was assembled by effectively gluing a pipette tip to the inside of a glass tube. In order to hold aggregates of desired sizes, each aggregate's diameter was accounted for. The length, width, and height were measured to the nearest tenth of a millimeter and averaged to determine this value. This gave insight to the specific interior diameters (I.D.) of tubing that were needed to conduct the experiment. It was determined that an 8 millimeter I.D. was necessary to hold transitional and exterior aggregates. To finish creation of the WRC, a pipette tip was cut right below the filter to allow water to flow through but no soil. This part of the pipette tip was then glued, using silicon adhesive, 3 millimeters into the tubes. The glue was then allowed to set for a period of 24 hours before it could be utilized.

Figure 2: Assembled Water Retention Capacitor (WRC)

After the 24 hours has passed, the WRC in Figure 2 was then tested not only for functionality but also for leaks. Leaks in the system were detected by placing a rubber stopper at the open end of the tube and a syringe at the other. The syringe was then pulled back and released to see if it would return to the starting position; if it did, this confirmed no leaks were present. In order to test the filter was functional, the WRC was placed on a ring stand and the height of the water in the tube was compared to the amount of water that flowed out of the pipette per minute.

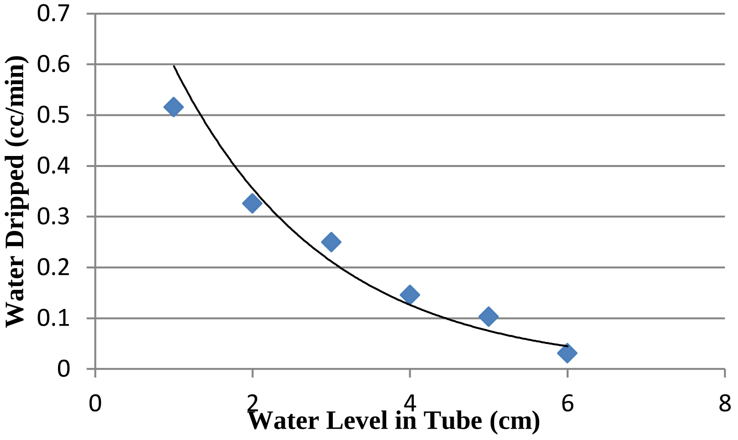

Figure 3: Cubic Centimeters/Minute Dripped at Various Water Levels

As depicted in Figure 3, there is an exponential regression comparing the water level in the WRC to the amount of water dripped. This means that the filter was functioning as should and could be utilized for future experiments once dried in a 60°C oven for one hour.

At this point, the WRCs were weighed to the closest hundredth of a gram and were then filled with aggregates of designated sizes (6-8 of each layer and tillage). The WRCs were then reweighed to calculate the dry soil weight. Water was then gradually added utilizing a syringe to wet the first 3-4 millimeters of the tube until the aggregates absorbed the water; subsequent increments of the tube were filled with water after each similar absorption. A small flexible capillary tube was then placed at the end of the WRC.

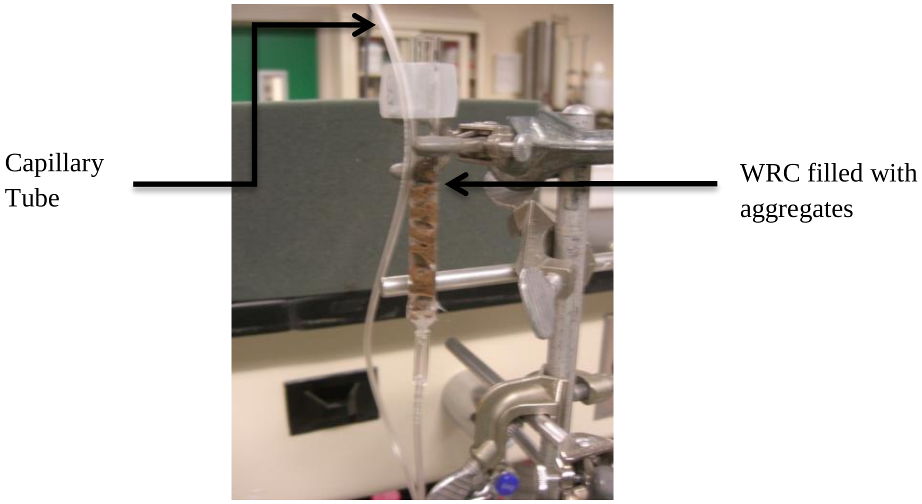

Figure 4: Aggregates in WRC being soaked

After all the aggregates were saturated as depicted in Figure 4, water was added to the base with a syringe to full coverage up to top half of the highest aggregate. This soaking was maintained for 30 minutes. The tube was lower to a height equivalent to that of the filter of the WRC and was attached using adhesive tape. This would allow the water inside the WRC to be drained at a slow enough rate that none of the aggregates would collapse. Once this process was completed, the wet soil weight was calculated by re-massing the WRC and subtracting the original WRC weight.

The WRC were then placed securely in punctured rubber stoppers. 6 Erlenmeyer vacuum flasks were collected and placed on ring stands. A small piece of Styrofoam was inserted with a hole large enough to fit a small vial.

These vials were each measured for dry weight and placed carefully onto the Styrofoam. Tubing was used to connect one vial to another via Y connectors to create a secure vacuum, as picture in Figure 5.

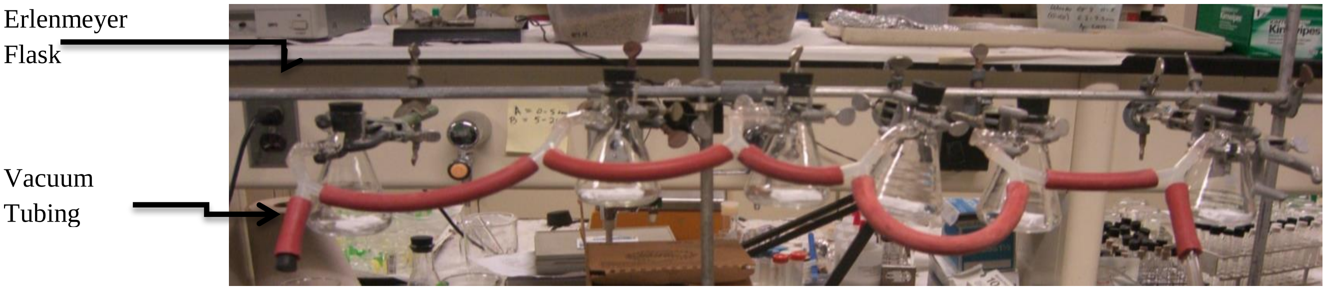

Figure 5: Vacuum Tubing used to connect Erlenmeyer Flasks on Ring Stand

The WRCs secured inside the rubber stoppers were then placed directly over the vials so drops of water would be accurately accounted for. The rubber stoppers would then be secured in the opening of the Erlenmeyer flask in order to secure the vacuum system that could be tested by using the manometer. The system was connected to the Vaccubrand Matric Potential Controller (MPC) and the gauge was monitored so that the pressure was kept constant and therefore verified no leaks were present. The WRC was then set to various matric potentials of 370, 570, 770, and 960 millibars in order for the water retention capacity of each aggregate to be measured by the water loss at different vacuum extractions, ex. $-h_c$ (calculated from capillary rise equation).

The volume of water displaced at equilibrium with each vacuum level was calculated to identify specific water retention by the average pore size radius. This leads to new inferences of which type of soil, comprised of either large or small aggregates, is superior for water retention. Furthermore, the effect of tillage on water retention could be investigated since aggregates were picked from both conventionally tilled and never tilled natural soils (Smucker & Park, 2006).

4. Data:

Aggregates were simultaneously massed and measured in order to determine bulk density (B.D.). Bulk density, in this situation, was calculated by equation 2:

$$B.D. = \frac{MassMass_{Aggregate}(g)}{Volume_{Aggregate}\,(cm^3)} \tag{2}$$

The volume was calculated by the equation 3:

$$Volume_{Sphere} = \frac{4}{3}\pi r^3 \tag{3}$$

The radius, in equation 3, was calculated by dividing the diameter, which was found by averaging the length, width, and height of each aggregate measured to the nearest tenth of a millimeter, by 2.

The Bulk Density was then compared amongst aggregates of various layers (exterior, transitional and interior) beginning with Wooster CT:

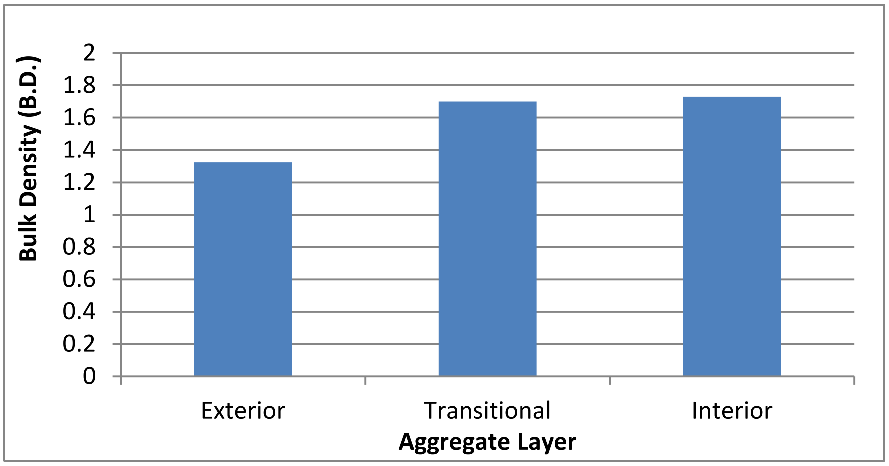

Figure 6: Wooster CT Aggregate Layer vs. Bulk Density

As depicted in Figure 6, the bulk density increases as the aggregate layer decreases. This leads to the inference that smaller aggregates have lesser free space, in the form of pores, than their larger counterparts. This also translates to greater water retention as well as less groundwater seepage. The same can be said about Wooster Forest aggregates:

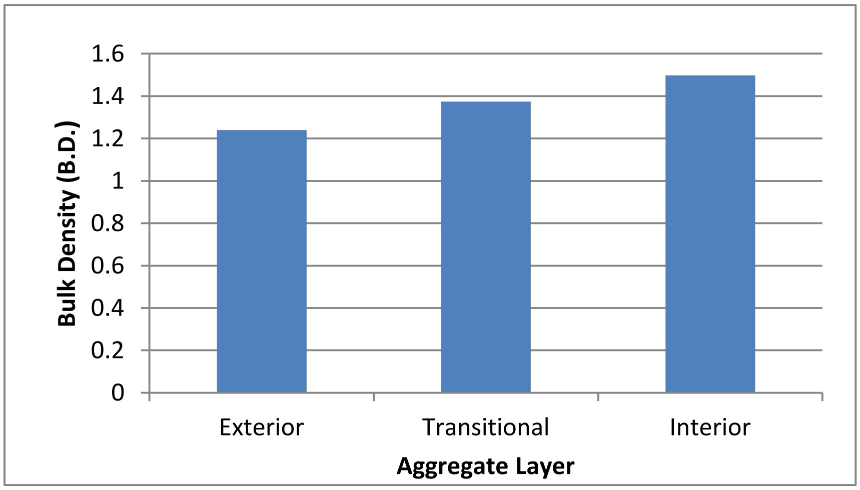

Figure 7: Wooster Forest Aggregate Layer vs. Bulk Density

Although the bulk density increases as the aggregate layer decreases, Figure 7 reveals there is a significant difference between Forest and CT aggregates when comparing bulk density. CT aggregates have an overall lower bulk density for each aggregate layer category. This means that they have greater empty space/ aggregate compared to non-tilled aggregates. This sheds light on the fact that the thought to be beneficial process of tillage has actually detrimental effects on water retention.

Knowing the Bulk Density, the specific porosities of aggregates could be calculated using equation 4, in which P.D. (Particle Density) remains constant at 2.65 g/cm^3:

$$\%Porosity = \left[1 - \frac{B.D.}{P.D.}\right] \times 100 \tag{4}$$

This will give an exact percentage as to what percent of the aggregate is porous. The percent porosity can also be compared among different layers and management practices of aggregates.

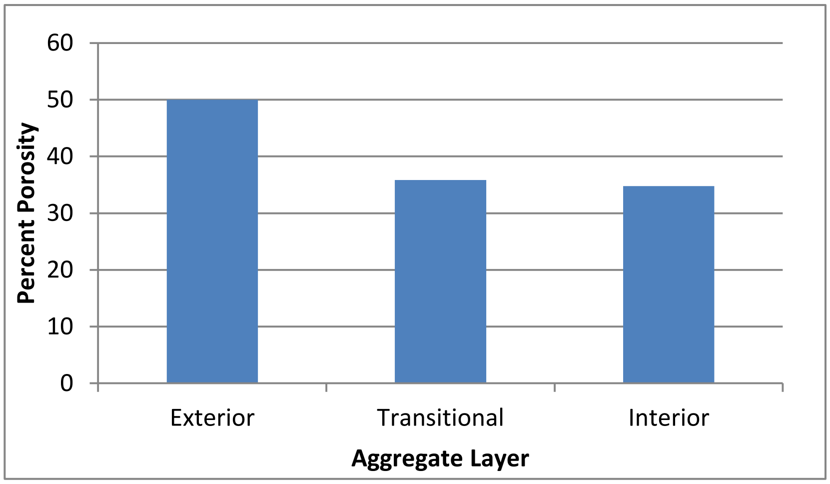

Figure 8: Wooster CT Aggregate Layer vs. Porosity

As depicted by Figure 8, as aggregate layer decreases the porosity also declines. This is inverse of Bulk Density vs Aggregate Layer. Similar results were achieved when comparing non-tilled aggregates to porosity:

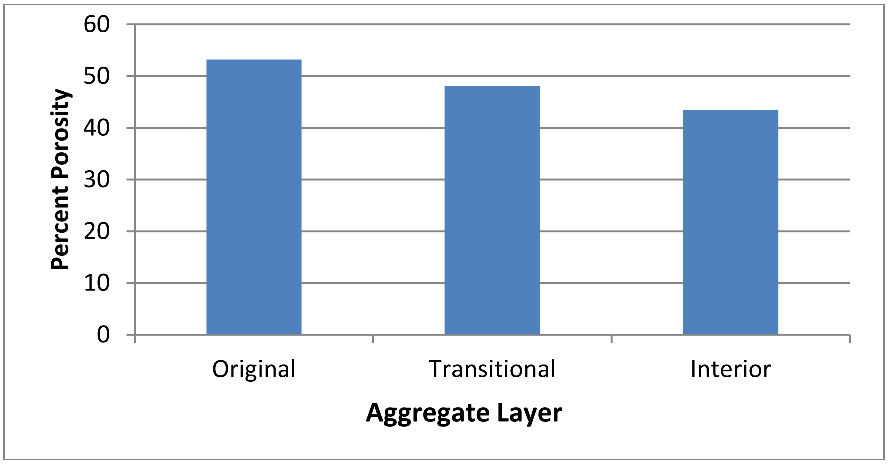

Figure 9: Wooster Forest Aggregate Layer vs. Porosity

However, the Forest aggregates have a notably less porosity compared to CT aggregates, meaning they are superior at retaining water. This bolsters the claim that tillage does not aid in preventing groundwater seepage.

The final experiments using the vacuum system were quantified by measuring the amount of water that remained in the each of the WRCs by evaluating the wet soil weight, exemplified by Figure 10.

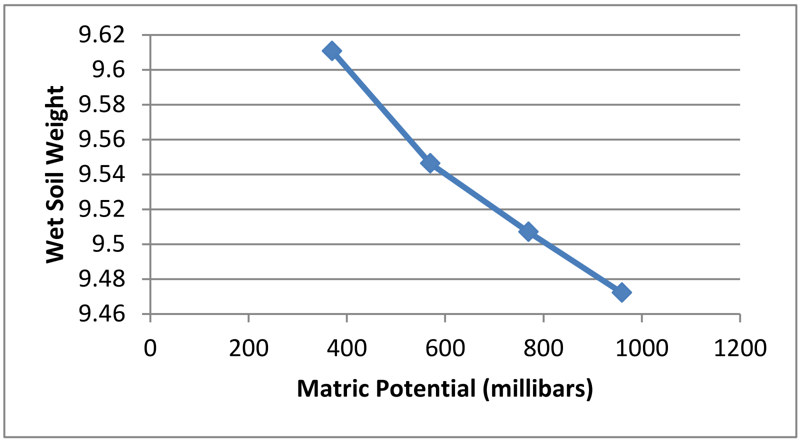

Figure 10: Matric Potential vs. Wooster Forest Exterior Wet Soil Weight

Next, the total water lost from each WRC was calculated and averaged among three replications and thus compared the water retention level of different layered aggregates and tillage (Figure 11 & 12).

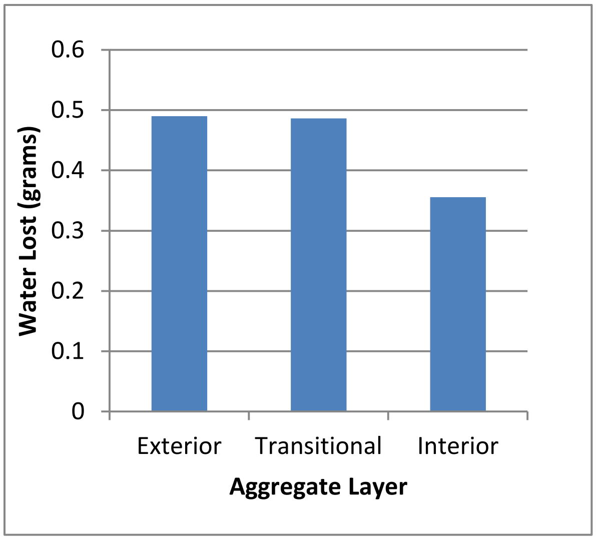

Figure 11: Wooster CT Aggregate Layer vs. Total Water Lost

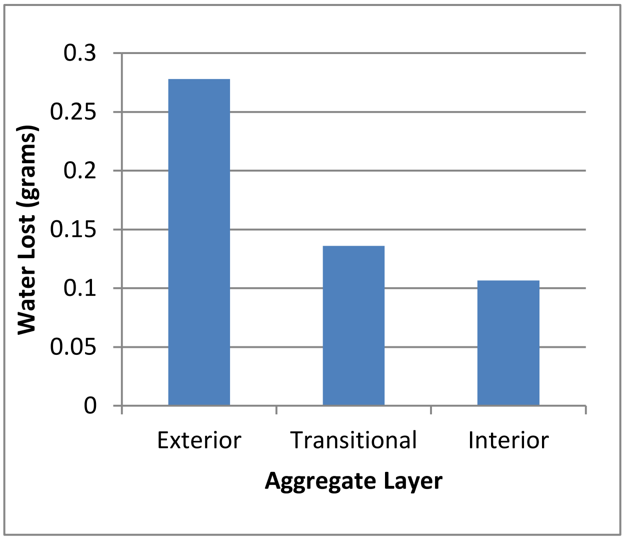

Figure 12: Wooster Forest Aggregate Layer vs. Total Water Lost

As the above graphs depict, the total water lost, as aggregate layer increased, actually decreased. This confirms that smaller aggregates do in fact have greater water retention due to smaller pore sizes. In addition, the conventionally tilled aggregates released a greater amount of water than their natural counterparts; contradicting the common misconception that tillage is entirely beneficial for the soil.

5. Discussion

This research method was radically different than counterparts in the same laboratory since the others involved additions to the soil to boost water retention. This aggregate research, however, was concerned with altering the physics of the soil itself, to decrease water seepage. The results collected present a clear correlation between shaved aggregates, especially those of interior layer, and water-retention ability, achieving the goal of the lab. Implications of smaller aggregates means that finer pored soil surrounding root systems of crops will stay moist for a greater period of time and resist seepage into groundwater. This can lead to significantly less amount of fresh water needed to irrigate crops to sustain grown. Therefore, global implications of these studies include the distribution of additional fresh-water to all nations, greatly improving the living conditions of the rapidly growing number of numerous inhabitants in third world countries. In addition, areas now quickly falling to desertification can also benefit from these results. Desertification is primarily caused by prolonged drought (lack of rainfall) that leaves sandy soil unsaturated and susceptible to wind erosion. This could be avoided by boosting the soil's water retention, by reducing the layer of aggregates, thus allowing it to be saturated for a greater amount of time and preventing the increasing problem of desertification. Smaller pore pathways, found in interior aggregates, will also absorb and retain more soil solutions. This would boost mineral and nutrient composition in soil that can be translated to not only optimal growth of crops but less polluted run-off, caused by nutrient rich fertilizer, which is a major source of eutrophication (excessive nutrients in water-ways that cause animal death) of Earth's water-ways.

6. Conclusion

If the aggregates are shaved to smaller layers, their total volumetric water capacity will in fact decrease because the total porosity and pore size declines. This means smaller aggregates will retain a higher percentage of their pores filled with water, yet lower total soil water volumes. This means that smaller aggregates will retain water at greater matric potentials than their larger counterparts, thus resisting groundwater seepage at a greater degree.

Knowing that smaller aggregates are superior to their larger counterparts at retaining water, a plethora of functional implications can be proposed. Firstly, agricultural fields that are prepared for the growing season of certain crops can now be refined to contain primarily smaller (interior) aggregates. This would effectively help retain water, prevent groundwater seepage, and ultimately reduce the expenditure of total fresh water utilized by agriculture. Another implication regards the fact that conventional tillage increases aggregate porosity and thus decreases water retention. A precaution that many cultivators could take into account before preparing their land is reducing the intensity of tillage they perform or discontinuing the tillage if possible. This would allow aggregates to remain at the lower forest-level porosity and retain water at greater negative matric potentials.

7. References:

1. Park, E.J. and A.J.M. Smucker. 2005. Dynamics of carbon sequestered in concentric layers of soil macroaggregates. Korean J. Ecol. 28:181-188.

2. Santos, D., S.L.S. Murphy, H. Taubner, A.J.M. Smucker and R. Horn. 1997. Uniform separation of concentric surface layers from soil aggregates. Soil Sci. Soc. Amer. J. 61(3):720-724.

3. Smucker, A.J.M. and E.J. Park, 2006. Soil Biophysical Responses by Macroaggregates to Tillage of Two Soil Types. (Eds. Rainer Horn, Heiner Fleige, Stephan Peth and Xinhua Peng). Adv. in GeoEcology 38:456-460. Catena Verlag Publishers, 35447 Reiskirchen.

4. Smucker, A.J.M., D. Santos, Y. Kavdir and E.A. Paul. 1998. Concentric gradients within stable soil aggregates. Proceedings of the 16th World Congress of Soil Science, Montpellier, France.

5. Urbanek, E., et al., Total and fresh organic carbon distribution in aggregate size classes and single aggregate regions using natural $^{13}C/^{12}C$ tracer, Geoderma2011.doi: 10.1016/j.geoderma.2011.05.020

6. "How Much Water Is There On, In, and above the Earth?" *The USGS Water Science School*. N.p., n.d. Web. 29 May 2013.

6. Fierer, N., J.P. Schimel, and P.A. Holden. 2002. Influence of Drying-Rewetting Frequency on Soil Bacterial Community Structure. Microbial Ecology. New York, New York.

7. Smucker, A.J.M. 2011.Soil Water Content and Water Potential Relationships. Soil BioPhysics Laboratory, Michigan State University, East Lansing, Michigan.