Impact of Dairy Wastewater Irrigation and Manure Application on Soil Structural and Water-Holding Properties

T. C. Pinkerton, A. T. Assi, V. A. Pappa, E. Kan, R. H. Mohtar

Highlights

- Quantitative evaluation was performed of dairy waste on soil water-holding capacity.
- Considering the soil variability on a farm is significant for management practices.
- Soil aggregate structure plays a pivotal role in studying the impact of waste reuse.

Abstract. *The livestock sector contributes about 40% of global agricultural output and uses over 30% of total feed-crop land. The sector's continuing growth has led to increased technology and larger-scale, commercialized agriculture, and it correlates to growth in by-products and waste, which can compromise the environment and human health. Although organic manure is an excellent soil fertilizer whose nutrient content increases crop yield, untreated and/or overapplied manure pollutes local water resources and can alter soil aggregate structure, potentially affecting soil health and available water. Proper livestock waste management is essential for sustainable food production. Waste reuse strategies exist, with goals such as minimizing freshwater consumption, improving food production, and contributing to energy production, However, each strategy has tradeoffs in environmental, energy, or monetary costs. This study provides a quantitative approach to evaluating waste impact on soil health and helps to better manage irrigation practices and water supply gaps in arid and semi-arid areas by better understanding how management practices affect physical soil health. The TypoSoil apparatus was used to measure and analyze the hydrostructural parameters (water-holding capacity and soil structure) of fine sandy loam (A horizon) and sandy clay (B horizon). Soils from the Texas A&M AgriLife Research Dairy (Stephenville, Texas) were collected and compared with control (untouched) soils. Waste (manure, bedding materials, wash water) was separated into liquid (passed through a natural lagoon treatment process) and solid components (applied as fertilizer). Approximately half the wastewater was reused as wash water, the remainder for irrigation. Although the soil varied substantially between sample locations, a statistically significant difference existed between the control and manure/wastewater applications in both the A and B horizons. Both applications improved plant-available water (AW) in the A horizon (40% and 30%, respectively) but deteriorated AW in the B horizon (25% and 30%). Thus, dairy farm waste is a viable source for agricultural use.*

Keywords. *Available water capacity, Pedostructure, Soil health, Soil shrinkage curve, Soil water characteristic curve.*

A growing population leads to a direct increase in the demand for food, energy, and water supplies, each with its accompanying waste. These resources are interconnected: approximately 15% of the global freshwater supply is used for energy production, 80% to 90% for consumptive water use, and 30% of the world's energy is used to produce food (Mohtar, 2015). Sustainably meeting all of these demands requires the implementation of conservation strategies and reuse technologies across local and regional scales in a manner that minimizes negative impacts on the environment, economy, and society. 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, the industry leads the nation in cattle operations (USDA, 2017a). Each head of dairy cattle produces about 68 kg (150 lb) of manure and requires approximately 189 L (50 gal) of water daily for drinking, cooling, and washing (Safferman and Wallace, 2015).

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Dairy Waste Management Practices

As the average size of dairy herds increases, the need for proper waste management becomes even more important for the health of both the animals and the environment. A

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common management practice is to store the waste, including the water from milking facilities, as slurry in ponds or lagoons and then apply it to fields as fertilizer (Safferman and Wallace, 2015). Manure serves as a soil conditioner due to its high carbon and nitrogen content, along with other essential plant nutrients (Liu et al., 2016). Waste reuse techniques have potential to improve soil aggregation and water-holding properties (Fares et al., 2008), increase crop yield (Jing et al., 2016), produce energy (Cuéllar and Webber, 2008), and reduce irrigation demand (Liu and Haynes, 2011), all leading to decreased stress on freshwater use. However, reuse strategies may contaminate nearby water sources with bacteria or excessive nutrient concentrations if waste is over-applied (Cameron and MacLaren, 1997). 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 manure or find other uses for it (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 can be composted, anaerobically digested, used to create biochar, or a combination of these processes (Lorimor et al., 2006). Each waste management strategy is associated with different environmental, energy, and water footprints. This study promotes the safe use of wastewater for food production to reduce the stress on freshwater use in agriculture. This study focuses on the environmental impacts of raw manure used as a soil conditioner and wastewater used for irrigation, as indicated through soil hydrostructural properties and irrigation demand.

Soil Properties

Soil hydrostructural properties are heavily influenced by land use patterns and management practices (e.g., tillage, crop rotation, fertilizer application) (Shi et al., 2015). Plant-available water (AW) capacity is the soil property most relevant to agricultural irrigation demands: the more water available to plants in the soil, the healthier the soil. The amount of AW depends on two conditions, field capacity and permanent wilting point, which depend on soil and plant types. Field capacity is commonly accepted as the soil water content after excess water has drained by gravity, typically the soil water content at which the pressure within the soil is -33 kPa. Historically, permanent wilting point is defined at -1500 kPa, the soil water content at which plants can no longer extract water from the soil and wilt. Therefore, the AW 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 consider the thermodynamics and structure of the soil (Assi et al., 2019).

Changes in Soil Properties

Manure contains many of the elements required for plant growth, including organic matter, N, P, and K. Studies have shown that long-term application of cattle manure in fields improves soil organic carbon (Barkle et al., 2000). Changes in the organic carbon content of soil leads to changes in the soil's structure and adsorption properties, which in turn can alter water retention (Rawls et al., 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, influencing 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 was measured by saturating the soil and then using pressure extractors and volumetric bulk density (Blanco-Canqui et al., 2015). A 28-year study on a silt loam soil derived from loess showed evidence of organic manure application increasing the soil water retention by 3.2% to 10.8% depending on suction tension (Shi et al., 2015).

Many previous studies used pressure plate methods to measure the field capacity and water availability within the soil. However, those methods do not necessarily consider the soil aggregate structure as a key element in soil health, nor its relationship to water-holding capacity. Long-term fertilization can alter soil hydrostructural properties by modifying the soil aggregates and structure (Mamedov et al., 2014). The impact of organic fertilizers, such as manure, on aggregate stability may depend on soil type and pH. The soil aggregate structure and composition play a huge role in water retention due to the physical interaction between the water film at the surfaces of particles and aggregates and the soil structure itself (Braudeau and Mohtar, 2014). Recognizing the soil aggregate structure in quantifying soil water-holding properties was the main goal of Braudeau et al. (2004a, 2004b) in introducing the pedostructure concept. Pedostructure describes the assembly of soil particles (minerals "sand, silt, clay" and natural organic matter) into aggregates and also describes the way in which soil aggregates thermodynamically interact with water (Braudeau et al., 2014). The pedostructure concept was later used to measure important agronomic parameters, including field capacity, permanent wilting point, and available water (Assi et al., 2018).

Informed Waste Management

Informed waste management and irrigation decisions require more attention to the localized effects of manure and wastewater applications on physical soil health. The objective of this study is to quantify the impacts of dairy farm waste management practices, such as manure application and wastewater irrigation, on physical soil health, as reflected in soil properties (aggregate structure and AW). The in-field variability of soil parameters, such as soil texture, is also considered to provide a more in-depth understanding of the effects of dairy waste application on physical soil properties in fine sandy loam and sandy clay soils.

Theoretical Background: Pedostructure Concept

The pedostructure concept and its complementary concept, structural representative elementary volume (SREV), were introduced by Braudeau et al. (2004a) and Braudeau and Mohtar (2009). The pedostructure-SREV concept considers the soil aggregate structure and its thermodynamic interaction with water and air by delineating the representative soil volume as a fixed mass of solids belonging to a non-rigid structure. With this definition, all state variables and parameters in the pedostructure-SREV concept are referenced to a fixed mass of solids, and thus the change in soil specific volume is attributed to changes in the mass of water and the mass of air within the soil. The pedostructure concept makes use of the soil shrinkage curve to quantitatively characterize the soil aggregate structure. A pedostructure (fig. 1a), as defined by Braudeau et al. (2004a), consists of an assembly of primary peds, which are in turn an assembly of primary particles (minerals "sand, silt, clay" and organic matter). This soil hierarchal organization (aggregate structure or pedostructure) is unique to each soil type and each soil horizon. Moreover, it is highly affected by agro-environmental practices. Practically speaking, any physical changes in the soil medium will be reflected in its aggregate structure (pedostructure), not in its texture (percentages of sand, silt, and clay).

According to Braudeau et al. (2004a), the unique organization of each pedostructure is characterized by the different shrinkage phases in the soil shrinkage curve. Figure 1b illustrates the different shrinkage phases, starting from saturation (right). The interpedal shrinkage phase is comprised of water held between primary peds and is mostly controlled by gravitational and thermodynamic forces. Structural water, which corresponds to the structural shrinkage phase, is also held mostly outside of the primary peds. However, the soil water interaction in this phase is largely defined by adhesion forces (thermodynamic forces resulting from the surface charges of clay particles within). Together, the structural water and interpedal water comprise the macropore region, or "macro" water. The basic water pool, held within the primary peds, has a high potential for shrinkage. Residual water is what remains after all the accessible water has disappeared and the volume of the soil core remains constant. The residual and basic water pools comprise the "micro" water and are controlled by thermodynamic forces within the primary peds.

The parameters that characterize the natural organization of a pedostructure and its interaction with water are the hydrostructural parameters, which are physical parameters (fig. 1). A methodology for extracting these parameters was outlined by Assi et al. (2014) and is used in this study. The hydrostructural parameters are characteristics for thermodynamic equations developed by Braudeau et al. (2014) for the soil water retention curve (WRC) and soil shrinkage curve (ShC). According to Braudeau and Mohtar (2014), at the thermodynamic equilibrium between the two water pools, water retention inside and outside the primary peds is the same.

Accordingly, at the point of thermodynamic equilibrium, the soil suction measured with a tensiometer (h^{eq}) corresponds to both the soil suction inside the primary peds and the soil suction outside the primary peds. This implies the division of the pedostructure water content (W) into two water pools: gravimetric macropore water content "outside the

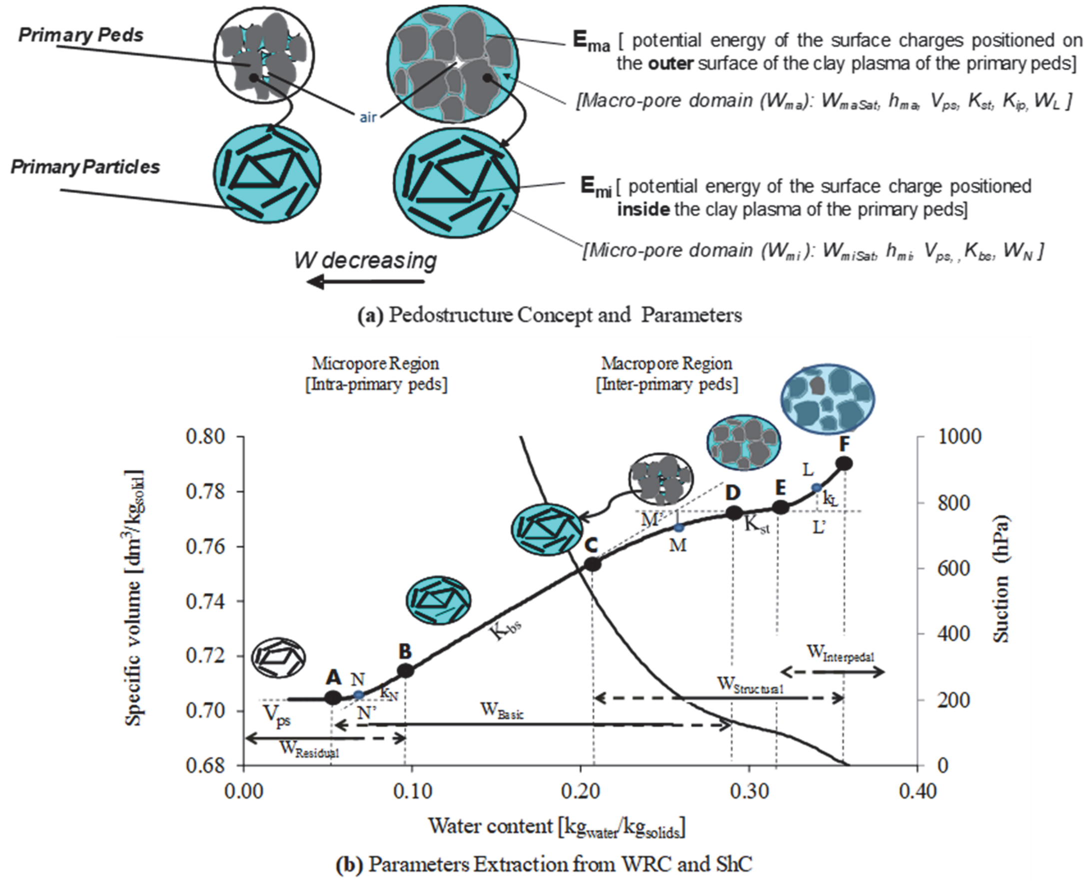


Figure 1. Pedostructure-SREV concept: (a) pedostructure and its hydrostructural parameters (assembly of primary peds forms a primary particle, and assembly of primary particles forms a pedostructure), and (b) delineating two water types of a pedostructure by soil shrinkage curve (ShC) and water retention curve (WRC). On the ShC, points A, N, B, C, M, D, E, L, and F are characteristic points of the water pools of different shrinkage phases: interpedal, structural, basic, and residual (modified from Braudeau et al., 2004a, and Assi et al., 2018).

primary peds" (W_{ma}, kg water kg^{-1} soil) and gravimetric micropore water content "inside the primary peds" (W_{mi}, kg water kg^{-1} soil). Braudeau et al. (2004a) described the derivation of the equation used for the soil shrinkage curve:

$$\bar{V} = \bar{V}_0 + K_{bs} w_{bs}^{eq} + K_{st} w_{st}^{eq} + K_{ip} w_{ip} \quad (1)$$

where $\bar{V}$ is the specific volume of the pedostructure (dm^3 kg^{-1} soil); $\bar{V}_0$ is the specific volume of the pedostructure at the end of the residual phase (dm^3 kg^{-1} soil); K_{bs}, K_{st}, and K_{ip} are the slopes of the shrinkage curve segments between the inflection points of the measured shrinkage curve and represents the basic, structural, and interpedal linear shrinkage phases, respectively (dm^3 kg^{-1} water); and w_{bs}, w_{st}, and w_{ip} are the water pools associated with the linear shrinkage phases of the pedostructure (kg water kg^{-1} soil) (fig. 1b). The values of the water pools associated with the basic shrinkage phase (w_{bs}), the structural shrinkage phase (w_{st}), and the interpedal shrinkage phase (w_{ip}) can be determined by equations also discussed by Braudeau et al. (2004a).

Materials and Methods

Site Description

This study site is the Southwest Regional Dairy Center, Stephenville, Texas, where a closed-loop concept of waste management is applied (fig. 2). Cows are housed in pens from which water washes solid and liquid waste into a pit at the end of the building (fig. 2b). As the waste travels through the pit, the solids are separated from the liquid waste, which continues to a set of two lagoons in which settling and natural biological treatment occur (fig. 3). The water in the second lagoon is still of poor quality and high in chemical oxygen demand (COD) and PO_4^{3-}, which can cause nutrient buildup when reused as wash water. Solid manure is applied to the land as a fertilizer in accordance with plant nutrient requirements. Some fields receive treated wastewater irrigation from the second lagoon.

Figure 3 shows the waste stream of the dairy farm, and figure 4 shows the elevation changes and soil series at the dairy farm and the locations of soil sampling (New Kirk West and Field 1B). The fields receiving dairy effluent or manure are under perennial crops, mostly Tifton 84 or

(a) (b)

Figure 2. Southern Regional Dairy Center, Stephenville, Texas: (a) location and (b) facilities at the center, as shown in figure 3.

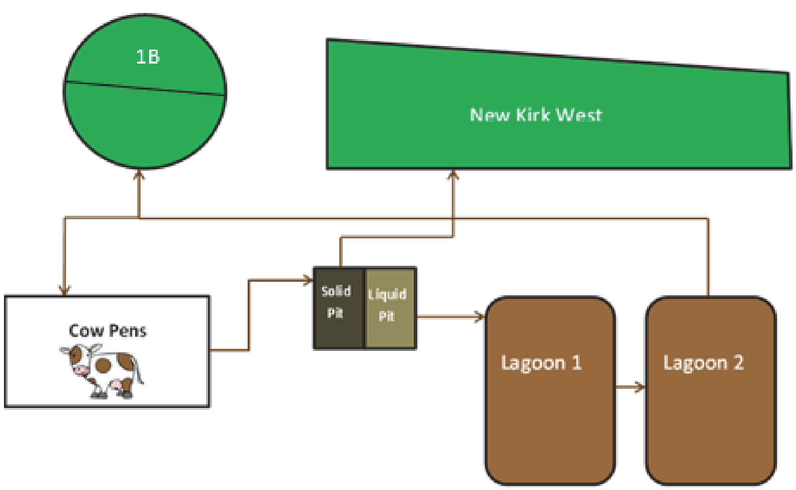


Figure 3. Waste stream schematic for the Southwest Regional Dairy Center. Agricultural fields 1B and New Kirk West are direct users of the dairy waste, and soil samples were taken from these fields.

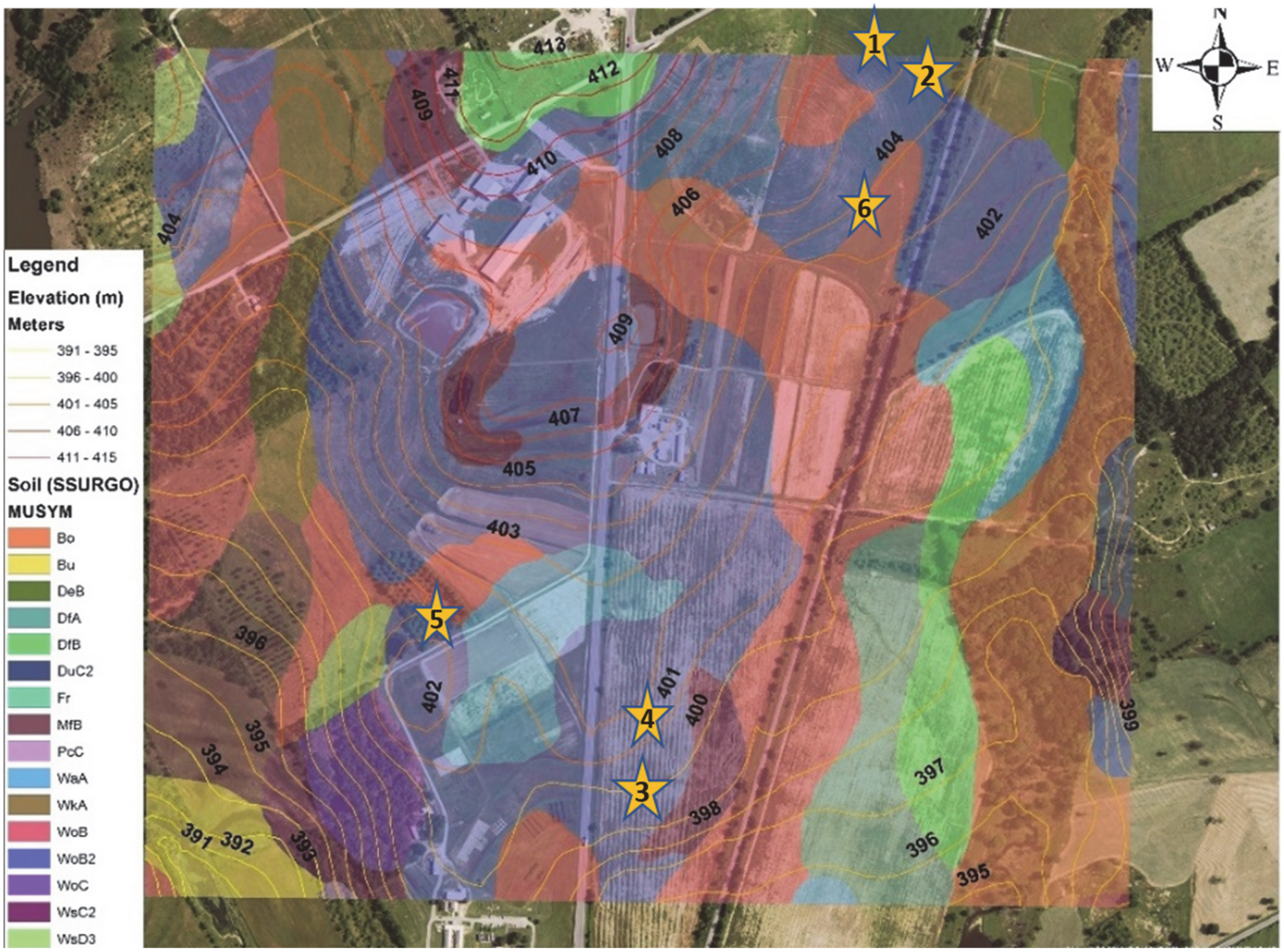


Figure 4. Elevation changes and soil series at the dairy farm. Soil sampling sites are indicated with stars. The numbers inside the stars indicate the site number and treatment type: control sites (1 and 2), manure application sites (3 and 4), and treated wastewater application sites (5 and 6) (USDA, 2017b).

Bermuda grass (*Cynodon dactylon*), implying that tillage is minimal. The amount and frequency of manure application and wastewater irrigation have varied over the last few years. According to the National Oceanic and Atmospheric Administration, the average annual precipitation in Stephenville, Texas, is about 819 mm (32 in.) (NOAA, 2021), with about a third of the rain occurring in the spring; the average annual temperature is 17.6°C (63.7°F).

Soil Sampling and Preparation

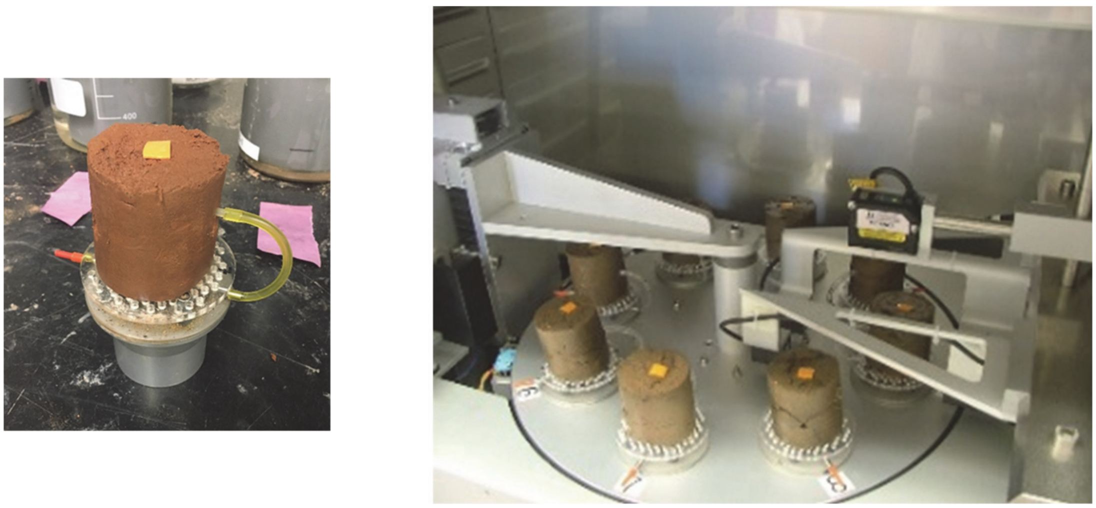
The soil sampling locations were chosen, based on figure 4, to ensure that samples were taken from the same soil series and at the same location on the hillslope. Six sampling locations were chosen, two for the control (no waste application), two for solid manure application, and two for wastewater application.

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 from 0 to 3 cm of fine sandy loam and a Bt1 horizon from 3 to 28 cm of sandy clay (USDA, 2017b). The different soil types and associated treatments are summarized in table 1. Soil cores of 5 cm diameter and 5 cm height were taken using cylindrical metal sampling rings and a hand sampler. Samples were taken directly from the top layer of soil for the A horizon. After the four A horizon samples were taken, a hole about 7 to 10 cm was dug before taking four samples to represent the B horizon. At each of the six sample locations indicated by stars in figure 4, eight soil cores were taken: four from the A horizon and four from the Bt1 horizon. Soil samples were also taken to determine the particle size distribution (percentages of sand, silt, and clay), as shown in table 1, using the pipette method (Miller and Miller, 1987).

The methods used for preparing the undisturbed soil cores for the TypoSoil apparatus (Valorhiz, Montpellier, France) followed the same methods described by Assi et al. (2014). The soil cores were placed on a sand box bath for saturation through capillary wetting. The support platform and tensiometers were prepared using degassed water, free from air bubbles. Saturated soil cores were placed on the support platforms containing pressure gauges, and tensiometers were carefully inserted into the middles of the cores (fig. 5a). Data recorded by the TypoSoil apparatus (fig. 5b) include the height, diameter, mass, and suction within the soil of each core at 8 min intervals. The measurements are then used to construct the soil water retention curve (WRC) and the soil shrinkage curve (ShC).

Table 1. Summary of soil samples in the study area.

Soil Horizon	USDA-NRCS Texture	Treatment	Site	No. of Replicates	Particle Size Distribution (%) Sand (2 to 0.05 mm)	Silt (0.05 to 0.002 mm)	Clay (<0.002 mm)	Texture Class
A	Fine sandy loam	Control	1	4	57.6	19.6	22.8	Sandy clay loam
			2	4	74.3	11.9	13.8	Silt loam
		Manure	3	4	57.1	20.3	22.6	Sandy clay loam
			4	4	73.1	10.4	16.5	Silt loam
		Wastewater	5	4	70.5	11.3	18.2	Silt loam
			6	4	76.4	8.7	14.9	Silt loam
B	Clay loam	Control	1	4	53.9	20.4	25.7	Sandy clay loam
			2	4	58.0	12.5	29.5	Sandy clay loam
		Manure	3	4	45.9	15.3	38.8	Silt loam
			4	4	62.1	11.5	26.4	Sandy clay loam
		Wastewater	5	4	60.8	11.6	27.6	Sandy clay loam
			6	4	73.6	8.4	18.0	Silt loam



(a) (b)

Figure 5. Soil hydrostructural characterization: (a) soil core prepared for the TypoSoil apparatus, and (b) TypoSoil apparatus for continuously and simultaneously measuring the soil shrinkage curve (ShC) and water retention curve (WRC).

Using the data collected from the TypoSoil apparatus and assuming isotropic radial shrinkage and uniform distribution of water content within the soil, the specific volume ($\bar{V}$) and specific water content ($\bar{W}$) of the sample were determined using equations 2 and 3:

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

where $\bar{V}$ is the specific volume of the soil sample (dm^3 kg^{-1} 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.

$$\bar{W} = \frac{m - M_s}{M_s} \tag{3}$$

where $\bar{W}$ is the specific water content (kg water kg^{-1} solids), and m is the measured mass of the soil sample (kg).

These two variables, along with internal soil suction measurements during a drying cycle, are used to develop the soil shrinkage curve (ShC) and the water retention curve (WRC).

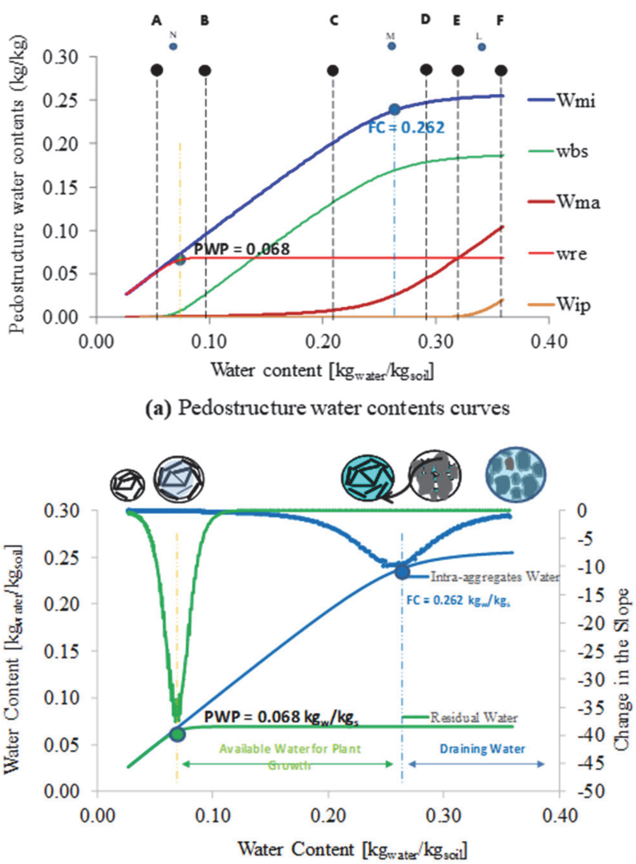
The water retention curve (WRC) is constructed by drawing the calculated soil water content (W, kg water kg^{-1} solids) versus the measured soil suction (h, dm ~ kPa). The soil shrinkage curve (ShC) is constructed by drawing the calculated soil water content (W, kg water kg^{-1} solids) versus the calculated specific volume ($\bar{V}$, dm^3 kg^{-1} solids).

Extracting Hydrostructural Parameters and Calculating Available Water Capacity

The hydrostructural parameters (table 2) for each soil sample were extracted by adjusting the measured water retention curve (WRC) and soil shrinkage curve (ShC) to thermodynamic equations 1 to 6 as provided by Assi et al. (2014). These parameters were then used to model the pedostructure water pools (interpedal, macropore, micropore, and residual water content curves). The curves were used to quantitatively define the water contents at field capacity and permanent wilting point (fig. 6). According to Assi et al. (2018), the water content at field capacity occurs when the pedostructure micropore water content starts to significantly contribute to the water loss from the soil medium and can be best observed by the maximum change in the slope of the micropore water content curve (fig. 6). The permanent wilting point occurs when the pedostructure residual water content starts to significantly contribute to the water loss from the soil medium and can be best observed by the maximum

Table 2. State variables and corresponding parameters of the pedostructure WRC and ShC.

Symbol	Definition	Unit	Corresponding Hydrostructural Parameters
W_{sat}	Pedostructure saturated water content	kg water kg^{-1} soil	W_{maSat}^{eq} and W_{miSat}^{eq}
W	Pedostructure water content	kg water kg^{-1} soil	$\bar{E}/A$ and $\bar{E}_{ma}/A$
W_{mi}^{eq}	Micropore water content of pedostructure	kg water kg^{-1} soil	
W_{ma}^{eq}	Macropore water content of pedostructure	kg water kg^{-1} soil	
$h^{eq}(W)$ $h_{mi}\left(W_{mi}^{eq}\right)$ $h_{ma}\left(W_{ma}^{eq}\right)$	Pedostructure water potential, which is in instantaneous equilibrium between inside and outside the primary peds such that $h_{mi} = h_{ma} = h$	dm ~ kPa	W_{maSat}^{eq}, W_{miSat}^{eq}, $\bar{E}_{ma}$, $\bar{E}_{mi}$
$\bar{V}$	Specific volume of pedostructure	dm^3 kg^{-1} soil	$\bar{V}_o$, K_{bs}, K_{st}, K_{ip}
w_{re}^{eq}	Specific water content of water pool associated with residual linear shrinkage phase of pedostructure	kg water kg^{-1} soil	k_N and W_N
w_{bs}^{eq}	Specific water content of water pool associated with basic linear shrinkage phase of pedostructure	kg water kg^{-1} soil	
w_{st}^{eq}	Specific water content of water pool associated with structural linear shrinkage phase of pedostructure	kg water kg^{-1} soil	
w_{ip}^{eq}	Specific water content of water pool associated with interpedal linear shrinkage phase of pedostructure parallel to the saturation line	kg water kg^{-1} soil	k_L and W_L



(a) Pedostructure water contents curves

(b) Field capacity and permanent wilting points

Figure 6. Available water capacity based on pedostructure concept: (a) modeled pedostructure water contents from saturation to dry state (the thermodynamic and structure-based modeling identifies the efficient contribution of the different water pore systems as a response to soil-water loss and thus can be used to identify the water-holding properties of a specific soil type and soil horizon), and (b) identifying the field capacity based on the maximum slope change of the pedostructure micropore water content curve and identifying the permanent wilting point based on the maximum slope change of the pedostructure residual water curve (Assi et al., 2018).

change in the slope of the pedostructure residual water content curve (fig. 6). Finally, AW was calculated as the difference between field capacity (FC) and permanent wilting point (PWP):

$$\text{AW} = \bar{W}_{FC} - \bar{W}_{PWP} \tag{4}$$

Statistical Analysis

Once all the parameters and hydrostructural properties of each sample were determined using the optimization technique discussed above, indicator parameters were selected to analyze the statistical significance of the differences 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 the 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 resulting two-tailed probability value was compared to the confidence level (α) to determine whether or not the means of each sample set were significantly different from each other.

For analysis between different treatments (i.e., control, manure application, and wastewater application), a paired t-test was used to compare the means of two sample sets. The paired t-test was used based on the assumption that the soil being tested was the same soil type and was being evaluated pre- and post-treatment. The test was conducted on AW as an indicator of water-holding capacity and K_{bs} as an indicator of micropore soil aggregate structure. The one-tailed probability value 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 or less than that of the control.

Results and Discussion

Manure and Wastewater Effects on Hydrostructural Characterization and Soil Water-Holding Properties

The hydrostructural parameters were extracted by adjusting the measured WRC and ShC with the thermodynamic equations of these two curves, as outlined by Assi et al. (2014). The extracted hydrostructural parameters can be divided into two types: (1) the characteristic parameters of the soil aggregate structure, including the shrinkage limit specific volume ($\overline{V}_0$), the slopes of the shrinkage phases of the shrinkage curve (K_{bs}, K_{st}, and K_{ip}), and the shrinkage amplitude ($\Delta ShC = \overline{V}_{Sat} - \overline{V}_0$); and (2) the characteristic parameters of the soil water-holding properties, including micropore water (W_{miN}, W_{maSat}), macropore water (W_{maSat}), saturated water content (W_{Sat}), permanent wilting point (W_{PWP}), field capacity (W_{FC}), and available water capacity (AW).

The values in table 3 are the means of six samples between two locations for each treatment. Two parameters were selected to study the changes in the soil aggregate structure within each treatment group and among the groups. Shrinkage amplitude (ΔShC) was chosen to provide insight into the total shrinkage of the soil core as a whole, and K_{bs} was chosen to understand how the microaggregate structure was affected by the treatments (manure application and wastewater application compared with the control).

For the A horizon (the horizon most vulnerable to changes) and under manure application, the shrinkage amplitude (ΔShC) did not change much, but the K_{bs} value declined from 0.400 to 0.322 dm^3 kg^{-1} water. This means that manure application could compact the primary peds, but adding organic matter increased the shrinkage in the macropore domain (i.e., between the primary peds). However, for the same soil horizon and under wastewater reuse, both the shrinkage amplitude and the slope of the basic shrinkage phase decreased, indicating an effect of compaction in the soil pedostructure. To evaluate how significant these changes were, other soil water-holding properties were analyzed (table 4). These properties are highly dependent on the potential energy of the surface charges on clay and organic matter particles. For both manure and wastewater application of horizon A, the available water capacity (AW) improved compared to the control, which tells us that the characteristic parameters of the soil aggregate structure are not, by themselves, able to explain the observed changes in the soil water-holding properties. However, changes in the potential energies of the surface charges on clay and organic matter can play a significant role in explaining the changes observed in the soil water-holding properties.

As described earlier, 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 at which 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 4 shows that the manure and wastewater applications both had little or no significant effect on permanent wilting point; thus, much of the improvement in AW can be attributed to the increase in field capacity. Although K_{bs} was reduced for horizon A, the curve was elongated along the water content axis, allowing a higher field capacity value. The differences in the shrinkage curves for each treatment in both the A and B horizons can be seen by a representative sample (fig. 7). Each sample was chosen as representative based on its proximity to the average value for most of the parameters.

Interestingly, the manure and wastewater applications 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 to manure application. According to table 3, it appears again as though the changes in AW are connected to the changes in field capacity.

Table 3. Means and standard deviations for two pedostructure shrinkage parameters: shrinkage amplitude (ΔShC) and slope of basic shrinkage phase (K_{bs}). Both parameters are important characteristics of the soil aggregate structure. The values shown are for six soil samples and three replicates from each site for each treatment.

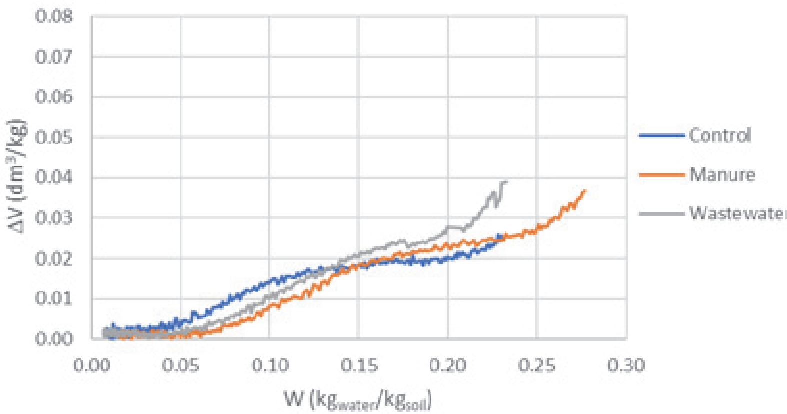
Soil Horizon	Treatment	ΔShC (dm^3 kg^{-1} soil)	K_{bs} (dm^3 kg^{-1} water)
A	Control	0.042 ±0.021	0.400 ±0.051
	Manure	0.043 ±0.012	0.322 ±0.053
	Wastewater	0.038 ±0.009	0.282 ±0.042
B	Control	0.043 ±0.004	0.400 ±0.042
	Manure	0.053 ±0.019	0.642 ±0.220
	Wastewater	0.065 ±0.009	0.470 ±0.175

Significance of Variations in Pedostructure Properties in Different Soil Types and under Application of Manure and Wastewater

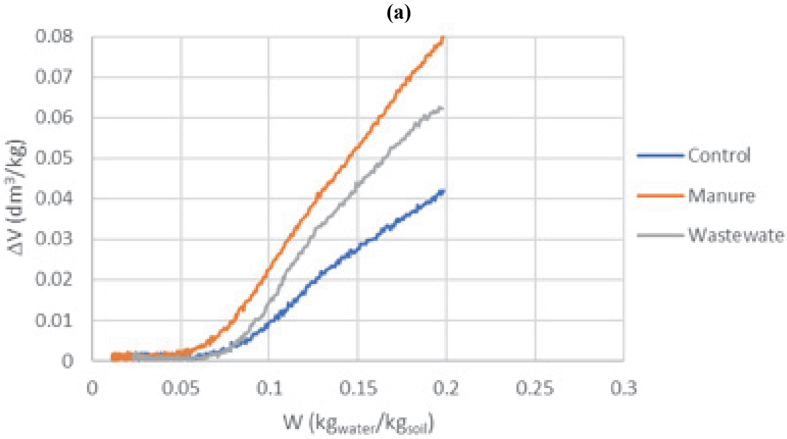
The high variability between locations within the same field highlights the need for better understanding of the dynamic soil properties within the same field and the same soil texture. This understanding would shed light on the way in which management practices can affect soil properties. In addition to the variability among soil samples, different waste applications affected the various hydrostructural properties in

Table 4. Means and standard deviations for pedostructure water-holding parameters: saturated water content (W_{sat}), field capacity (W_{FC}), micropore saturated water content (W_{miSat}), permanent wilting point (W_{PWP}), water content of specific pore volume of dry primary ped (W_{miN}), and available water capacity (AW). Values shown are for six soil samples and three replicates from each site for each treatment.

Soil Horizon	Treatment	Pedostructure Water-Holding Parameters (kg water kg^{-1} soil)					
		W_{sat}	W_{FC}	W_{miSat}	W_{PWP}	W_{miN}	AW
A	Control	0.245 ±0.021	0.126 ±0.039	0.126 ±0.038	0.058 ±0.010	0.057 ±0.010	0.068 ±0.031
	Manure	0.242 ±0.019	0.151 ±0.032	0.144 ±0.027	0.055 ±0.017	0.054 ±0.010	0.096 ±0.031
	Wastewater	0.239 ±0.038	0.153 ±0.020	0.150 ±0.022	0.066 ±0.011	0.063 ±0.011	0.088 ±0.028
B	Control	0.216 ±0.015	0.191 ±0.013	0.164 ±0.023	0.078 ±0.009	0.073 ±0.010	0.114 ±0.016
	Manure	0.222 ±0.033	0.158 ±0.035	0.157 ±0.033	0.072 ±0.004	0.071 ±0.004	0.086 ±0.034
	Wastewater	0.189 ±0.008	0.151 ±0.023	0.135 ±0.016	0.071 ±0.011	0.069 ±0.007	0.080 ±0.013



(a)



(b)

Figure 7. Shrinkage curves of representative samples from the control, manure, and wastewater treatments for (a) soil horizon A and (b) soil horizon B. The change in the volume (Δ V) from the saturation state to the dry state represents the shrinkage amplitude (ΔShC).

different ways. The statistical significance between the average values of indicative parameters is shown in table 5.

There was not much significant difference among the overall changes in specific volume of the soil samples for the whole shrinkage curve (ΔShC); however, manure application seems to have had a significant effect on the total shrinkage in the B horizon. The parameters most affected by waste application were K_{bs} and field capacity. Interestingly, K_{bs} and field capacity unexpectedly had a negative correlation and opposite effects between the two horizons. Compared to the control, K_{bs} decreased by almost 30% and 20% for manure and wastewater application, respectively, while field capacity increased by about 20% 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 had no significant changes between treatments.

For the 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% increase in K_{bs} from control to manure was significant with a 95% confidence interval. While K_{bs} increased, field capacity was reduced by about 17% and 21% for the manure and wastewater treatments, respectively. The difference in how waste applications affected the A and B horizons 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 differences in the chemical and physical compositions of the two soils. The chemical components of a soil play a huge role in how

Table 5. Significant differences between mean values of pedostructure parameters in control, manure application and wastewater reuse

		Pedostructure Characteristic Parameters[a]					
		Shrinkage Properties		Soil Water-Holding Properties (kg water kg^{-1} soil)			
Soil Horizon	Treatment	ΔShC (dm^3 kg^{-1} soil)	K_{bs} (dm^3 kg^{-1} water)	W_{Sat}	W_{FC}	W_{PWP}	AW
A	Control	0.042	0.400	0.245	0.126	0.058	0.068
	Manure	0.043	0.322***	0.242	0.151*	0.055	0.096***
	Wastewater	0.038	0.282***	0.239	0.153*	0.066	0.088*
B	Control	0.043	0.400	0.216	0.191	0.078	0.114
	Manure	0.065***	0.642**	0.222	0.158**	0.072	0.086*
	Wastewater	0.053	0.470	0.189***	0.151**	0.071	0.080**

[a] Asterisks indicate significant differences at (***) 99%, (**) 95%, and (*) 90% confidence level.

tightly water is held by the soil. Clay soils tend to hold water more tightly than sandy soils, which allow water to flow through more easily. The addition of manure and wastewater seems to have had a better hold on water than the sandy soil because an improvement was detected, whereas waste application might not hold water as well as the clayey soil because a deterioration of available water was detected.

As shown in tables 3 and 4, variability can be high among soil samples within each horizon and treatment. To determine whether or not the variance differed greatly among the same soil type and treatment, a two-sample t-test was performed between each sample location within each treatment. Table 6 summarizes the test results, showing significant differences between each of the means for three parameters.

Four parameters were chosen to test for significant differences between locations. First, K_{bs} is an indicator of the soil aggregate structure. It represents the slope of the basic portion of the shrinkage curve and was chosen to reflect the microaggregate structure. Second, W_{miSat} is the saturated water content of the micropore domain, which represents the foundation of the soil aggregates. Waste application also has potential to affect the macropore domain; thus, W_{Sat} was chosen to represent total water-holding capacity. Finally, AW was chosen to show the significant changes in the soil water-holding properties due to the dairy wastewater and manure applications on agricultural soil.

As shown in table 6, the variance between two field sites with the same treatment can potentially be high. Part of the observed variations can be explained by the variation in the soil texture between the two sites (table 1), which shows a difference in soil texture between the two control sites within the A horizon and between the two manure application sites in both the A and B horizons, as well as between the two sample locations for wastewater in the B horizon. This correlates to the significant variance seen in the pedostructure parameters. However, according to table 6, manure application enhanced the available water capacity (AW) for both sites regardless of the variability in soil texture, mainly for the A horizon, while wastewater application had no significant enhancement of the AW in the A horizon. Furthermore, neither manure nor wastewater application had a significant impact on AW in the B horizon.

CONCLUSIONS

The goal of this study was to gain better understanding of how soil responds to waste management practices (manure and wastewater application) on a dairy farm. The pedostructure concept, including thermodynamic and soil aggregate structure-based parameters, was used to track the changes in the soil aggregate structure and soil water-holding properties under two applications: manure and wastewater reuse. The results illustrate three key points: (1) there was high variability within fields of the same soil type and treatment, (2) different waste applications affected soil properties differently, and (3) different soil horizons and different soil types were affected differently by dairy waste (manure and wastewater) applications. For the two soils studied, most of the effects of manure and wastewater application were seen in the micropore domain of the soil. In most cases, there was a clear shift in micropore soil aggregation (shown by K_{bs}) and a change in field capacity. Plant-available water capacity (AW) increased in the A horizon with both waste applications, with a better enhancement under manure application. However, a statistically significant decrease was observed in available water capacity for the B horizon with both wastewater and manure applications. This means that agricultural practices (tillage, harvest, etc.) compact the lower horizons (B horizon) and affect the water-holding capacity.

Implications of this study include potential alteration of irrigation practices based on the changes in available water in the soil. As mentioned, the change in available water depends on both the soil type and treatment. If changes in available water can be accurately estimated, a more precise

Table 6. Statistically significant differences between means of K_{bs}, W_{Sat}, W_{miSat}, and AW for different treatments and two soil sampling sites for soil horizons A and B.

Treatment	Soil Horizon	Statistic	K_{bs} (dm^3 kg^{-1} water)		W_{Sat} (kg water kg^{-1} soil)		W_{miSat} (kg water kg^{-1} soil)		AW (kg water kg^{-1} soil)	
			Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
Control	A	Mean	0.44	0.36	0.26	0.23	0.16	0.09	0.10	0.04
		Variance	8.00E-04		2.86E-04		4.67E-05		8.98E-05	
		Significance	95% confidence		No sig. diff.		99% confidence		99% confidence	
	B	Mean	0.40	0.40	0.23	0.21	0.15	0.18	0.12	0.11
		Variance	2.18E-03		9.47E-05		3.56E-04		2.23E-04	
		Significance	No sig. diff.		90% confidence		No sig. diff.		No sig. diff.	
			Site 3	Site 4	Site 3	Site 4	Site 3	Site 4	Site 3	Site 4
Manure	A	Mean	0.36	0.28	0.25	0.23	0.16	0.13	0.12	0.07
		Variance	1.50E-03		2.66E-04		5.96E-04		4.29E-04	
		Significance	90% confidence		No sig. diff.		No sig. diff.		90% confidence	
	B	Mean	0.79	0.50	0.19	0.25	0.15	0.17	0.08	0.10
		Variance	2.89E-02		1.16E-04		1.21E-03		1.23E-03	
		Significance	No sig. diff.		99% confidence		No sig. diff.		No sig. diff.	
			Site 5	Site 6	Site 5	Site 6	Site 5	Site 6	Site 5	Site 6
Wastewater	A	Mean	0.28	0.28	0.23	0.24	0.16	0.14	0.10	0.07
		Variance	2.20E-03		1.79E-03		5.00E-04		6.41E-04	
		Significance	No sig. diff.		No sig. diff.		No sig. diff.		No sig. diff.	
	B	Mean	0.62	0.32	0.19	0.19	0.14	0.13	0.08	0.09
		Variance	4.70E-03		8.57E-05		2.89E-04		1.61E-04	
		Significance	99% confidence		No sig. diff.		No sig. diff.		No sig. diff.	

amount of water can be added to the soil for optimal plant growth, thus minimizing the amount of water wasted due to runoff or percolation. In this study, approximately the same amount of water would be needed for irrigation as was used five years previously. Bermuda grass roots grow mostly in the top 15 cm of the soil. Because the plant-available water increased in the A horizon, only 3 cm deep, but decreased in the B horizon, the effects of plant-available water may cancel out. These observations require further study.

Limitations of this study include inconsistent frequency and quantity of manure and wastewater applications and that the data from the farm only reached back approximately five years; 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 the soil in that field. Tillage and potentially crop type also have an impact on soil composition and structure. At this point, more work is needed to confidently conclude that manure application is generally beneficial to physical soil health. Future work should include testing of different soil types to study how each type responds to waste application. Biological and chemical analyses of the soil would provide greater insight into the reactions of soil to manure and wastewater applications.

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