

**Reaping the benefits of conservation tillage:
Implications of increased soil organic matter and
aggregation in surface soils**

Kenna E. Rewcastle

A senior thesis presented to:

The College Scholars Program

University of Tennessee, Knoxville

May 10, 2015

ACKNOWLEDGMENTS

This series of projects would not have been possible without the guidance, wisdom, and support provided by Dr. Jie Zhuang who was present at every part of this study, from teaching me the methodological techniques involved, to designing the experiments, and finally, to giving insight to the underlying mechanisms that shaped my results during data analysis and interpretation. Thanks are due to the graduate students, especially Xu Qiufeng and Qin Qin, and senior research faculty of the Institute of Applied Ecology, a division of the Chinese Academy of Sciences in Shenyang, China, and to Dr. Fu-Min Menn for his technological support and insight into the chemical nature of herbicides and how best to analyze their presence. Thanks also to Dr. Edmund Perfect for allowing me to use his fraction collector for the duration of this study, a small gesture that contributed significantly to the feasibility and success of the project.

ABSTRACT

In light of the US Department of Agriculture's initiatives to reduce herbicide application on agricultural lands by 10% and increase soil carbon sequestration by 15%, the agriculture industry is in need of a cultivation practice that allows for more efficient herbicide application and fosters soil carbon accumulation. Our study presents a broad evaluation of the ability of conservation tillage techniques to meet the demands of this goal while maintaining high crop yields. We investigate the implications of increased organic matter and improved soil structure in conservation tillage soils for increased water infiltration and retention, the protection and storage of soil carbon within stable microaggregates, and the retention of herbicide chemicals in the bulk soil. To do so, we employ a well-described model to quantify the role of soil organic matter in water retention, complete a soil respiration study to analyze carbon storage in different soil size fractions, and design a novel column system to analyze herbicide transport through surface soils. The results of this preliminary study suggest that conservation tillage is a viable method of fulfilling the USDA's initiatives to ensure the sustainability of the agriculture industry in the face of climate change.

INTRODUCTION

Since the development of effective herbicides in the 1940s, farmers have begun abandoning conventional tillage methods as a weed-prevention mechanism to instead reap the soil quality improvements that conservation tillage agriculture stimulates. This transition is occurring at a time when the US Department of Agriculture has issued the Agriculture and Food Research Initiative which includes amongst its goals a challenge to reduce herbicide application by 10% and increase soil carbon sequestration by 15% in order to mitigate and adapt to climate change (USDA National Institute of Food and Agriculture 2008). These changes must occur while simultaneously maintaining high levels of productivity, and a growing body of research indicates that widespread adoption of conservation tillage farming will allow our agricultural industry to accomplish more efficient uses of herbicide chemicals and increased terrestrial carbon sequestration (Huggins and Reganold 2008, Lal 1976).

Conservation tillage practices do indeed result in several significant benefits for the farmers that employ these methods. First and foremost, use of conservation tillage reduces the erosion of valuable topsoil by an estimated 60% to 90% when compared to conventional tillage methods (Huggins and Reganold 2008). Soil organic matter (SOM) increases the surface horizons when plowing ceases, effectively reducing the rate of biological oxidation of SOM and preventing soil erosion (Huggins and Reganold 2008, Angers et al. 1997, Reicosky et al. 1995, Karlen et al. 1994, Mielke et al. 1986, Doran 1980, Lal 1976). Other metrics of soil health, such as soil content of essential nutrients like organic and inorganic N, P, K⁺, Ca²⁺, and Mg²⁺, also increase under no-till farming (Angers et al. 1997, Doran 1980, Lal 1976).

Several secondary benefits stem from the accumulation of SOM through the use of conservation tillage practices. Chemically, SOM contains a diversity of surface functional groups that allow the soil to bind and retain many agrochemicals that would otherwise be repelled by soil mineral particles (Arias-Estévez et al. 2008, Bollag et al. 1992, Senesi 1992). SOM content, especially fulvic and humic acid concentrations, are the strongest predictors of agrochemical retention, with soil structure and compaction also influencing the interaction between these organic molecules and the soil system (Arias-Estévez et al. 2008, Bollag et al. 1992). Furthermore, conservation tillage drives enhanced water infiltration and water holding capacity in surface soils by increasing the SOM content in affected agricultural systems (Franzluebbers 2002, Hudson 1994).

In soils with increased SOM content, this organic matter contributes to increased macroaggregation of soil particles and increased stability of the soil structure (Beare et al. 1994, Oades 1984, Tisdall and Oades 1982). The formation of these conglomerate units also protects the organic matter that becomes encapsulated in soil pores as the aggregates form (Balesdent et al. 2000). Because the implementation of reduced-till practices minimizes soil disturbance, the rate of macroaggregate turnover is drastically reduced, further stabilizing the soil carbon that is bound within the aggregate structures (Six et al. 2000). These mechanisms of protecting soil carbon held in smaller soil pores within aggregates from physical and biological degradation may allow conservation tillage to be used as a method of soil carbon sequestration, where organic matter accumulates in the soil instead of turning over quickly in conventional tillage systems (Kern and Johnson 1993, Smith et al. 1998).

While SOM clearly plays a role in restructuring the soil pore network through driving aggregation and increased structural stability in the surface soil, my research aims to clarify the implications of these physical changes stemming from aggregation for water infiltration and retention, soil respiration, and herbicide transport through the soil medium. I hypothesize that: 1) SOM will create greater heterogeneity in the size of soil pores present by stimulating aggregation, causing greater water retention and water hysteresis, 2) SOM's role in aggregation will allow for greater protection of soil carbon from microbial degradation in stable microaggregate structures, and 3) SOM's chemical nature will allow soils with greater SOM content to better retain herbicides by binding these agrochemicals to the surface of SOM particles. These questions directly address the suitability of conservation tillage practices, a technique that stimulates SOM accumulation, in fulfilling the USDA's goals to establish a more sustainable and environmentally sound agriculture sector.

General Soil Characteristics

The soils used in this study were obtained from the University of Tennessee Organic Farm from a study conducted by Dr. David Butler of the Department of Plant Sciences. The treatment used to cultivate these soils in this agricultural study was a continuous organic vegetable crop rotation used with a clover cover crop under reduced-till conditions. These soils have been cultivated under this treatment for two years before collection. Soils from three different replicate plots. *Table 1* summarizes relevant soil physical properties and compares the structure and organic matter content of these soils to those that had been subjected to conventional tillage practices.

Treatment	Continuous organic vegetable cultivation, clover cover crop, reduced-till	Conventional tillage, continuous vegetable cultivation
Duration of Treatment	2 years	2 years
Microaggregate Content (%)	30.95%	8% (Six et al. 2000)
Macroaggregate Content (%)	63.09%	30% (Six et al. 2000)
Bulk Soil Total Carbon (%)	1.55%	1.28%
Microagg Total Carbon (%)	1.36%	1.08%

Table 1: Conservation tillage (reduced-till management practices) results in improved soil structure by stimulating an increase in soil carbon content and fostering aggregate formation. The physical properties of reduced-till soils are compared to those of conventional-till soil. The aggregate content values highlighted in orange come from Six et al. (2000), a study where the treatment had been applied for 9 years for the sake of comparison.

IMPACT OF SOIL ORGANIC MATTER ON WATER HYSTERESIS

Soil water hysteresis is a measurement of the heterogeneity of the size of soil pores present in the soil structure (Zhuang et al. 2008). Larger soil macropores are connected by smaller intermediate and micropores. This hierarchical network of soil pores, where larger aggregates contain smaller aggregates that are separated by pore spaces, causes differences in the rate of water transport into and out of soil pores during wetting and drying processes. While water can easily flow through smaller pores to fill macropores during wetting processes, the smaller pore creates a bottleneck that slows movement of water as it leaves the larger soil pore. This difference in the rate of drying vs. wetting processes can be seen by plotting soil gravimetric water content, θ_g , as a function of water potential, ψ , in a water retention curve and examining the differences in the slopes of the curves. Here, we analyze the extent of water hysteresis in the microaggregate fraction of agricultural soils in which conservation tillage has resulted in the accumulation of SOM.

Methods

We first extracted water-stable microaggregates (53 – 250 μm) from the bulk soil samples by sieving allowing the soils to absorb deionized water to field capacity over night, and then gently shaking the soil sample through wire mesh screens while immersed in deionized water. This procedure allows for the collection of free microaggregates and microaggregates that are loosely bound in unstable macroaggregates. The extracted microaggregates were then freeze-dried using lyophilizer. To quantify the influence of SOM on soil water retention and water hysteresis, microaggregate samples were also combusted at 350 °C for 24 hours to remove organic matter entirely from the soil samples.

Drying and wetting retention curves were then constructed using the chilled mirror dew point method (Scanlon et al. 2002). Water content throughout the drying and wetting processes was measured gravimetrically, and water tension was measured using a WP4 Dew Point PotentialMeter.

The data were then fit to the prefractal gravimetric water retention model derived by Perfect et al. (2004) (*Equation 1*). In this model, gravimetric water content, θ_g , is a function of water tension, ψ , the density of water and soil particle density, ρ_w/ρ_s , and the values of two water retention parameters, a and D . The parameter a is a compound parameter influenced by soil bulk density and air entry tension that represents the presence of large pores in the model. The parameter D describes pore size distribution and the connectedness of the pore network. Both parameters, a and D were estimated for the drying and wetting curves from the collected data using the prefractal model.

$$\theta_g = a\psi^{D-3} - \rho_w/\rho_s \quad (1)$$

Coupled drying/wetting retention curves were constructed for three replicates of each SOM treatment (combusted and intact SOM). We used a t-test to evaluate whether the presence of SOM affects the difference between the a and D parameters in the drying vs. wetting curves, i.e. the degree of hysteresis.

Results

The presence of SOM in the microaggregate soil fraction results in observable, yet statistically insignificant increases in the extent of water hysteresis in the soil system. Our data fit the prefractal water retention model extremely well, with the statistical fit ranging

from $0.981 < R^2 < 0.999$. Removing SOM from the soil particles did not significantly affect the difference in a and D parameters between drying and wetting curves, despite an observable difference in water hysteresis between the two treatments (a hysteresis $p = 0.339$, D hysteresis $p = 0.119$) (Figure 1). This result is evident from the increased distance between the wetting and drying branches of the water retention curve seen when SOM is present in the microaggregates. This distance between the two branches decreases with the removal of SOM during combustion. Table 2 documents differences in the water retention parameters that stem from the presence or absence of the SOM that effectively restructures the pore network and contributes to greater diversity in the size spectrum and size distribution of pores present in aggregate structures.

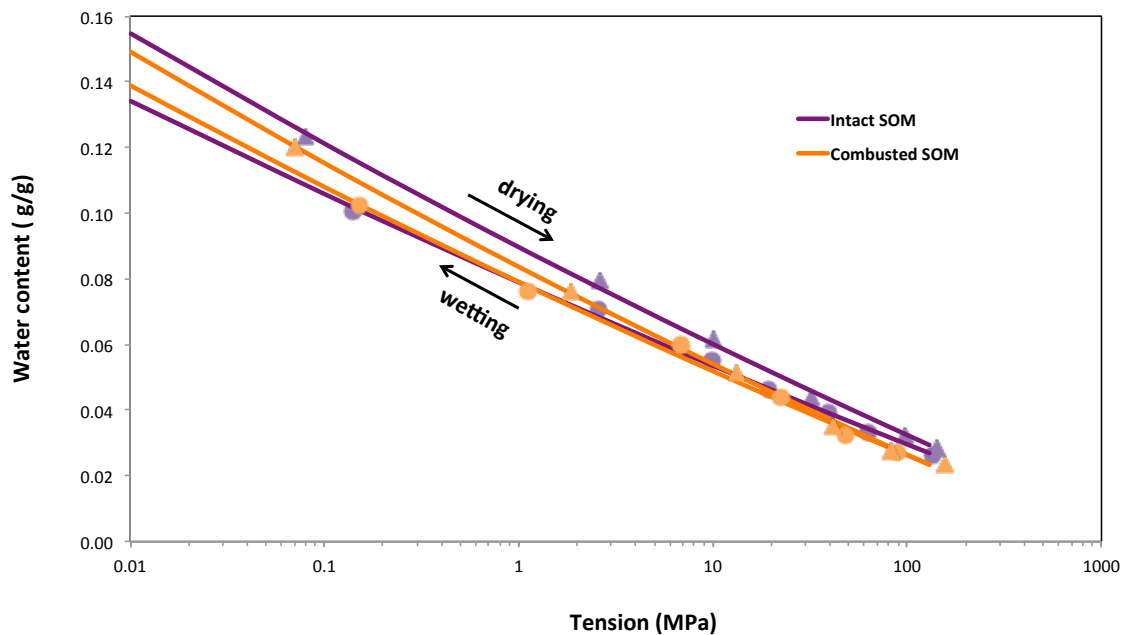


Figure 1: The presence of organic matter increases water hysteresis by restructuring the pore network during SOM-mediated aggregation. Hysteresis is evident by increased distance between drying and wetting curves in the intact OM samples as compared to the soil samples in which OM was removed.

	Intact OM	Combusted OM
a_{drying}	0.489	0.462
a_{wetting}	0.480	0.456
D_{drying}	2.972	2.973
D_{wetting}	2.975	2.974
wetting R^2	0.997	0.990
drying R^2	0.998	0.997

Table 2: *The presence of SOM drives observable, but not statistically significant differences in the water retention parameters obtained from the fractal model, possibly indicating that SOM restructures the pore network, introducing greater pore size heterogeneity by stimulating the formation of stable aggregates (a hysteresis $p = 0.339$, D hysteresis $p = 0.119$).*

These results have clear implications for farmers that seek to achieve the USDA's Agriculture and Food Research Initiative goals of increasing the environmental sustainability of farming practices while maintain high crop yields. We show that SOM increases the retention of water in microaggregates, meaning that adopting agricultural practices like conservation tillage which stimulate an accumulation of organic matter will create added resilience in the agricultural industry as climate change continues to alter precipitation regimes and irrigation reservoirs dry up.

SOIL CARBON SEQUESTRATION IN CONSERVATION TILLAGE SOILS

As the presence of SOM under minimal disturbance stimulates aggregate formation, the structure of the surface improves while simultaneously protecting the soil carbon that is encapsulated in the pore structure of micro- and macroaggregates. This process of encapsulation physically protects SOM from aeration and restricts microbial access to the organic matter bound in the smallest pores, preventing microbial degradation of these organic substrates (Balesdent et al. 2000). In this study, we analyze the role of microaggregates, the most stable soil fraction, in shielding soil carbon from microbial degradation during soil respiration.

Methods

Soil from the UT Organic farm was again used in this study. Five 20g samples of bulk soil were placed in water- and air-tight stainless steel tubes for incubation. For the microaggregate samples, microaggregates were extracted using the sieving procedure detailed above. 10 g of extracted microaggregates were combined with 10 g of macroaggregate-sized pure quartz sand particles to maintain the aggregate-size distribution of the natural soil within the incubation vessel. Soil moisture content was maintained at 20% of sample mass (the mass of the soil sample plus the mass of soil water). The incubation tubes were placed in a 25 °C incubation bath, and a constant flow rate of 80 mL/min was maintained. All air entering the incubation tubes was first passed through a desiccator that removed any ambient CO₂ from the gas flow. The CO₂ efflux released during microbial soil respiration was measured using a LiCOR infrared gas analyzer (*Figure 2*). Soil respiration measurements were recorded every hour until the rate of CO₂ discharge peaked, after which measurements were taken daily for a total duration of

21 days. Release of CO₂ from the soil incubators during respiration at each time step was compared between microaggregate samples and bulk soil samples using a Mann Whitney U test. This test allowed us to evaluate the differences between respiration of organic matter stored in soil microaggregates as opposed to respiration occurring in the bulk soil as a whole.



Figure 2: The pictures above depict the soil respiration study setup. The left picture shows the incubation bath, the LiCOR gas analyzer, the cylindrical desiccator, and the flow regulators and tubing apparatus. The right picture shows the individual incubation vessels and the gas-flow tubing that extends from them for measurements and flow regulation.

Results

Soil microaggregates are the dominant soil size fraction involved in protection and storage of organic matter in the soil system ($p = 0.001$) (Figure 3). These results support the idea of a hierarchical soil structure, where organic matter is encapsulated in increasingly smaller aggregate particles that adhere to one another in the formation of larger macroaggregates. SOM held in the smallest micropores within the microaggregate structures is, to some degree, inaccessible to the soil microbes involved in degrading this

soil carbon during soil respiration. Therefore, because conservation tillage practices stimulate the formation of the microaggregates that are involved in storing and protecting carbon in the depths of the micropore network, conservation tillage can be used as a mechanism of soil carbon sequestration in accordance with USDA climate mitigation and adaptation goals.

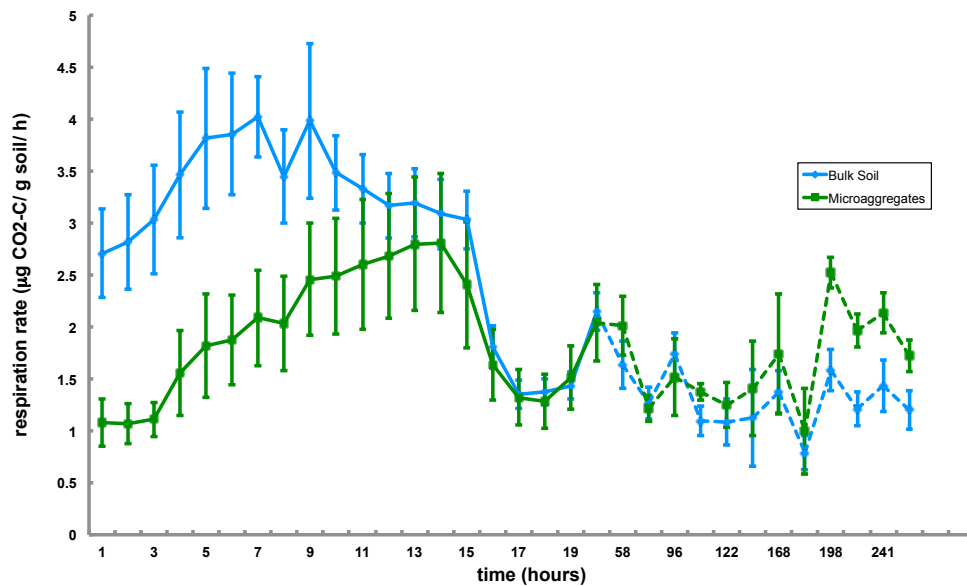


Figure 3: Soil microaggregates are more effective than the bulk soil size-fraction in storing and protecting SOM against microbial degradation during soil respiration ($p = 0.001$). Error bars represent the standard deviation of the respiration rate from the average respiration rate amongst all replicates at each time step.

THE ROLE OF SOIL ORGANIC MATTER IN RETAINING HERBICIDE CHEMICALS

To achieve the USDA's AFRI goal of reducing herbicide application by 10% while maintaining current levels of agricultural productivity, a more effective method of herbicide use must be employed. As already described in detail, conservation tillage results in an accumulation of SOM that has a diverse array of functional groups necessary for binding and retaining herbicides in the soil system (Arias-Estévez et al. 2008, Bollag et al. 1992, Senesi 1992). Herbicide retention in agricultural soils would increase the longevity of herbicide, meaning that a single herbicide application would be active in the soil for a longer period of time as opposed to readily leaching out of the system or quickly degrading due to rapid exposure to microbial activity. This third study analyzes the role of SOM and soil aggregate structure in retaining herbicides in soils that have been managed using conservation tillage practices.

Methods

With the help of the University of Tennessee Biological Facility Services, we designed and fabricated a stainless steel column system coupled with a high-pressure liquid chromatography (HPLC) pump and a fraction collector (*Figure 4*). The materials used in the column system were chosen to avoid any interactions between the herbicide chemical and plastic components of the column system. We selected the herbicide Alachlor for this study because of its widespread use in the agriculture industry and because Alachlor is one of the few commercially available deuterated herbicides, a property that we plan to take advantage of in future small angle neutron scattering (SANS) studies that will analyze the diffusion of herbicide molecules into the soil pore network. The experimental

solution contains a 5 ppm concentration of alachlor which reflects the manufacturer's recommended application concentration for agricultural use.

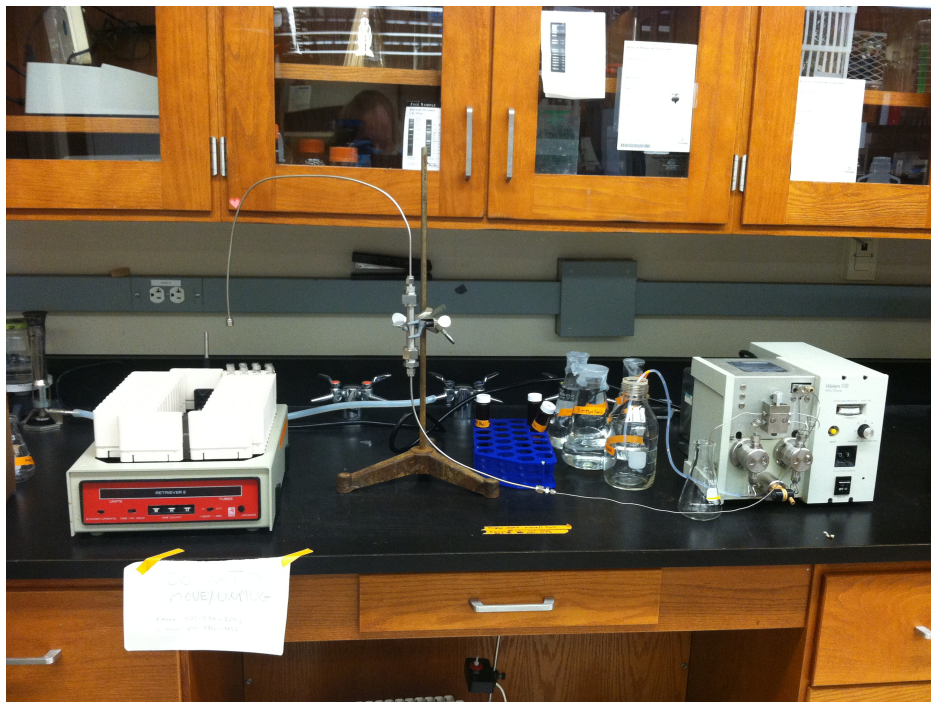


Figure 4: *This picture depicts the custom-designed soil column system used in this study. Depicted to the far right is the HPLC pump which actively pumped fluid through the Teflon and stainless steel tubing to the soil column. Fluid flowing out of the soil column was collected at regular intervals in quartz vials by a fraction collector system.*

To investigate the importance of soil structure on herbicide retention, we again extracted microaggregates from the bulk soil to compare herbicide retention in these highly stable aggregates as compared to herbicide retention in the bulk soil as a whole. Then, to explicitly study the role of soil organic matter in retaining herbicides, we compared herbicide retention in bulk and microaggregate soils when the organic matter was left intact and when the organic matter was removed using combustion. These two variables, SOM presence and soil size-fraction, were crossed in a factorial design and all four resulting treatments were replicated twice, totaling to eight individual column trials.

Four distinct fluids were passed through the soil column in this study. In the first phase, a 5 ppm NaCl background solution was introduced to the soil column in order to fill all pore space with an initial fluid. In the second phase, a 5 ppm Alachlor solution dissolved in 5 ppm NaCl was pumped into the column for 23 pore volumes. A pore volume (PV) here is defined as the sum volume of all pore space present in the soil system and was calculated using the known volume of the soil column, the mass of soil contained in the column, and the bulk density and porosity inherent to the soil. After the experimental solution had been introduced, the column was again flushed with an NaCl solution to dislodge any loosely bound herbicide from the soil system. Finally, an ethanol solution was used to mobilize the Alachlor, a bulky, aromatic compound that dissolves well in organic alcohols. This final flush allowed us to analyze how tightly the herbicide remaining in the soil column was bound to the soil organic matter and mineral surfaces. All fluids were pumped through the soil column at a rate of 0.22 mL/min, a rate that is reflective of the natural hydrological movement that agricultural soils experience.

Once the column effluent was collected in quartz vials, the Alachlor was extracted from the saline background solution using an ethyl acetate solvent so that the concentration of Alachlor in the effluent could be measured using gas chromatography-mass spectrometry (GCMS). The concentration of Alachlor in the effluent was plotted against the effective PV to construct an herbicide transport diagram. This procedure was carried out for the bulk soil and microaggregate samples with SOM intact and combusted.

Logistic curves were fitted to each herbicide transport curve, and the parameters that characterize the shape of these curves were compared using a t-test to analyze the

influence of SOM presence and soil structural stability (microaggregate soil fraction vs. bulk soil) on herbicide retention (*Equation 2*). In this equation, C is the concentration of herbicide at pore volume (PV) t , K is the ‘carrying capacity’ of the model, or the concentration of herbicide on which the effluent stabilizes over time. We analyzed several parameters that influence the shape of the logistic curves that describe herbicide transport in soils with and without SOM present, and between bulk soil and microaggregate size fractions. Here, ‘*asym*’ is the asymptote around which the model stabilizes (*Equation 3*), ‘*xmid*’ is the PV at which the inflection point in the logistic curve occurs (*Equation 4*), and ‘*scale*’ is the scaling parameter for the x-axis (*Equation 5*). The parameter r , in each of these definitions, is the growth rate for the model. C_0 represents the initial herbicide concentration at the start of each herbicide transport column experiment.

$$C = \frac{K}{1+e^{C_0+rt}} \quad (2)$$

$$asym = K \quad (3)$$

$$xmid = \frac{-C_0}{r} \quad (4)$$

$$scal = \frac{-1}{r} \quad (5)$$

Additionally, the percentages of Alachlor retained by each soil sample were calculated and compared using a T-test, and the time of soil herbicide saturation for each soil was also compared using a T-test.

Results

Our results suggest that soil organic matter plays a vital role in retaining herbicide chemicals in the soil system (*Figure 5*). Logistic curves were fit to each individual herbicide transport curves with a fit ranging from $0.753 < R^2 < 0.973$. However, due to the low

replication inherent in this preliminary study, our results lack statistical significance, and our conclusions, as such, are based on the patterns observed in the few replicates present. In both the microaggregate and bulk soil size fractions, removing the SOM seemed to impair the soil's ability to retain herbicides, and more herbicide was consistently retained when SOM was present ($p = 0.413$). SOM presence did not significantly change the parameters that describe herbicide transport through the soil (*asym* $p = 0.485$, *xmid* $p = 0.114$, *scale* $p = 0.457$). Soil structural stability (microaggregates vs. bulk soil) also did not affect the shape of the herbicide transport curves (*asym* $p = 0.563$, *xmid* $p = 0.651$, *scale* $p = 0.657$).

Observationally, the data suggest that microaggregates retained less herbicide than was retained by the bulk soil, indicating that aggregate stability may not be an important factor in herbicide retention. This conclusion was not supported statistically owing to the small sample size used in this study ($p = 0.521$) (*Figure 6*). However, this effect may also stem from a flaw in the experimental design, where air bubbles that fill the smallest micropores within soil microaggregates may become trapped in the column so that the herbicide solution completely bypasses the internal pores within soil microaggregates. In future studies, this problem could be avoided by first flushing the column with CO₂ gas that will readily dissolve into the herbicide solution, eliminating this 'pore bypassing' effect.

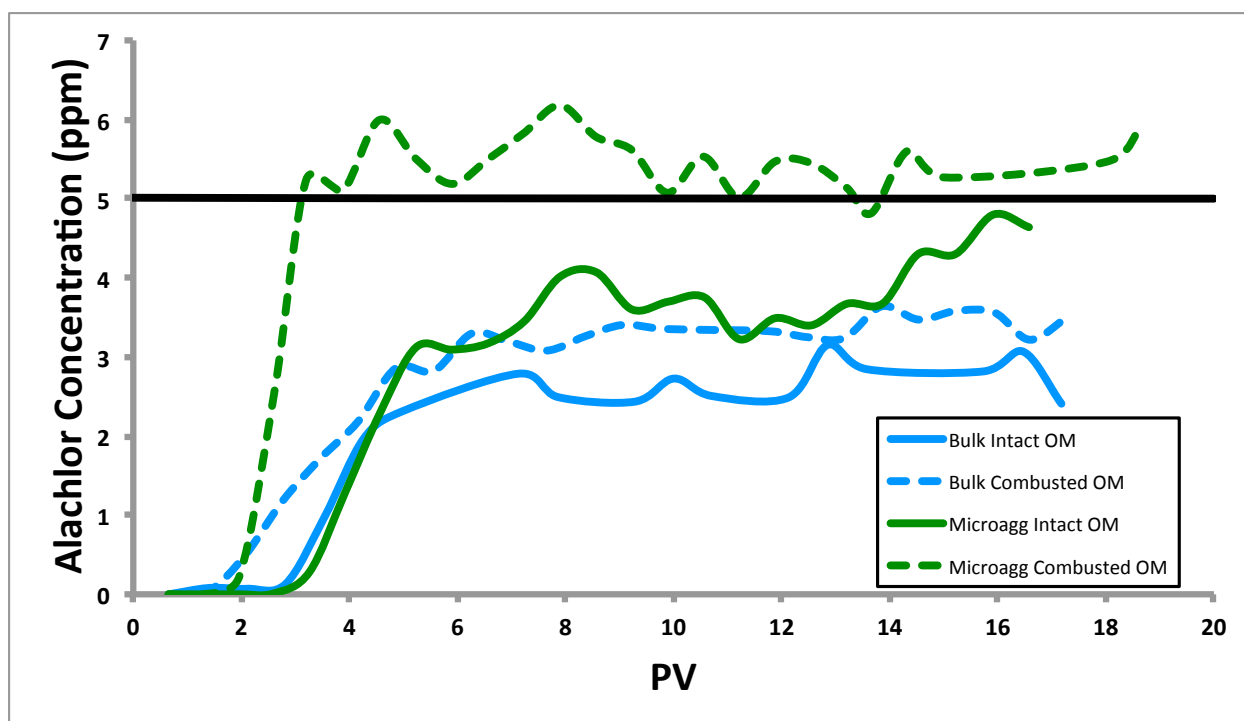


Figure 5: In these herbicide transport curves, it is apparent that removing OM from the soil impedes the soils' ability to retain herbicide, and more herbicide is therefore released into the column effluent (asym $p = 0.485$, xmid $p = 0.114$, scale $p = 0.457$). Bulk soil retains more herbicide than does the isolated microaggregate size fraction (asym $p = 0.563$, xmid $p = 0.651$, scale $p = 0.657$).

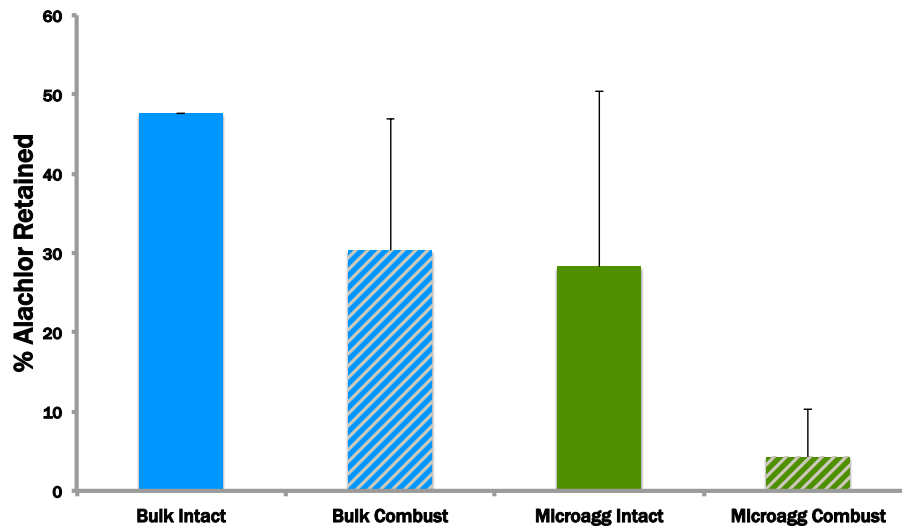


Figure 6: *Less herbicide may be retained by soils when SOM is removed via combustion ($p = 0.413$). Bulk soils with SOM intact are generally best at retaining herbicides that are pumped through the soil column, and microaggregate soils with SOM removed retain the least amount of herbicides overall ($p = 0.521$).*

Finally, it is also apparent that the presence of SOM allows soils to retain herbicides for much longer than soils without SOM ($p = 0.001$). In other words, SOM retards the release of herbicide from the soil system and delays the point of herbicide saturation (Figure 7).

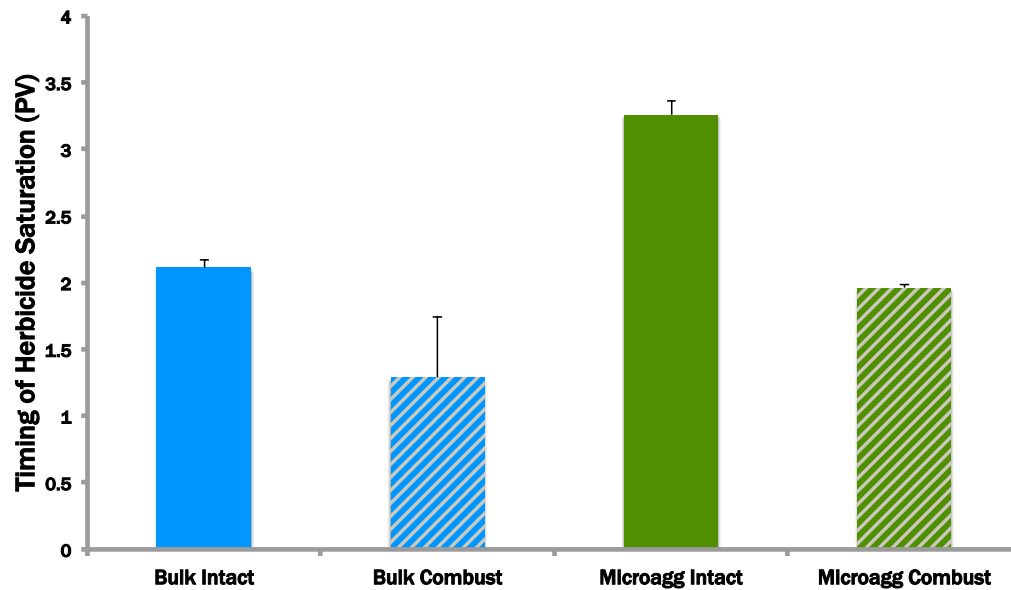


Figure 7: *SOM slows the release of herbicide into the soil solution and delays the point of herbicide saturation ($p = 0.001$). Microaggregate soils in which SOM is present are able to retain herbicide for the longest before becoming saturated and slowly releasing additional herbicide into the soil solution.*

Increasing herbicide retention in soils is one way to increase the efficacy of herbicide application because it lengthens the time period over which a single application of herbicide will remain active in deterring weed growth. Because conservation tillage, by causing a buildup of SOM, will foster herbicide retention in the surface soils of agricultural fields, conservation tillage again becomes a way for farmer's to balance the USDA's environmental sustainability initiatives that encourage the reduction of herbicide usage while maintaining competitive crop yields.

CONCLUSIONS

In the USDA Agriculture and Food Research Initiative, the federal government has challenged farmers to strike a balance between environmentally sustainable agriculture under the constraints of climate change while simultaneously maintaining or even increasing agricultural productivity to feed the growing global population. Achieving these goals will require the widespread adoption of agricultural techniques that involve more efficient use of herbicides and foster long-term carbon storage in the soil. By reducing disturbance of the surface soil, conservation tillage practices results in an accumulation of SOM that also stimulates aggregation and improved soil structure. Our results show that this increase in organic matter and heightened aggregation has consequences for increased water retention in surface soils, enhanced protection and storage of soil carbon within soil aggregates, and retaining herbicides in the bulk soil. As such, employing conservation tillage in more of our nation's agricultural lands is a comprehensive way to mitigate and adapt to continued climate change in a way that benefits agricultural yields and environmental sustainability.

REFERENCES

- Angers, D.A., Bolinder, M.A., Carter, M.R., Gregorich, E.G., Drury, C.F., Liang, B.C., Voroney, R.P., Simard, R.R., Donald, R.G., Beyaert, R.P. and Martel, J. 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. *Soil & Tillage Research*. 41: 191-201.
- Arias-Estévez, M., López-Periago, E., Martínez-Carballo, E., Simal-Gándara, J., Mejuto, J.C. and García-Río, L. 2008. The mobility and degradation of pesticides in soils and the pollution of groundwater resources. *Agriculture, Ecosystems and Environment*. 123: 247-260.
- Balesdent, J., Chenu, C. and Balabane, M. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil & Tillage Research*. 53: 215-230.
- Beare, M.H., Hendrix, P.F. and Coleman, D.C. 1994. Water-Stable Aggregates and Organic Matter Fractions in Conventional- and No-Tillage Soils. *Soil Science Society of America Journal*. 58: 777-786.
- Bollag, J.M., Myers, C.J. and Minard, R.D. 1992. Biological and chemical interactions of pesticides with soil organic matter. *The Science of the Total Environment*. 123/124: 205-217.
- Doran, J.W. 1980. Soil Microbial and Biochemical Changes Associated with Reduced Tillage. *Soil Science Society of America Journal*. 44: 765-771.
- Franzluebbers, A.J. 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil & Tillage Research*. 66: 197-205.
- Hudson, B.D. 1994. Soil organic matter and available water capacity. *Journal of Soil and Water Conservation*. 49:2 189-194.
- Huggins, D.R. and Reganold, J.P. 2008. No-Till: the Quiet Revolution. *Scientific American*. 299:1 70-77.
- Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S. and Jordahl, J.L. 1994. Long-term tillage effects on soil quality. *Soil & Tillage Research*. 32:4 313-327.
- Kern, J.S. and Johnson, M.G. 1993. Conservation Tillage Impacts on National Soil and Atmospheric Carbon Levels. *Soil Science Society of America Journal*. 57: 200-210.
- Lal, R. 1976. No-tillage Effects on Soil Properties under Different Crops in Western Nigeria. *Soil Science Society of America Journal*. 40: 762-768.
- Mielke, L.N., Doran, J.W. and Richards, K.A. 1986. Physical environment near the surface of plowed and no-tilled soils. *Soil & Tillage Research*. 7: 355-366.

- Oades, J.M. 1984. Soil organic matter and structural stability: mechanisms and implications for management. *Plant and Soil*. 76: 319-337.
- Perfect, E., Kenst, A.B., Diaz-Zorita, M. and Grove, J.H. 2004. Fractal analysis of soil water desorption data collected on disturbed samples with water activity meters. *Soil Science Society of America Journal*. 68:1177-1184.
- Reicosky, D.C., Kemper, W.D., Langdale, G.W. and Douglas Jr., C.L., Rasmussen, P.E. 1995. Soil organic matter changes resulting from tillage and biomass production. *Journal of Soil and Water Conservation*. 50:3 253-261.
- Scanlon, B.R., Andraski, B.J. and Bilskie, J. 2002. Miscellaneous methods for measuring matric or water potential. p. 643-670. In J.H. Dane and G.C. Topp (ed.) *Methods of soil analysis*. Part 4. Book Ser. 5. SSSA, Madison, WI.
- Senesi, N. 1992. Binding mechanisms of pesticides to soil humic substances. *The Science of the Total Environment*. 123/124: 63-76.
- Six, J., Elliott, E.T. and Paustian, K. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology & Biochemistry*. 32: 2099-2103.
- Smith, P., Powlson, D.S., Glendining, M.J. and Smith, J.U. 1998. Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. *Global Change Biology*. 4: 679-685.
- Tisdall, J.M. and Oades, J.M. 1982. Organic matter and water-stable aggregates in soils. *Journal of Soil Science*. 33(2): 141-163.
- USDA National Institute of Food and Agriculture. 2008. AFRI Climate Variability and Change Challenge Area. <http://nifa.usda.gov/program/afri-climate-variability-and-change-challenge-area>
- Zhuang, J., McCarthy, J.F., Perfect, E., Mayer, L.M. and Jastrow, J.D. 2008. Soil Water Hysteresis in Water-Stable Microaggregates as Affected by Organic Matter. *Soil Science Society of America Journal*. 72: 212-220.