IMPACT OF DAIRY WASTEWATER IRRIGATION AND MANURE APPLICATION ON SOIL WATER HOLDING CAPACITY AS A WATER-SOIL-WASTE NEXUS STUDY

A Thesis

by

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ABSTRACT

The livestock sector contributes to about 40 percent of the global value of agriculture output and takes over a third of total crop land for use as feed crop. The industry continues to grow in demand leading to an increase in technology and more large-scale, commercialized agriculture. However, large growth in operations correlates to large growth in by products and waste, which can compromise environment and human health. Organic manure can act as a wonderful soil fertilizer for increasing crop yield due to its nutrient content; however, if left untreated or over applied nutrients can pollute local water resources. The application of waste on land has been shown to alter soil structure, potentially changing the amount of water available in the soil for plants to grow. Thus, proper waste management from livestock production is an important part of maintaining sustainable food production. There are a handful of different waste reuse strategies with various goals such as minimizing the consumption of fresh water, improving food production, or contributing to energy production. However, each management technique comes with tradeoffs and associated environmental, energy, or monetary costs.

At the Texas A&M AgriLife Research Dairy in Stephenville, Texas, waste composed of manure, bedding materials, and wash water is separated between liquid and solid components. Currently, a portion of the solids are applied to the land as fertilizer while the liquid waste goes through a natural lagoon treatment process. Approximately half of the wastewater is reused as wash water and the other half is for irrigation. To better understand how these management practices effect the physical soil health and thus food production, parameters indicative of water holding capacity and soil structure will be analyzed. Using the TypoSoil™ machine to collect measurements, the hydro-structural parameters of a fine sandy loam (A horizon) and a sandy clay (B horizon) soil were evaluated under current conditions of the dairy and compared to untouched soil. Although the soil itself was highly variable among the sample locations, a statistically significant difference between available water and K_{bs} was detected between the control and the manure and wastewater application in both A and B horizons. Interestingly, both manure and wastewater application improved plant available water in the A horizon by 30 and 40 percent respectively, but deteriorated plant available water in the B horizon by 30 and 25 percent.

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1. INTRODUCTION

1.1 Background

Within the next 50 years, the population of Texas is projected to increase by 73 percent to approximately 51 million people (Texas Water Development Board, 2017). With an increase in population comes the need for a direct increase in food, energy, and water supplies that each come with accompanying waste. The other side of the story is the interconnectedness between each of the resources. Approximately 15 percent of global freshwater supply is used for energy production while 80 to 90 percent of consumptive water use and 30 percent of world's energy goes to food production (Mohtar, 2015). To meet the needs of the population in a sustainable way, conservation strategies and reuse technologies need to be implemented across local and state-wide scales in such a manner that the negative impacts on the environment, the economy, and society are minimized. The beef and dairy industry of Texas is one of the main agro-economic industries in the state with almost 4.5 million beef cows and about 500,000 dairy cows; it leads the nation in the number of cattle operations (USDA National Agricultural Statistics Service, 2017). Each head of dairy cattle produces about 150 pounds of manure and requires approximately 50 gallons of water per day for drinking, cooling, and washing (Safferman & Wallace, 2015).

As the average size of dairy herds increase, the need for proper waste management becomes even more important for the health of the animals and the environment. A common management practice is to store the waste as a slurry, including the water from the milking facility, in ponds or lagoons and apply it to the fields as fertilizer (Safferman & Wallace, 2015). The manure serves as a soil conditioner due to the high carbon and nitrogen content, along with a few other essential plant nutrients (Liu, Sharara, Gunasekaran, & Runge, 2016). Waste reuse techniques have the potential to improve crop yield, produce energy, and reduce irrigation demand, thus decreasing the stress on freshwater use. However, reuse strategies may have negative impacts that include contamination of nearby water sources from bacteria or excessive nutrient concentrations due to over application of waste and runoff. As a result of the environmental degradation, federal and state regulations demand less concentrated manure spreading based on plant nutrient requirements and soil conditions, resulting in the need to transport the manure elsewhere or find a different use (Liu et al., 2016). Other methods for waste management include separating the liquid and solid portions of the manure before treatment or land application. The solid portion of the waste can be composted, sent through anaerobic digestion, used to create biochar, or a combination of these processes (Lorimor et al., 2006). Each of the waste management strategies are associated with different environmental, energy, and water footprints. This study focuses on the environmental impacts of using raw manure as a soil conditioner and using wastewater for irrigation, as shown through soil hydraulic properties and irrigation demand.

Soil hydraulic properties are heavily influenced by land use patterns and management practices such as tillage, crop rotation, and fertilizer application (Shi, Zhao, Zhang, & Wu, 2015). Manure contains many elements required for plant growth including organic matter and nutrients such as N, P, and K. Many studies have shown that long term application of cattle manure in crop fields improves soil organic carbon. Changes in organic carbon content of soil leads to change in soil structure and adsorption properties, which can in turn lead to alteration of water retention (Rawls, Pachepsky, & Ritchie, 2003). In one study with 71 years of manure application on a very fine sandy loam, soil organic carbon concentrations doubled in the 0-30 cm depth which heavily influenced the increased water retention by 18% at field capacity and 21%

at permanent wilting point. Water retention at both field capacity and permanent wilting point were measured by saturating the soils and using pressure extractors combined with volumetric bulk density (Blanco-Canqui, Hergert, & Nielsen, 2015). A 28 year study on a silt loam soil derived from loess shows evidence of organic manure application increasing soil water retentions by 3.2-10.8% depending on suction tensions (Shi et al., 2015).

Many of the previous studies have used pressure plate methods to measure for field capacity and water availability within the soil. The previous methods mentioned do not necessarily take into consideration the hierarchical structure of the soil aggregates and how it relates to the water holding capacity. Long term fertilization can result in alteration of soil hydraulic properties by modifying soil aggregates and structure (Mamedov et al., 2014). The impact of organic fertilizers, such as manure, on aggregate stability may be dependent upon soil type and pH. Soil structure and composition play a huge role in water retention due to the physical interaction between the water film at the surface of particles and aggregates, and the structure itself (E. F. Braudeau & Mohtar, 2014). The structure representative volume (SREV) modeling approach takes into account the hierarchical organization of the soil structure and will be used with the soil shrinkage curve as shown in Braudeau & Mohtar, 2014 to measure values of field capacity, permanent wilting point, and available water.

1.2 Objectives

The localized effects of manure application and wastewater application on physical soil health require more attention for making informed waste management and irrigation decisions. Therefore, the objective of this work is to quantify the impacts of dairy farm waste management practices, such as manure application and wastewater irrigation, on physical soil health as indicated by soil properties such as soil aggregate structure and plant available water. The secondary objective includes studying the variability of parameters from soil within the same field. The outcome of the study will provide a more in depth understanding about the effects of dairy waste application on physical soil properties of fine sandy loam and sandy clay soils.

1.3 Theoretical Background

1.3.1 Defining Hydraulic Properties

The main property that will be discussed is the plant available water (AW) in the soil. This property is the most relevant relative to agricultural irrigation demands; the more water that is available to plants in the soil, the less irrigation needed. The amount of AW depends on two states; the field capacity of the soil and permanent wilting point, which is dependent on both the soil and the plant type. Field capacity is commonly accepted as the water content of the soil after excess water has drained from gravity; it is typically considered the point at which the pressure within the soil is -33 kPa. Historically, permanent wilting point has been defined at -1500 kPa, the point at which the plant can no longer obtain water from the soil and it will wilt. Therefore, the plant available water in the soil can be defined as the difference between field capacity and permanent wilting point. However, these values are experimentally based estimates and lack physically based definitions that take into consideration the thermodynamics and structure of the soil.

1.3.2 Pedostructure Methods

The Structural Representative Elementary Volume (SREV) modeling approach takes into consideration the soil structure and thermodynamics of a soil system by delineating the representative volume as a fixed mass of solids belonging to a non-rigid structure and assuming that the solids cannot migrate like the air and water phases can (Erik Braudeau & Mohtar, 2009). With this definition, the change in specific volume can be attributed to the change in mass of water and mass of air within the soil. The SREV concept helps to bridge the gap of pedology and soil physics to physically model the hydrostructural characteristics of the soil pedon (Erik Braudeau & Mohtar, 2009). Using the data collected from the TypoSoil machine and assuming isotropic radial shrinkage and uniform distribution of water content within the soil, the specific volume, $\bar{V}$, and the specific water content, $\bar{W}$, of the sample can be determined using the following equations (1) and (2).

$$\bar{V} = \frac{\pi d^2 H}{4M_s} \tag{1}$$

Where $\bar{V}$ is the specific volume of the soil sample (dm^3/kg_{solid}), d is the diameter of the sample (dm), H is the height of the sample (dm), and M_s is the dry mass of the sample.

$$\bar{W} = \frac{m - M_s}{M_s} \tag{2}$$

Where $\bar{W}$ is the specific water content (kg_{H2O}/kg_{solids}) and m is the measured mass of the soil sample (kg). These two variables along with internal pressure measurements during a drying cycle are used to develop the soil shrinkage curve (SSC) and the water retention curve (WRC). The physically measured, continuous soil characteristic curves are important for obtaining accurate estimates of hydrostructural parameters by finding zones of transition corresponding to soil water structure and aggregate organization. The SSC contains four phases of soil water interaction and six transition points (A-F) characteristic of hydrostructural behavior as seen below (Figure 1).

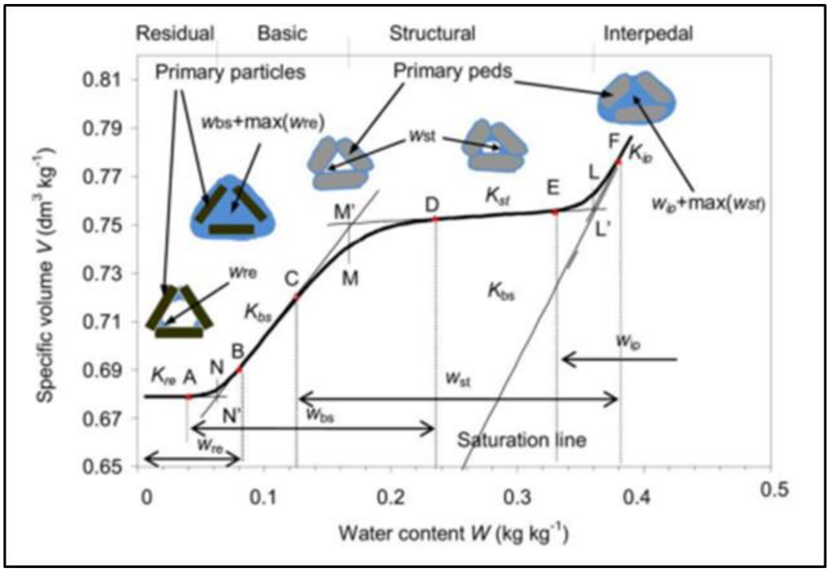


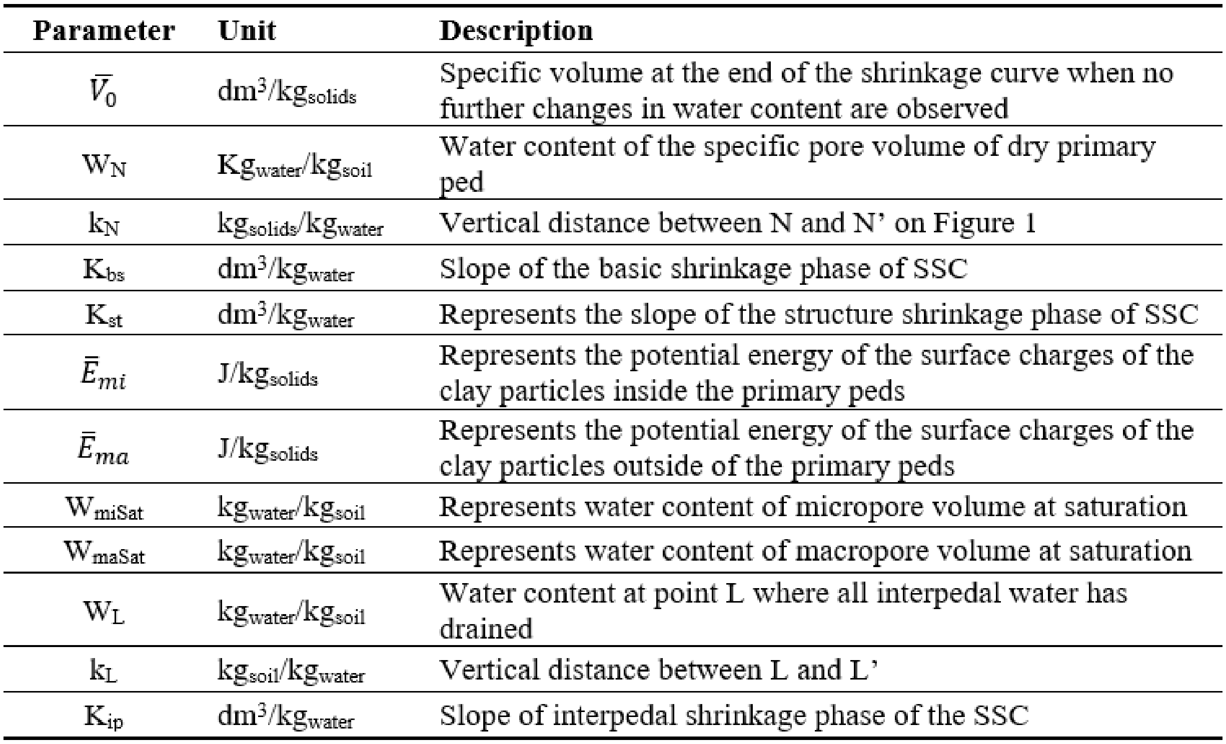
Figure 1. Soil shrinkage curve with transition points (Reprinted from: Erik Braudeau, Assi, Boukcim, & Mohtar, 2014)

Primary peds can be described as the most basic aggregation of soil particles and cannot be divided into smaller peds, meaning they persist through wetting and drying cycles. The interpedal phase is comprised of water held in between primary peds and is mostly controlled by gravitational forces. Structural water is also held outside of the primary peds; however, the soil water interaction in this phase is mostly defined by adhesion forces. Together, the structural and interpedal water make up what will be referred to as the macropore region, or “macro” water. The basic water pool is held within the primary peds and has a high potential for shrinkage. Lastly, the residual water is what is left after all the accessible water has disappeared and the volume of the soil core remains constant. The residual and basic water pools make up what will be referred to as the “micro” water and are controlled by capillary action from adhesive properties within the primary peds.

The positions labeled A, B,…, F in Figure 1 correspond to water contents at transitions points where configuration of the structure begins to change. For example, point D is when the primary peds begin to shrink and point B is the point at which air starts to enter the primary peds

(E. Braudeau, Sene, & Mohtar, 2005). There are 12 parameters mentioned by Assi, Accola, Hovhannissian, Mohtar, & Braudeau (2014) that characterize the water retention curve and the soil shrinkage curve. The parameters along with their definitions are listed below in Table 1.

Table 1. Description of 12 hydrostructural parameters



Parameter	Unit	Description
$\bar{V}_0$	dm^3/kg_{solids}	Specific volume at the end of the shrinkage curve when no further changes in water content are observed
W_N	Kg_{water}/kg_{soil}	Water content of the specific pore volume of dry primary ped
k_N	kg_{solids}/kg_{water}	Vertical distance between N and N’ on Figure 1
K_{bs}	dm^3/kg_{water}	Slope of the basic shrinkage phase of SSC
K_{st}	dm^3/kg_{water}	Represents the slope of the structure shrinkage phase of SSC
$\bar{E}_{mi}$	J/kg_{solids}	Represents the potential energy of the surface charges of the clay particles inside the primary peds
$\bar{E}_{ma}$	J/kg_{solids}	Represents the potential energy of the surface charges of the clay particles outside of the primary peds
W_{miSat}	kg_{water}/kg_{soil}	Represents water content of micropore volume at saturation
W_{maSat}	kg_{water}/kg_{soil}	Represents water content of macropore volume at saturation
W_L	kg_{water}/kg_{soil}	Water content at point L where all interpedal water has drained
k_L	kg_{soil}/kg_{water}	Vertical distance between L and L’
K_{ip}	dm^3/kg_{water}	Slope of interpedal shrinkage phase of the SSC

The parameters lead into the derivation of equation (3) for the SSC as described in E. Braudeau et al. (2014).

$$\bar{V} = \bar{V_0} + K_{bs}w_{bs}^{eq} + K_{st}w_{st}^{eq} + K_{ip}w_{ip} \quad (3)$$

Where $\bar{V_0}$ is the specific volume of sample at end of residual phase (dm^3/kg_{soil}), K_{bs}, K_{st}, and K_{ip} are the slopes at inflection points of measured shrinkage curve at the basic, structural, and interpedal linear shrinkage phases, respectively (dm^3/kg_{water}), and w_{bs}, w_{st}, and w_{ip} are the water pools associated with linear shrinkage phases of pedostructure (kg_{water}/kg_{soil}) and are defined below by equations (4) through (6).

$$w_{bs}^{eq} = W_{mi}^{eq} - w_{re} = \frac{1}{k_N} \ln\left[1 + exp\left(k_N\left(W_{mi}^{eq} - W_{miN}^{eq}\right)\right)\right] \tag{4}$$

$$w_{st} = W_{ma}^{eq} = W - W_{mi}^{eq} \tag{5}$$

$$w_{ip} = \frac{1}{k_L} \ln\left[1 + exp\left(k_L(W - W_L)\right)\right] \tag{6}$$

Where W_{mi}^{eq} is the micropore water content inside the primary peds (kg_{water}/kg_{soil}) calculated by equation (7), W_{ma}^{eq} is the macropore water content outside the primary peds (kg_{water}/kg_{soil}) calculated by equation (8), W is the total pedostructure water content (kg_{water}/kg_{soil}), and W_{miN}^{eq} is the micropore water content calculated by equation (7) using W_N instead of W. Equations (7) and (8) below define the Pedostructure micro and macro pore water contents at equilibrium.

$$W_{ma}^{eq} = \frac{\left(W + \frac{\bar{E}}{A}\right) + \sqrt{\left(W + \frac{\bar{E}}{A}\right)^2 - \left(4\frac{\overline{E_{ma}}}{A}W\right)}}{2} \tag{7}$$

and

$$W_{mi}^{eq} = W - W_{ma}^{eq} = \frac{\left(W - \frac{\bar{E}}{A}\right) - \sqrt{\left(W + \frac{\bar{E}}{A}\right)^2 - \left(4\frac{\overline{E_{ma}}}{A}W\right)}}{2} \tag{8}$$

Where, A is a constant calculated by $A = \frac{\bar{E}_{ma}}{W_{maSat}} - \frac{\bar{E}_{mi}}{W_{miSat}}$, $\bar{E} = \bar{E}_{mi} + \bar{E}_{ma}$, and W_{miSat} and W_{maSat} are the micro and macro water content at saturation such that $W_{Sat} = W_{miSat} + W_{maSat}$.

Once the shrinkage curve has been defined, many parameters and hydrostructural characteristics can be determined. Field capacity and permanent wilting point can be connected to transitional phases on the shrinkage curve. Field capacity can be defined as the water content at point D (Figure 1), where a rapid decrease in water suction as moisture content decreases begins to occur. As previously mentioned, point B on the curve indicates air entry into the micropores, which corresponds to a capillarity break. Point B also corresponds to the location on the residual water content curve where the largest change occurs. The result being that water cannot move to reach the roots, meaning permanent wilting point can be estimated by point B (E. Braudeau et al., 2005). Once the field capacity and permanent wilting point have been determined, the available water can be approximated as follows:

$$AW = \frac{1}{\rho_w}\left(\frac{W_D}{V_D} - \frac{W_B}{V_B}\right) \tag{9}$$

Where, W_D is the water content at point D in Figure 1 (kg_{water}/kg_{soil}), W_B is the water content at point B in Figure 1 (kg_{water}/kg_{soil}), ρ_W is the bulk density of water at 1 kg/dm^3, and V_D and V_B are the specific volumes at point D and B in Figure 1 (dm^3/kg_{soil}).

2. METHODS

2.1 Site Description

This study is located at the Southwest Regional Dairy Center in Stephenville, Texas where a closed-loop concept of waste management is applied. The cows are housed in pens where water washes solid and liquid waste into a pit at the end of the building. As the waste travels through the pit, the solids are separated from the liquid waste. The liquid waste continues on to a set of two lagoons where settling and natural biological treatment occurs. The water in the second lagoon is still of poor quality and is high in COD and PO_4^{3-}, which can cause nutrient buildup when reused as wash water.

The solid manure, depending on plant nutrient requirements, is applied to the land as a fertilizer. Some fields receive treated wastewater irrigation from the second lagoon. Figure 2 shows the waste stream of the dairy farm with New Kirk West and Field 1B being the locations of soil sampling. The fields receiving dairy effluent or manure are under perennial crops, mostly Tifton 84 or Coastal Bermudagrass, the implications being that tillage is minimal. Application amount and frequency of manure application and wastewater irrigation have varied over the last few years and can be seen in Appendix A. Lastly, according to the National Oceanic and Atmospheric Administration, the average annual precipitation in Stephenville, Texas is about 32 inches with about a third of the rain occurring in the spring and the average annual temperature is 63.7˚F.

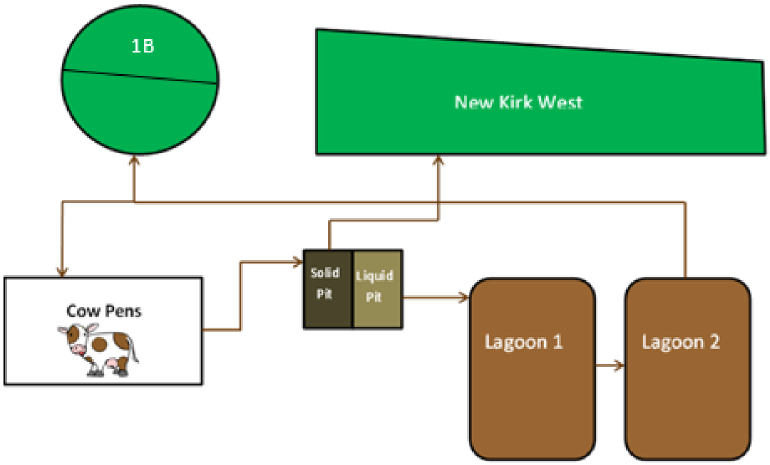


Figure 2. Waste stream for the Southwest Regional Dairy Center

2.2 Soil Sampling

The soil sampling locations were chosen based on Figure 3 to ensure that the samples were taken from the same soil series and at the same location on the hillslope. Six sampling locations were chosen, two for the control (no waste application), two for solid manure application, and two for wastewater application.

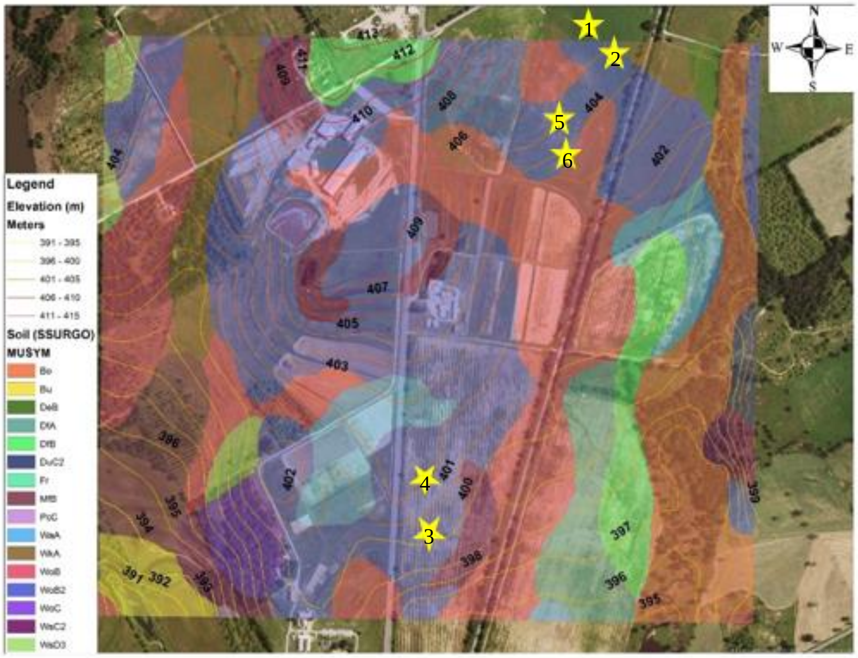


Figure 3. Elevation changes and soil series at the dairy farm (USDA NRCS, 2017 & Jordan Muell)

The samples were taken from the WoB2 soil series, Windthorst fine sandy loam. The WoB2 series are moderately well drained soils with an A horizon of 0 to 3 cm of fine sandy loam and a B_{t1} horizon from 3 cm to 28 cm of sandy clay (USDA NRCS, 2017). Table 2 shows the different soil types and associated treatments. Soil cores 5 cm in diameter and 5 cm in height were taken using cylindrical metal sampling rings and a hand sampler. To prevent swelling of the sample, the soil was saturated before taking the sample core by slowly pouring water over the ground as to avoid disturbing the soil surface. A thin coat of Vaseline was used on the inside of the metal cylinders to allow the soil to be taken out without destruction of the core. Samples were taken directly from the top layer of soil for the A horizon. After all four samples were taken, 7 to 10 cm of soil was dug out before taking four samples to represent the B horizon. Plastic lids sealed the core on both ends. At each of the six sample locations shown above, 8 soil cores were taken, 4 from the A horizon and 4 from the B_{t1} horizon.

Table 2. Soil type and treatment

Horizon	Soil Type	Treatment	Sites	Replicates
A	Fine Sandy Loam	Control	1, 2	8
		Manure	3, 4	8
		Wastewater	5, 6	8
B	Sandy Clay	Control	1, 2	8
		Manure	3, 4	8
		Wastewater	5, 6	8

The methods used for preparing the undisturbed soil cores for the TypoSoil machine follow the same methods as described by Assi et al. (2014) . The soil cores were placed on a sand box bath for saturation to occur through capillary wetting. The support platform and tensiometers were prepared using degassed water so they will be free from air bubbles. Saturated soil cores were placed on the support platforms that contain pressure gages and the tensiometers were carefully inserted to the middle of the core, as seen in Figure 4. The orange plastic was placed on top so the laser that measures height could read it better. Data recorded by the TypoSoil machine includes the height, diameter, mass, and the pressure within the soil of each core every 8 minutes to obtain semi-continuous soil shrinkage curves and water retention curves.

Figure 4. Soil core prepared for the TypoSoil machine

2.3 Data Analysis

2.3.1 Extracting Parameters

The estimation of hydrostructural parameters was carried out using equations (3) through (6) for the SSC and an optimization technique in Excel described by Assi et al. (2014) to minimize the sum of square errors. First, the shrinkage curve was fit by fixing V_0 based on measured data. The micropore region of the curve was fit, first by fixing W_{miN}, which can be found from measured data and then optimizing $k_N/100$, K_{bs}, F (-E/A), and 100*D. Next, the whole SSC is optimized by fixing W_L (if applicable) and changing k_L, K_{st}, $K_{ip,}$ F, and 100*D to minimize the sum of square errors. The values for F, 100*D and W_L were then transferred to the WRC and the curve was optimized by adjusting E_{mi}, k_L, C_{te} h_{ip}, and W_{ip0}. By fitting curves to the measured shrinkage data and water retention data, all of the characteristic parameters can be obtained.

2.3.2 Calculating Available Water

As previously mentioned, field capacity is defined as the water content where a rapid decrease in water suction as moisture content decreases begins to occur in the micropore domain. Therefore, the measured curve and defining equation for micropore water content can be used to find field capacity by calculating where the maximum change in slope occurs. Permanent wilting point was discussed as being the point at which air enters the micropores and mostly residual water is left. This point can be found by using the measured curve for residual water and finding the point at which the maximum change of slope occurs. Lastly, available water is the difference in water content at those two points. This method for calculating available water is described in detail by Assi, A., Braudeau, E., Mohtar, R. (2018). Available water can also be approximated by Equation 9, as described previously.

2.3.3 Statistical Analysis

Once all of the parameters and hydrostructural properties of each sample were determined using the optimization technique discussed above, indicator parameters were chosen to conduct an analysis in determining the statistical significance of the difference between the sample locations and the sample treatments. To indicate the variance or similarity in soil by sample location, a two-sample t-test was conducted on each parameter between three samples of Site 1 and three samples of Site 2 for each treatment of A horizon and B horizon. First an F test was conducted to determine whether or not the sample sets had statistically equal variances. The results of the F test determined the type of t-test to be conducted (assuming equal variance or assuming unequal variance). The two-tail probability value given was compared to α, confidence level, to determine whether or not the means of each sample set were significantly different from each other.

For analysis between the different treatments (i.e. control, manure applied, wastewater) a paired t-test to compare the means of two sample sets was utilized. A paired t-test was used based on the assumption that the soil being tested is the same soil type and is being evaluated pre- and post-treatment. The test was conducted on available water as an indicator of water holding capacity and K_{bs} as an indicator of micropore soil aggregate structure. The one tailed probability value given from the paired t-test was compared to the confidence level to determine whether or not the mean of the treatment parameter was significantly greater than or less than that of the control.

3. RESULTS

3.1 Hydrostructural Characterization

Extracting the hydro-structural parameters was done by adjusting the measured WRC and ShC with the thermodynamic equations of these two curves. The extracted hydro-structural parameters can be divided into two parts: (1) characteristic parameters of the soil aggregates structure: the shrinkage limit specific volume ($\bar{V}_0$); the slopes of the shrinkage phases of shrinkage curve (K_{bs}, K_{st}, K_{ip}), and the shrinkage amplitude ($\Delta ShC = \bar{V}_{Sat} - \bar{V}_0$); (2) characteristic parameters of the soil-water holding properties: the micro-pore waters (W_{miN}, W_{miSat}); macro-pore water (W_{maSat}); saturated water content (W_{Sat}); and the permanent wilting point (W_{PWP}), field capacity (W_{FC}) and the available water (AW).

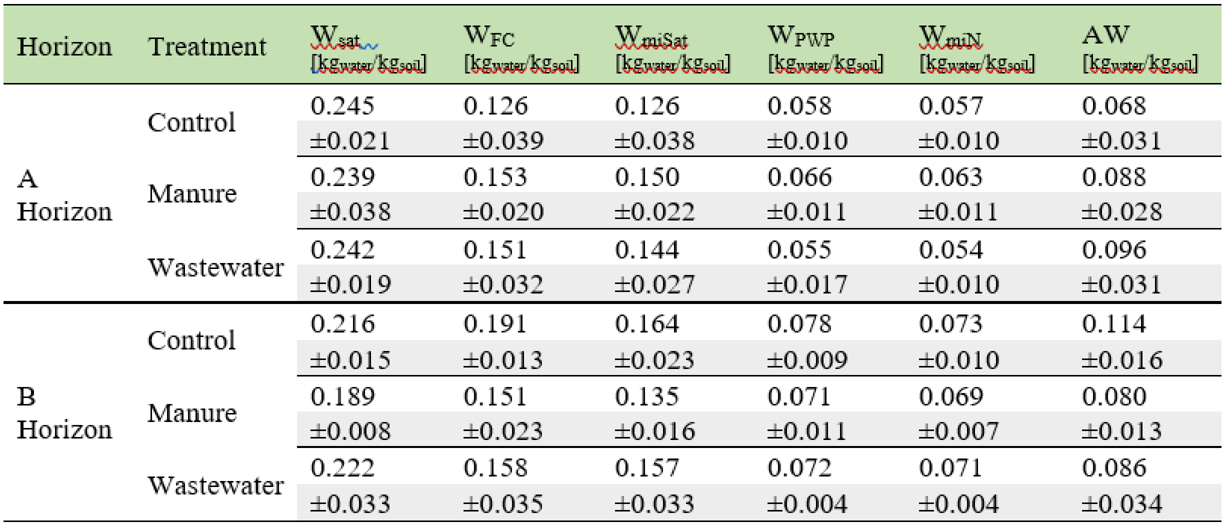
The values displayed in Table 2 represent the mean of six samples between two locations for each treatment. Two parameters were selected to study the changes in the soil aggregates structure within each treatment group and among the groups. Shrinkage amplitude (ΔShC) was chosen to give insight into the total shrinkage of the soil core as a whole, and K_{bs} was chosen to understand how the micro aggregates structure was affected with the treatments (manure application and wastewater application compared with the control).

Table 3. Mean values and standard deviation of two shrinkage parameters for each of the treatments

Horizon	Treatment	ΔShC [dm^3/kg_{soil}]	K_{bs} [dm^3/kg_{water}]
A Horizon	Control	0.042 ± 0.021	0.400 ± 0.051
	Manure	0.043 ± 0.012	0.322 ± 0.053
	Wastewater	0.038 ± 0.009	0.282 ± 0.042
B Horizon	Control	0.043 ± 0.004	0.400 ± 0.042
	Manure	0.053 ± 0.019	0.642 ± 0.220
	Wastewater	0.065 ± 0.009	0.470 ± 0.175

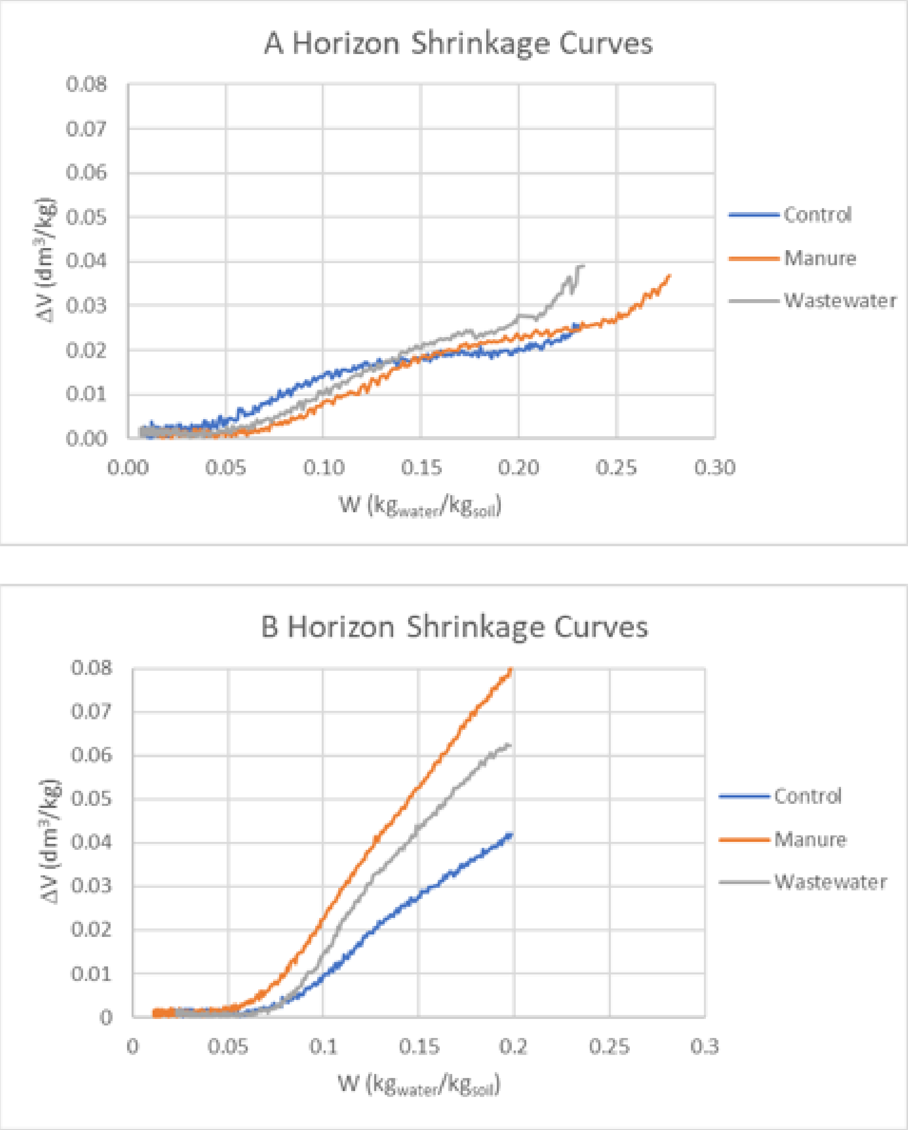
Although the shrinkage amplitude (ΔShC) did not change much overall in the A horizon, K_{bs} has declined for both manure and wastewater application when compared to the control value. Since plant available water mostly comes from the water held in the micropores, from this result alone, one might assume that the plant available water has also decreased. However, in the A horizon manure application and wastewater have improved available water when compared to the control (Table 3). This tells us that the characteristic parameters of the soil aggregates structure are not able alone to explain the observed changes. However, the changes in the potential energies of the surface charges on the clay and organic matter can play a significant role in explaining the observed changes in the soil water holding properties.

Table 4. Mean values and standard deviation for soil-water holding properties



Horizon	Treatment	W_{sat} [kg_{water}/kg_{soil}]	W_{FC} [kg_{water}/kg_{soil}]	W_{miSat} [kg_{water}/kg_{soil}]	W_{PWP} [kg_{water}/kg_{soil}]	W_{miN} [kg_{water}/kg_{soil}]	AW [kg_{water}/kg_{soil}]
A Horizon	Control	0.245	0.126	0.126	0.058	0.057	0.068
		±0.021	±0.039	±0.038	±0.010	±0.010	±0.031
	Manure	0.239	0.153	0.150	0.066	0.063	0.088
		±0.038	±0.020	±0.022	±0.011	±0.011	±0.028
	Wastewater	0.242	0.151	0.144	0.055	0.054	0.096
		±0.019	±0.032	±0.027	±0.017	±0.010	±0.031
B Horizon	Control	0.216	0.191	0.164	0.078	0.073	0.114
		±0.015	±0.013	±0.023	±0.009	±0.010	±0.016
	Manure	0.189	0.151	0.135	0.071	0.069	0.080
		±0.008	±0.023	±0.016	±0.011	±0.007	±0.013
	Wastewater	0.222	0.158	0.157	0.072	0.071	0.086
		±0.033	±0.035	±0.033	±0.004	±0.004	±0.034

As described in the Pedostructure method, AW is the difference between field capacity and permanent wilting point. Something to be noted is the similarity between field capacity and saturated micropore water content (W_{miSat}), and between permanent wilting point and the water content where only residual water remains (W_{miN}). This shows that W_{miSat} and W_{miN} are good indicators of field capacity and permanent wilting point, respectively. Table 3 shows that the both the manure and wastewater applications had little to no significant effect on permanent wilting point, thus much of the improvement in available water content can be attributed to the increase in the field capacity. Therefore, although K_{bs} was reduced, the curve was elongated along the water content axis allowing for a higher value of field capacity. The differences in the shrinkage curves for each treatment in both A horizon and B horizon can be seen by a representative sample in Figure 5(a) and 5(b), respectively. Each sample was chosen as a representative based on its proximity to the average value for most of the parameters.


a)

b)

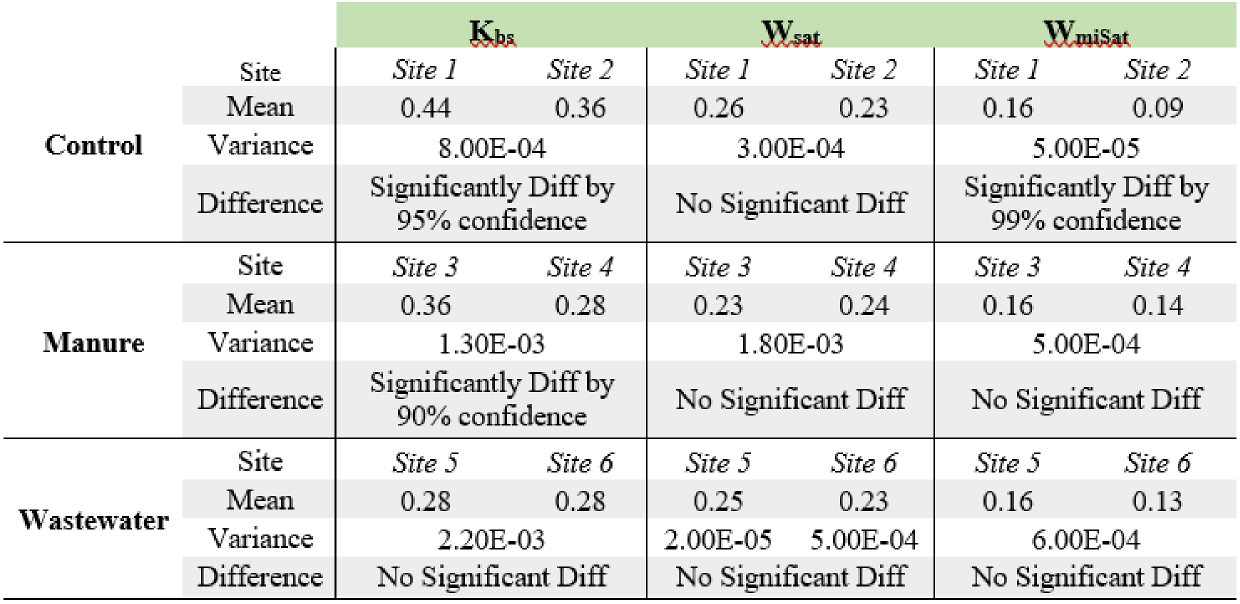
Figure 5. Shrinkage curve of a representative sample from control, manure application, and wastewater

Interestingly enough, the manure and wastewater application had the opposite effect on the sandy clay soil of the B horizon. The value for K_{bs} increased from control to wastewater to manure application while AW decreased from control to wastewater and manure application. According to Table 3, it appears again as though the changes in available water are connected to the changes in field capacity.

3.2 Variation in Soil Characteristics between Sites

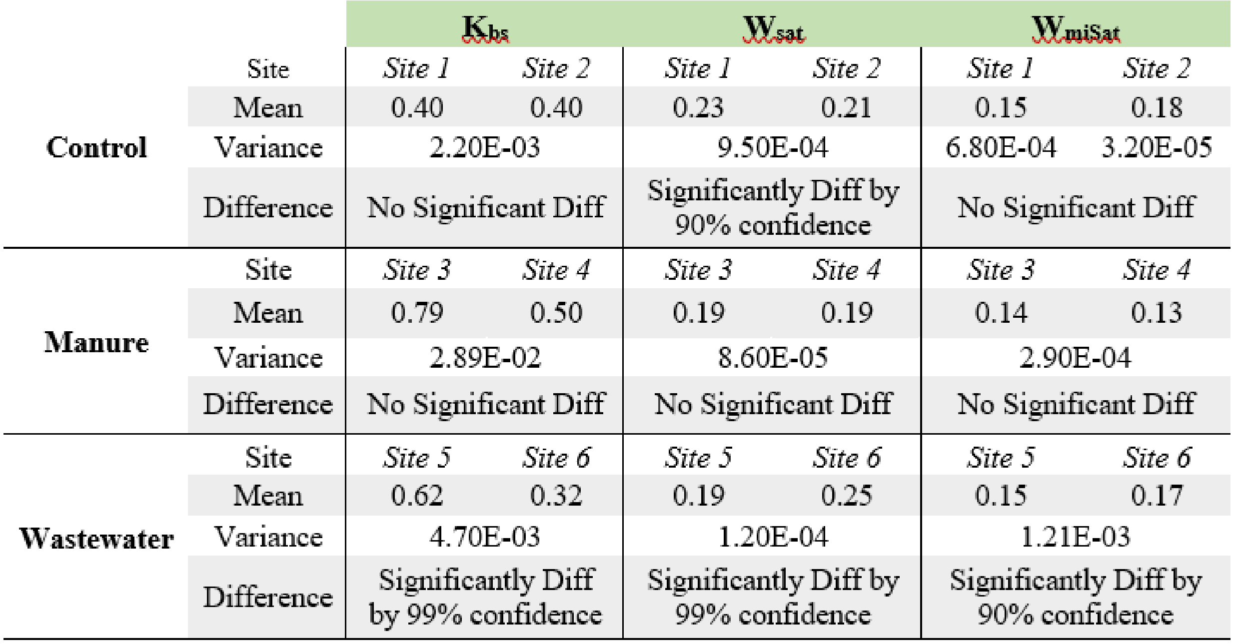
As can be seen in Tables 3 and 4, variability can be high among soil samples within each horizon and treatment. The complete data set of 10 different parameters for each sample analyzed can be found in Appendix B. To determine whether or not the variance differs greatly among the same soil type and treatment a two-sample t-test was performed between each sample location within the treatment. The summary of results showing significant differences between each of the means for three parameters can be seen in Tables 5 (A Horizon) and 6 (B Horizon) below.

Table 5. Statistically significant differences between the means of K_{bs}, W_{Sat}, and W_{miSat}t from each sample location in the A Horizon



		K_{bs}		W_{sat}		W_{miSat}	
Control	Site	*Site 1*	*Site 2*	*Site 1*	*Site 2*	*Site 1*	*Site 2*
	Mean	0.44	0.36	0.26	0.23	0.16	0.09
	Variance	8.00E-04		3.00E-04		5.00E-05	
	Difference	Significantly Diff by 95% confidence		No Significant Diff		Significantly Diff by 99% confidence	
Manure	Site	*Site 3*	*Site 4*	*Site 3*	*Site 4*	*Site 3*	*Site 4*
	Mean	0.36	0.28	0.23	0.24	0.16	0.14
	Variance	1.30E-03		1.80E-03		5.00E-04	
	Difference	Significantly Diff by 90% confidence		No Significant Diff		No Significant Diff	
Wastewater	Site	*Site 5*	*Site 6*	*Site 5*	*Site 6*	*Site 5*	*Site 6*
	Mean	0.28	0.28	0.25	0.23	0.16	0.13
	Variance	2.20E-03		2.00E-05	5.00E-04	6.00E-04	
	Difference	No Significant Diff		No Significant Diff		No Significant Diff	

Table 6. Statistically significant differences between the means of K_{bs}, W_{Sat}, and W_{miSat} from each sample location in the B Horizon



		K_{bs}		W_{sat}		W_{miSat}	
Control	Site	*Site 1*	*Site 2*	*Site 1*	*Site 2*	*Site 1*	*Site 2*
	Mean	0.40	0.40	0.23	0.21	0.15	0.18
	Variance	2.20E-03		9.50E-04		6.80E-04	3.20E-05
	Difference	No Significant Diff		Significantly Diff by 90% confidence		No Significant Diff	
Manure	Site	*Site 3*	*Site 4*	*Site 3*	*Site 4*	*Site 3*	*Site 4*
	Mean	0.79	0.50	0.19	0.19	0.14	0.13
	Variance	2.89E-02		8.60E-05		2.90E-04	
	Difference	No Significant Diff		No Significant Diff		No Significant Diff	
Wastewater	Site	*Site 5*	*Site 6*	*Site 5*	*Site 6*	*Site 5*	*Site 6*
	Mean	0.62	0.32	0.19	0.25	0.15	0.17
	Variance	4.70E-03		1.20E-04		1.21E-03	
	Difference	Significantly Diff by 99% confidence		Significantly Diff by 99% confidence		Significantly Diff by 90% confidence	

Three parameters were chosen to test for significant differences between the locations. K_{bs} is the slope of the basic portion of the shrinkage curve and was chosen as a parameter to reflect micro aggregate structure. W_{miSat} is the saturated water content of the micropore domain, which is important in calculations of AW. Lastly, waste application also has the potential to affect the macropore domain, thus W_{Sat} was chosen to represent total water holding capacity.

As can be seen by Tables 5 and 6 above, the variance between the two field sites of the same treatment can potentially be very high. Within the A horizon, control there is a significant difference of micropore parameters, K_{bs} and W_{miSat}. Interestingly, the B horizon control samples (taken from the same sites as A horizon control) do not significantly vary. Whereas the two wastewater sites differ greatly within the B horizon and not at all within the A horizon.

3.3 Discussion

The high variability between locations within the same field display the need for a better understanding of the dynamic soil properties, within the same field of same soil texture, and how management practices can affect soil properties. On top of the variability among soil samples, different waste applications affect the various hydro-structural properties in different ways. The statistical significance between the average values of indicative parameters can be seen in Table 7.

Table 7. Significant differences between means of parameters between control and treated soils

		Shrinkage Properties		*Soil-water Holding Properties*			
Horizon	Treatment	ΔShC $[dm^3/kg_{soil}]$	K_{bs} $[dm^3/kg_{water}]$	W_{sat}	FC	PWP	AW
A Horizon	Control	0.042	0.400	0.245	0.126	0.058	0.068
	Manure	0.043	0.322^{***}	0.239	0.153^{*}	0.066	0.088^{*}
	Wastewater	0.038	0.282^{***}	0.242	0.151^{*}	0.055	0.096^{***}
B Horizon	Control	0.043	0.400	0.216	0.191	0.078	0.114
	Manure	0.053	0.642^{**}	0.189^{***}	0.151^{**}	0.071	0.080^{**}
	Wastewater	0.065^{***}	0.470	0.222	0.158^{**}	0.072	0.086^{*}

Significantly greater or less by a *** 99% confidence ** 95% confidence *90% confidence level

There was not much significant difference among the overall change in specific volume of the whole shrinkage curve; however, wastewater application seems to have had a significant effect on the total shrinkage in the B horizon. The parameters most affected by waste application are K_{bs} and field capacity. Interestingly, K_{bs} and field capacity unexpectedly have a negative correlation and opposite effect between the horizons in this case. Compared to the control, K_{bs} has decreased by almost 20 and 30 percent for manure and wastewater application while field capacity increased by about 20 percent for both treatments in the A horizon. The increase in field capacity is considered the most direct cause for the increase in AW, as permanent wilting point has no significant changes between treatments.

For B horizon, the effect on K_{bs} and field capacity was the opposite. There was an increase between control and wastewater, although not significant enough due to the high variance between sites. However, the 60 percent increase in K_{bs} from control to manure was significant to a 95 percent confidence interval. While K_{bs} was increased, field capacity was reduced by about 21 and 17 percent for manure and wastewater application, respectively. The difference in how the waste application affects the A and B horizon shows how treatment can affect different soil types in different ways. The sandy loam of the A horizon responded with an increase in plant available water while the sandy clay of the B horizon responded oppositely. The difference in reactions to the waste applications can possibly be attributed to the difference in chemical and physical compositions between the two soil textures. The chemical component of soil will play a huge role in how tightly water is held onto by the soil. Clay soils tend to hold onto water more tightly than sandy soils, which allow water to flow through more easily. The addition of manure and wastewater seems to have a better hold on water than sandy soil, since an improvement was detected, whereas it might not hold on to water as well as clayey soils, since a deterioration of available water was detected.

4. CONCLUSION

The goal of this study was to gain an increased understanding into how soil responds to waste management practices. By using methods of hydrostructural pedology, physically measured soil shrinkage curves were used to extract parameters relating to the micro aggregate structure and water holding capabilities of the soil. Results illustrate a couple key points: 1) there is high variability within fields of the same soil type and treatment and 2) different waste applications affect soil properties differently. For the two soils studied here, most of the effects of manure and wastewater application were seen in the micropore domain of the soil. There was a clear shift in micropore soil aggregation as shown by K_{bs} and a change in field capacity in most cases. Plant available water was increased in the A horizon with both manure application and even more so with wastewater. However, the sandy clay of the B horizon showed a decrease in available water with both wastewater and manure application.

Implications of this study could include alteration of irrigation practices based on the changes in available water in the soil. As previously mentioned, the change in available water depends on both soil type and treatment. If changes in available water can be accurately estimated, a more precise amount of water can be added to the soil for optimal plant growth, thus minimizing the amount of water waste due to runoff or gravitational water. In the case of this study, approximately the same amount of water would be needed for irrigation as was used 5 years previous. Bermudagrass roots do most of their growing in the top 15 cm of soil. Since the plant available water increased in the A horizon, which is only 3 cm deep, but decreased in the B horizon, the effects of plant available water mostly cancel out.

Limitations of this study include inconsistent frequency and amount of manure and wastewater application and data from the farm only reaches back about 5 years, meaning that previous management of the field is unknown. High variance between sample locations within the same field make calculations less accurate. More than two sample locations for each field would give a better statistical description of soil in that field. Also, tillage and potentially crop type have an impact on soil make up and structure.

Future work should include testing different soil types to study how each type responds to waste application. Biological and chemical analysis of the soil would give more insight as to why the soil reacts the way it does to manure and wastewater application. This work would be a great addition to better understand the soil and its environment.

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APPENDIX A

Table A-1. Wastewater Application on Field 1B

Start Date	Inches/Acre	Lbs N/Acre	Lbs P2O5/Acre
10/6/2012	0.17	18.03	8.62
10/10/2010	0.29	31.55	15.08
10/15/2012	0.21	22.53	10.77
10/19/2012	0.25	27.04	12.92
11/16/2012	0.21	22.53	10.77
11/19/2012	0.21	22.53	10.77
12/13/2012	0.25	27.04	12.92
1/2/2013	0.25	24.21	9.08
1/3/2013	0.31	29.45	11.04
1/8/2013	0.22	20.94	7.85
1/14/2013	0.25	23.56	8.84
1/16/2013	0.27	25.52	9.57
1/18/2013	0.42	39.92	14.97
1/26/2013	0.43	41.23	15.46
1/28/2013	0.46	44.5	16.69
1/30/2013	0.42	39.92	14.97
2/14/2013	0.25	9.08	5.04
2/19/2013	0.32	11.53	6.41
3/1/2013	0.31	30.1	11.29
3/5/2013	0.14	13.74	5.15
3/6/2013	0.21	20.29	7.61
9/26/2013	0.54	28.01	17.23
9/30/2013	0.43	22.33	13.74
10/16/2013	0.09	4.61	2.84
10/17/2013	0.4	20.92	12.87
10/18/2013	0.05	2.84	1.75
10/28/2013	0.18	9.57	5.89
10/29/2013	0.24	12.41	7.64
11/8/2013	0.18	9.22	5.67
11/9/2013	0.25	12.76	7.85
11/12/2013	0.21	10.99	6.76
11/19/2013	0.25	13.12	8.07
11/29/2013	0.29	14.89	9.16
12/11/2013	0.28	14.53	8.94
12/19/2013	0.4	20.92	12.87
12/30/2013	0.3	15.6	9.6
1/7/2014	0.2	10.28	6.33

1/11/2014	0.2	10.28	6.33
1/21/2014	0.2	10.63	6.54
2/1/2014	0.19	9.93	6.11
4/10/2014	0.32	16.66	10.25
4/11/2014	0.22	11.34	6.98
7/7/2014	0.2	19.3	6.33
7/8/2014	0.19	18.63	6.11
12/5/2014	0.18	17.97	5.89
12/8/2014	0.24	23.29	7.64
12/10/2014	0.17	16.64	5.45
12/16/2014	0.03	3.33	1.09
12/17/2014	0.23	22.63	7.42
1/17/2015	0.45	44.11	14.46
1/18/2015	0.25	24.51	8.03
5/19/2015	0.03	1.48	0.65
5/20/2015	0.03	1.48	0.65
7/1/2015	0.45	26.62	11.72

Table A-2. Manure Application on New Kirk West

Date	tons/ac (dry)	lbs N/ac	lbs P2O5/ac
9/11/13	0.39	2.52	0.95
9/13/13	0.29	1.89	0.71
9/16/13	0.39	2.52	0.95
9/17/13	0.2	1.26	0.47
4/22/14	0.59	3.78	1.42
4/23/14	0.39	2.52	0.95
6/12/14	0.2	1.26	0.47
8/21/14	0.34	5.93	2.9
8/22/14	0.26	4.45	2.17
4/12/16	1.42	8.43	2.79
4/13/16	0.44	2.6	0.86
4/25/16	1.32	7.79	2.58
4/26/16	0.66	3.89	1.29
5/2/16	0.11	0.65	0.21
5/3/16	0.88	5.19	1.72
5/4/16	0.77	4.54	1.5
5/23/16	0.66	3.89	1.29
5/24/16	1.1	6.49	2.15
6/7/16	0.22	1.3	0.43
6/8/16	1.1	6.49	2.15
6/9/16	1.1	6.49	2.15

6/10/16	0.33	1.95	0.64
7/11/16	0.14	4.42	1.16
7/18/16	0.23	7.37	1.94
7/19/16	0.39	12.28	3.23
7/20/16	0.46	14.74	3.87
7/22/16	0.12	3.69	0.97
7/28/16	0.12	3.69	0.97
8/5/16	0.15	4.91	1.29
8/8/16	0.08	2.46	0.65
8/15/16	0.19	6.14	1.61
8/30/16	0.27	8.6	2.26
8/31/16	0.12	3.69	0.97
9/1/16	0.08	2.46	0.65
9/9/16	0.15	4.91	1.29
3/21/17	0.19	6.14	1.61
3/22/17	0.54	17.2	4.52
3/23/17	0.39	12.28	3.23
3/31/17	0.27	8.6	2.26
4/4/17	0.19	6.14	1.61
4/5/17	0.19	6.14	1.61
4/6/17	0.27	8.6	2.26
4/17/17	0.27	8.6	2.26
4/19/17	0.27	8.6	2.26
4/20/17	0.23	7.37	1.94
4/25/17	0.12	3.69	0.97
4/27/17	0.27	8.6	2.26
4/28/17	0.23	7.37	1.94
5/11/17	0.04	1.23	0.32
5/18/17	0.85	16.52	6.66
5/24/17	1.42	27.53	11.09
5/25/17	0.85	16.52	6.66
5/26/17	0.85	1.52	6.66
6/7/17	1.99	38.54	15.53
6/8/17	0.71	13.77	5.55
6/23/17	0.71	13.77	5.55
6/27/17	2.13	41.3	16.64
7/11/17	0.71	13.77	5.55
7/18/17	0.71	13.77	5.55
7/20/17	2.13	41.3	16.64
7/21/17	0.57	11.01	4.44
8/10/17	0.43	8.26	3.33

APPENDIX B

Table B-1. A Horizon parameter data:

		Shrinkage Properties				Soil-water Holding Properties					
	Sample ID	ΔShC [dm^3/kg_{soil}]	ρ_{fc}	ρ_{pwp}	K_{bs} [dm^3/kg_{water}]	W_{sat}	FC	W_{miSat}	PWP	W_{miN}	AW
					Control						
Site 1	A1	0.058	1.556	1.651	0.450	0.247	0.163	0.161	0.063	0.063	0.100
	A3	0.056	1.566	1.647	0.460	0.243	0.153	0.152	0.068	0.068	0.086
	A2	0.069	1.455	1.533	0.410	0.285	0.167	0.170	0.067	0.066	0.100
Site 2	A1	0.025	1.576	1.600	0.390	0.230	0.095	0.095	0.048	0.047	0.047
	A2	0.027	1.533	1.550	0.360	0.228	0.091	0.092	0.045	0.049	0.046
	A3	0.019	1.516	1.524	0.330	0.239	0.084	0.088	0.056	0.047	0.028
Avg		**0.042**	**1.534**	**1.584**	**0.400**	**0.245**	**0.126**	**0.126**	**0.058**	**0.057**	**0.068**
Std Dev		**0.021**	**0.044**	**0.057**	**0.051**	**0.021**	**0.039**	**0.038**	**0.010**	**0.010**	**0.031**
					Manure Applied						
Site 1	A2	0.056	1.611	1.682	0.370	0.249	0.151	0.149	0.062	0.057	0.089
	A3	0.046	1.606	1.674	0.400	0.241	0.133	0.132	0.057	0.054	0.076
	A1	0.046	1.543	1.642	0.310	0.214	0.191	0.191	0.049	0.049	0.143
Site 2	A1	0.025	1.630	1.675	0.290	0.186	0.150	0.146	0.077	0.077	0.073
	A3	0.052	1.502	1.537	0.300	0.300	0.151	0.151	0.074	0.069	0.077
	A2	0.031	1.516	1.547	0.260	0.244	0.143	0.133	0.075	0.069	0.068
Avg		**0.043**	**1.568**	**1.626**	**0.322**	**0.239**	**0.153**	**0.150**	**0.066**	**0.063**	**0.088**
Std Dev		**0.012**	**0.055**	**0.067**	**0.053**	**0.038**	**0.020**	**0.022**	**0.011**	**0.011**	**0.028**
					Wastewater Applied						
Site 1	A1	0.042	1.570	1.634	0.310	0.255	0.184	0.169	0.060	0.058	0.124
	A2	0.041	1.584	1.653	0.270	0.248	0.185	0.176	0.063	0.062	0.122
	A3	0.053	1.567	1.626	0.270	0.256	0.131	0.129	0.021	0.033	0.111
Site 2	A2	0.030	1.532	1.563	0.230	0.251	0.147	0.142	0.060	0.055	0.087
	A3	0.037	1.599	1.646	0.260	0.233	0.156	0.145	0.063	0.059	0.093
	A1	0.027	1.587	1.603	0.350	0.206	0.103	0.103	0.062	0.056	0.041
Avg		**0.038**	**1.573**	**1.621**	**0.282**	**0.242**	**0.151**	**0.144**	**0.055**	**0.054**	**0.096**
Std Dev		**0.009**	**0.023**	**0.033**	**0.042**	**0.019**	**0.032**	**0.027**	**0.017**	**0.010**	**0.031**

Table B-2. B Horizon parameter data:

		Shrinkage Properties				Soil-water Holding Properties					
	Sample ID	ΔShC [dm^3/kg_{soil}]	ρ_{fc}	ρ_{pwp}	K_{bs} [dm^3/kg_{water}]	W_{sat}	FC	W_{miSat}	PWP	W_{miN}	AW
					Control						
Site 1	B2	0.047	1.675	1.773	0.441	0.238	0.174	0.163	0.076	0.071	0.098
	B3	0.041	1.719	1.815	0.427	0.215	0.196	0.120	0.068	0.060	0.128
	B1	0.038	1.697	1.797	0.330	0.226	0.208	0.167	0.071	0.067	0.138
Site 2	B2	0.046	1.721	1.832	0.370	0.213	0.187	0.184	0.077	0.075	0.110
	B3	0.041	1.729	1.838	0.410	0.198	0.180	0.173	0.078	0.077	0.103
	B1	0.045	1.656	1.764	0.420	0.204	0.201	0.176	0.095	0.090	0.106
Avg		**0.043**	**1.699**	**1.803**	**0.400**	**0.216**	**0.191**	**0.164**	**0.078**	**0.073**	**0.114**
Std Dev		**0.004**	**0.029**	**0.031**	**0.042**	**0.015**	**0.013**	**0.023**	**0.009**	**0.010**	**0.016**
					Manure Applied						
Site 1	B1	0.060	1.725	1.883	0.770	0.184	0.147	0.144	0.068	0.068	0.079
	B2	0.080	1.755	1.930	0.720	0.200	0.160	0.157	0.072	0.071	0.087
	B3	0.068	1.776	1.913	0.870	0.189	0.116	0.116	0.057	0.060	0.059
Site 2	B2	0.045	1.730	1.827	0.760	0.195	0.176	0.118	0.084	0.077	0.092
	B3	0.033	1.943	2.037	0.360	0.192	0.174	0.141	0.083	0.077	0.091
	B1	0.033	1.799	1.871	0.371	0.176	0.134	0.134	0.064	0.062	0.073
Avg		**0.053**	**1.788**	**1.910**	**0.642**	**0.189**	**0.151**	**0.135**	**0.071**	**0.069**	**0.080**
Std Dev		**0.019**	**0.081**	**0.072**	**0.220**	**0.008**	**0.023**	**0.016**	**0.011**	**0.007**	**0.013**
					Wastewater Applied						
Site 1	B2	0.059	1.734	1.870	0.610	0.183	0.148	0.146	0.070	0.073	0.078
	B3	0.061	1.796	1.976	0.580	0.198	0.173	0.174	0.076	0.075	0.097
	B1	0.056	1.820	1.920	0.670	0.198	0.121	0.120	0.071	0.068	0.050
Site 2	B2	0.060	1.940	2.033	0.400	0.238	0.139	0.137	0.067	0.064	0.072
	B3	0.078	1.930	2.013	0.330	0.263	0.148	0.151	0.077	0.074	0.071
	B1	0.076	1.900	2.105	0.230	0.251	0.221	0.214	0.073	0.073	0.147
Avg		**0.065**	**1.853**	**1.986**	**0.470**	**0.222**	**0.158**	**0.157**	**0.072**	**0.071**	**0.086**
Std Dev		**0.009**	**0.083**	**0.083**	**0.175**	**0.033**	**0.035**	**0.033**	**0.004**	**0.004**	**0.034**