ESTABLISHING QUANTITATIVE METRICS FOR SOIL HEALTH: AN IN-SITU METHOD FOR QUANTIFYING SOIL STRUCTURE

A Thesis

by

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ABSTRACT

Quantitative soil structure metrics would be beneficial not only for assessing soil health, but also optimizing biophysical models. A rapid and reliable field method of soil structure measurement that can obtain quantitative metrics, is needed so that the effects of land management on soil structure can be measured *in situ*. Successful methods and analyses quantifying soil structure of intact soil profiles transported to the lab have been established. The research objective of this thesis is to develop a method for quick and accurate field quantification of soil structure using 3D scanning technology. Once the field methodologies were established, scans of soil surface horizons were collected from three areas across the Blackland Prairie Major Land Resource Area of Texas, USA. In each of these three areas, scans were collected in triplicate from fields under three land management categories: conventional till, no till, and perennial. Measurements of bulk density and other physical properties of the scanned soil were made also. Two scanner resolutions for field data collection were evaluated; Wide (0.4 mm) and Macro (0.1 mm). Wide scan collection and processing was quicker by approximately 70 minutes and produced similar results to Macro. Tessellation analysis of the soil face topography data from the scans yielded useful quantitative soil structure data that were assessed in linking changes in soil condition to changes in management practices. Average tessellation polygon areas showed statistical structural differences between soil horizons ($p = 0.002$) and a statistical difference between managements in one of the studied areas ($p = 0.03$). Other measured soil properties did not show strong correlations with tessellation results or significant differences by management. The tessellation analysis was proven to be a successful analytic data method but needs further refinement for more widespread use in agricultural applications.

DEDICATION

For my lovely Husband. We did it. One day at a time.

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First and foremost I would like to thank my committee chair, Dr. Morgan, for her continual guidance, support, and patience. I can truly say that I would not be the person I am today without her impact on my life and career. She is the one that piqued my interest in Soil Science. Her commitment to and passion for soils and her students is inspiring.

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Thanks and Gig ‘Em

Sarah Balke

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professors Cristine Morgan and Terry Gentry of the Department of Soil and Crop Sciences, Professor Georgianne Moore of the Department of Ecosystem Science and Management, and Professor Alex McBratney of the Sydney Institute of Agriculture at the University of Sydney.

The data analyzed was collected with the help of other students Dianna Bagnall, Nicole Shigley, and Candice Medina. The analyses depicted were conducted in part by Edward Jones of the Sydney Institute of Agriculture at the University of Sydney.

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INTRODUCTION AND LITERATURE REVIEW

Soil structure is a key physical indicator of soil condition and function. It is one of the most important soil physical properties as it is linked directly and indirectly to several aspects of soil quality including biological and hydraulic function. Land use and management can modify these physical properties especially at the soil surface (Saxton and Rawls, 2006). Management that results in improvement or restoration of soil structure and other physical properties can lead to enhancement in soil function. Enrichment of soil function can have many benefits to the agricultural community and thus society as a whole. While soil structure is very relevant indicator of soil health (Friedman et al., 2001) and could be useful in parameterizing soil hydrology models (Morgan 2003; Lepore et al., 2009), the use of soil structure as a metric is hindered because there is not a non-subjective system to measure nor quantify soil structural properties. As a result, the effects that land management has upon soil structure are not well documented. Currently, the United States Department of Agriculture- Natural Resources Conservation Service (USDA-NRCS) has protocols for structure analysis, but these protocols can be biased and provide only qualitative descriptions. Multistripe laser triangulation (MLT) scanning has been employed for structural analysis based on scan gap size in lab conditions and a field excavation site (Eck et al., 2013). These methods are not easily transferrable for many rapid field measurements because of the method for sample preparation prior to scanning and because of the method employed to get the scanning data. While the methods of Eck et al. (2013) are successful and of high value, a more rapid *in situ* method would be more field deployable. The overall objective of this research is to develop a field method that can be quickly employed to assess structural conditions in the field using MLT scanning.

Structure as a Key Component of Soil Function

Soil structure is defined by the USDA-NRCS as “the naturally occurring arrangement of soil particles into aggregates that results from pedogenic processes” (Schoeneberger et al., 2012). Formation of soil structure is dependent upon many factors in soil development. First, aggregation is the flocculation of soil particles. Flocculation is encouraged and facilitated by inorganic and organic carbon amounts, microorganism activity, vegetation type, soil texture, and a lack of certain cations in the soil. Cations such as calcium and magnesium aid the flocculation process (Bronick and Lal, 2005) . Secondly, aggregation of flocculated particles leads to the formation of structural units of varying shape and size which are dependent on the same variables that aid flocculation. These variables change with soil depth. USDA methods classify structure based on grade, size, and type categories (Schoeneberger et al., 2012). An accurate description of structural properties can give insight to processes occurring and the functionality of soil.

Structure is a fundamental part of soil function because it directly and indirectly affects many soil properties and processes. Relationships between soil structure and nutrient cycling, carbon sequestration, soil strength, root penetration, biological activity, and water dynamics have been noted (Horn et al., 1994; Bronick and Lal, 2005; Rabot et al., 2018) . Increases in aggregation have been linked to increases in both microbial activity and diversity (Elliott and Coleman, 1988; Mendes et al., 1999; Denef et al., 2001). Improvements in structure can lead to decreases in bulk density, increased porosity and aeration, and increased root penetration (Horn et al., 1994; Bronick and Lal, 2005) .

Structure also plays a key role in the overall hydraulic function of soil. Soil structure influences water storage capabilities, plant available water, and water movement in and through the soil profile. Size of aggregates, distribution of aggregates, and bulk density have a direct effect on infiltration rates, depth of redistribution, and saturated hydraulic conductivity, K_s (Bouma & Dekker, 1978; Wu, et al., 1990, Jarvis et al., 2013). Improvement and maintenance of soil hydraulic function allows for optimal hydraulic and biological function as well as preservation of soil.

High water retention and hydraulic function in conjunction with higher nutrient retention and microbial diversity are indicators of better overall soil health (Friedman et al., 2001). All of these indicators play important roles in soil quality and productive capabilities. Since it has been shown that soil structure can have an effect on these soil health indicators, it is important to have a good understanding a of a soils current structural state. It is also important that the description of soil structure be non-subjective and quantitative for consistent evaluation. Quantitative evaluation of how a soils structural state can be improved is beneficial to better understanding of soil ecosystem function and biophysical modeling of soil function and processes.

Land management practices can change soil structure and hydraulic function. Land use and practices can have a significant effect on infiltration and hydraulic conductivity because of the disruption of soil structure and the macropore network, increases in bulk density, and decreases in porosity (Lin et al., 1998; Lin et al., 1999a; Lin et al., 1999b; Sobieraj et al., 2002; Gupta et al., 2006; Zhou et al., 2008; Price et al., 2010). Tillage also leads to lower overall aggregate stability which increases the soil's propensity to form a surface crust, thereby decreasing infiltration and increasing erosion hazard (Pagliai et al., 2004) . Differences in vegetation from alteration of land use can also impart change in function. Since varying root systems and architectures play an integral role in structure formation and other biological processes, a change in vegetation can have a tremendous effect (Bronick and Lal, 2005). It is imperative for sustainability efforts that we limit the changes in the functional capability of soil due to impacts from human management, or changes in soil condition (McBratney et al., 2014). Quantitative measurements of changes in soil structure would be helpful in the assessment of soil condition and decisions on land management practices.

Current Classification Methods and Use

The current methods of classifying soil structure are qualitative and can be biased by the person doing the assessment. Structure is classified in the field based on three basic categories: grade, size, and type. Grade refers to how well defined and strong the structural units are. Size is based on dimensions of an individual unit. Type refers to the shape of a unit. There are eleven structural types recognized by the USDA-NRCS: granular, angular blocky, subangular blocky, lenticular, platy, wedge, prismatic, columnar, single grain, massive, and cloddy (Schoeneberger et al., 2012). Figure 1 displays a pictorial representation of the various structural types. Judgements on quality of structural condition of the soil are made based on these observations. The USDA-NRCS uses structural condition as a soil quality indicator (Friedman et al., 2001) . If a quantitative method for structural analysis were readily available, structural classification would be more reliable and have wider application.

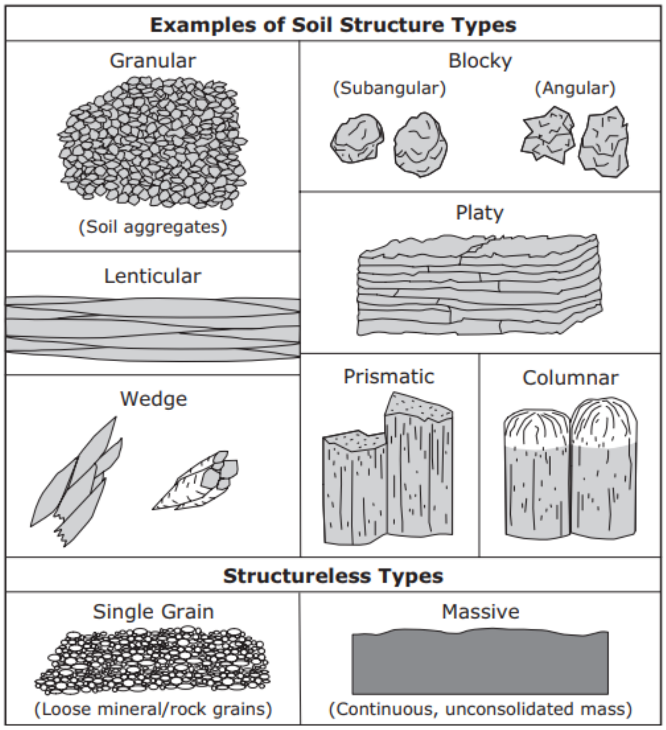


Figure 1: A depiction of structural types taken from the USDA-NRCS field description guide reprinted from Schoeneberger et al. (2012).

Another relevant use for structural classification is in hydrological and biophysical modeling. Currently, models use pedotransfer functions that are based on soil texture to estimate soil hydraulic and thermal properties (Rawls et al., 1982).

Considering that soil structure has a significant impact on water, nutrient, and contamination flow; attempts have been made to include soil structure in preferential flow modeling (Beven and Germann, 1982; Jarvis, 1991; Morgan, 2003; Lepore et al., 2009; Bagnall, 2014). Categorical soil structure data have been linked to soil water retention estimates for use in pedotransfer functions as well (Pachepsky and Rawls, 2003). However, despite these efforts, a lack of quantitative structural information and parameters make wide scale use of structural information in models impossible.

One possibility for analysis of soil structure focuses on the analysis of soil macropore space. Studies have been done on using digital binary imaging analysis on thin sections (Moran et al. 1989; McBratney and Moran 1990; Ringrose-Voase 1996). Young and Crawford (1991) also detail the possibility of using fractal geometry to classify pore space. While these methods have been successful, associated cost and time are big limiting factors. These methods are concentrated on a much smaller scale than can be widely applied.

Quantitative Structural Analysis

A possibility for acquiring quantitative structural metrics is through the use of MLT scanning technology. The MLT scanner is a three-dimensional (3D) laser scanner that can produce a 3D point cloud map of the scanned object. It has two operating resolutions: a Macro setting (0.1 mm) and a Wide setting (0.4 mm) (NextEngine, 2009; Eck et al., 2013). Figure 2 shows a Macro and a Wide resolution scan.

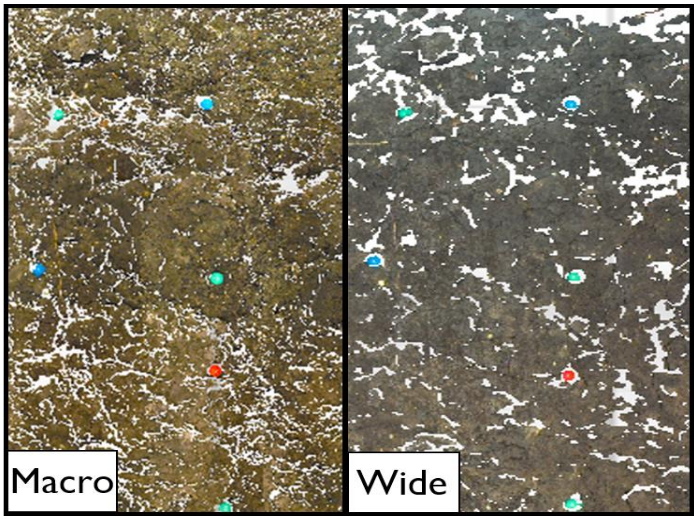


Figure 2: A comparison Macro and Wide resolution scans from the same soil face.

Some scanning of soil profiles has been done with this 3D laser scanning to assign quantitative values to structural units and relate them to K_s values (Eck et al., 2013; Eck et al. 2016). In studies by Eck et al. (2013) and Hirmas (2013), preparation of the soil profile includes freezing and removing the face, which is very time consuming and requires bringing soil monoliths of intact profiles into the lab. After scanning, processing methods included scan gap analysis. Scan gaps are areas of the 3D scan with missing data points. Theoretically, scan gaps are representative of gaps between structural units or that scan gaps represent the presence of pore space. The complication with quantifying scan gaps is that overlapping the scans can create a bias in the scan gap size. Scans need to be overlapped due to inaccuracies created by the angle of the laser to the face (Eck et al., 2013). The limiting factor of the current work is that most of this scanning has been done in a controlled lab environment and takes too much time to be a practical method for collecting many soil profiles *in situ*.

Study Scope

The purpose of this work is to develop a measurement method that can be accomplished quickly, in the field, and *in situ* to accurately identify and quantify soil structure using 3D scanning technology. To test the application of the method, the metrics resulting from scanning the profiles of soil surfaces under different management will be used to compare changes in soil structure as a result of changes in land management. The specific objectives are the following.

Objective 1: Obtain quantitative metrics from 3D scan data that can be used to identify structural properties. In collaboration with The University of Sydney, the scan data collected were processed using multiple algorithms. Several data processing techniques were evaluated. An algorithm was used to analyze structural condition by using terrain analysis and spatial relationships between data points.

Objective 2: Develop a robust, rapid field method for using a MLT scanner to rapidly and precisely capture quantitative structural data. The scan data from the first outdoor trials were used to assess needed preparation techniques to reproduce quality scans of soil surface horizons. The data were then used to evaluate which scanner resolution setting is the most advantageous. To ensure reproducibility of the scanning results, scan data were collected in triplicate at each site. Based on a comparison of results from processed scan data in Wide (0.4 mm) and Macro (0.1 mm), field protocol for exposing the surface horizon, preparing the area to be scanned, and scanning procedures were finalized.

Objective 3: Link scanning metrics to land management and soil properties. A field study was conducted to collect 3D scans from three areas within the Blackland Prairie Major Land Resource Area (MLRA) of Texas. Within each of the areas, sites under conventional till (CT), no till (NT), and perennial (P) conditions were measured. Scan data from each site was processed according to findings from Objective 1. The resulting structural metrics were used in quantitative comparison of structural conditions. Along with the scan data, samples for lab analysis were taken at each site.

This research has potential to advance our ability to deliver accurate, quantitative data on how land management is affecting soil structure, and in turn soil function, and aid in the ongoing process of accurately parameterizing preferential flow models. It is innovative in that it provides an *in situ* method that can be employed quickly to provide accurate and repeatable quantitative structural data.

MATERIALS AND METHODS

Study Sites

Three areas were chosen within the Blackland Prairie MLRA of Texas: Falls County, Milam County and Williamson County. Figure 3 shows the approximate locations of the scanning sites. Within each of these three areas CT, NT, and P agricultural fields (nine fields total) were selected. Perennial fields were included to be used a reference state for the CT and NT fields. Generally, soils with a perennial plant system are considered to have good soil health conditions by USDA-NRCS standards, as they are minimally disturbed and are characterized by complex continuously living root systems (Friedman et al., 2001). All the fields that were selected were mapped as similar soil series. The soil series included Houston Black (Fine, smectitic, thermic Udic Haplustert) and Branyon (Fine, smectitic, thermic Udic Haplustert). Houston Black soil originates from calcareous mudstone and Branyon soil formed in clayey alluvium derived from mudstone (Soil Survey Staff, 2012).

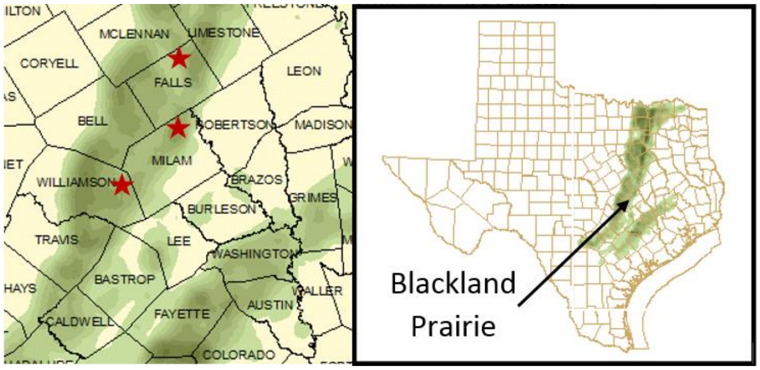


Figure 3: Scanning site locations (red stars) in the Texas Blackland Prairie MLRA (adapted from Texas Parks and Wildlife Ecological Mapping Systems of Texas: Texas Blackland Tallgrass Prairie).

Field Methodology

Scan data were taken with a NextEngine MLT scanner (NextEngine Desktop 3D Scanner, NextEngine Inc., Santa Monica, CA) in triplicate from each of the nine fields. For collection of 3D scan data, a 46 by 61 cm hole to a depth of 40 cm was dug to expose the A horizon and any horizon directly below. A field description of soil structure was completed for each face. The pit was left to dry for at least 24 hours to allow the soil structure to become more visible. After the drying period, a 25.4 cm wide by 30.5 cm deep face was marked with flagging tape. The outer layer of soil, which was disturbed through digging the pit, was carefully picked off of each profile face. The picking was done to remove shovel marks and expose undisturbed structural units. While picking out the structure, care was taken to not leave any knife or other artificial marks on the face. Larger structural units were exposed with a knife and smaller ones with a dental pick. If an extensive root system was present, it was burned out with a propane self-igniting torch to avoid interference with scanning. A soil face prepped for scanning is displayed in Figure 4. The bottom of the pit was leveled as a platform for the scanner. The process of prepping a singular pit took approximately 60 minutes.

Figure 4: Prepped soil face for scanning.

The scanner and laptop were powered using a 12 volt Marine battery and a 1000-Watt power inverter. To ensure the best scan quality, the pit was covered with a piece of black-out fabric during all scans. Figure 5 shows a pit that is set up for scanning. Each prepped face was scanned in both the Macro (0.1 mm) and Wide (0.4 mm) resolution settings.

Figure 5: Example of scanning set up (shown without blackout fabric).

The wide resolution required two individual scans to cover the width of the face, with a 10-cm overlap of the scans. Figure 6 shows the configuration of the two individual scans for the Wide resolution. Since the Macro resolution setting captures a smaller area, more individual scans are required. For the Wide resolution, the scanner was placed in the pit 43 cm from the face (NextEngine, 2009; Eck, 2013). The scanner was aligned to the right-hand side of the face and the first scan was taken. The scanner was moved 10 cm to the left to take the second scan. This allowed for the scans to be overlapped during processing to avoid edge effects (Eck et al., 2013). The process of taking the Wide scans required approximately 15 minutes. The macro resolution required nine individual scans (Fig. 6) to cover the length and width of the face, with a 6-cm overlap. For the Macro resolution, the scanner was placed 16.5 cm from the soil face (NextEngine, 2009). The scanner was again aligned with the right-hand side for the face and the first scan was taken. The scanner was moved 6 cm to the left for the second scan, and again for the third. For the shallow depth scan, the scanner was raised 10 cm and the next three scans were taken. Finally the scanner was raised a second time to collect the last three scans. The process of taking the Macro scans required approximately 60 minutes.

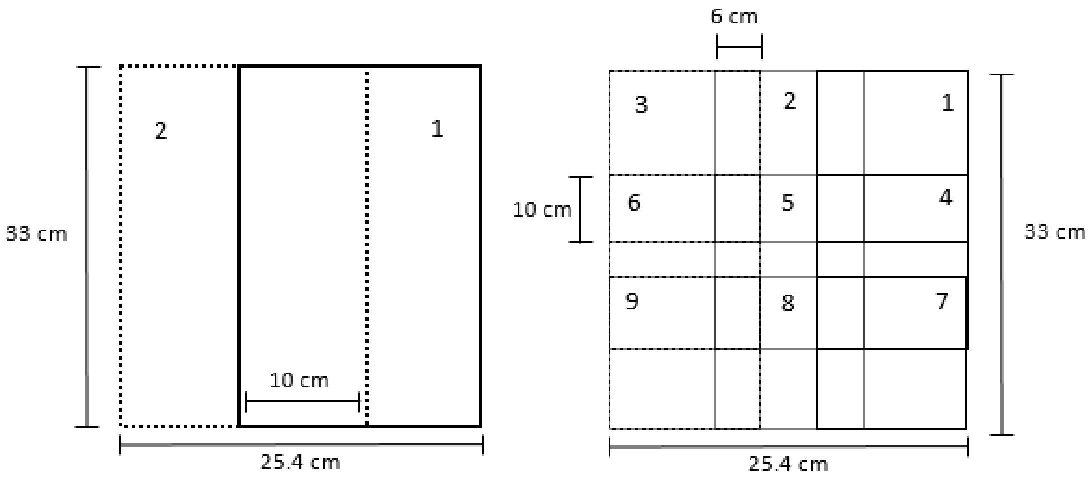


Figure 6: Diagrams of the overlap configuration of an individual scan of the soil surface. Wide resolution (left) scans required 15 minutes to collect and Macro resolution (right) scans required 60 minutes to collect.

Scan Processing

The individual scans from each soil face were aligned and stacked to form a single full scan using the ScanStudio^{TM} HD software (NextEngine Inc., Santa Monica, CA.) that comes with the scanner (NextEngine, 2009; Eck et al., 2013). After alignment, the edges of scans were trimmed using the same software to remove any of the flagging tape picked up in the scanning. Scans were then exported from ScanStudio^{TM} HD (NextEngine Inc., Santa Monica, CA.) as .XYZ files. Aligning and trimming a Wide resolution scan required approximately 5 minutes. The Macro resolution required approximately 30 minutes because of the additional scanning files that needed to be aligned.

The preliminary scans collected contributed to development of scanning protocol and data processing methods. The processing of raw files and testing of algorithms to identify soil structure metrics was done in collaboration with The University of Sydney.

Using the preliminary data, several methods were explored for analysis of the scans including scan gap size, terrain analysis, ridge and valley distribution, wavelets, and dirichlet tessellation methods.

The .xyz files were processed in the R software program (R Development Core Team, 2014). Scan gaps were identified in a similar manner as was done in the Eck et al. (2013). A second approach to analyzing the scan data, terrain analysis was used to identify high and low points and ridges and valleys in the 3D scan map to help isolate structural units. Dirichlet tessellation analysis was performed using the R "polygon" function (R Development Core Team, 2014) to obtain a polygon count and average size of polygons. The tessellation process looks at high and low points in the scans assigns all the points that are nearest to an individual high or low to that polygon, an example of a dirichlet tessellation was pulled from Sibson, (1980) and depicted in Fig. 7. For the purposes of this research, the polygons are thought to be indicative of a structural unit. It follows that we assume the average size of the polygons output from the tessellation could represent the average size of a structural unit identified in the scans.

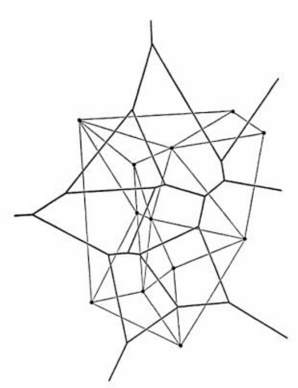


Figure 7: An example depiction of a dirichlet tessellation reprinted from Sibson, (1980).

Comparing Land Managements

The outputs from tessellation analysis were used to further the development of the field methodologies and comparison of land managements. Average polygon size was used for comparisons since size is one of the three factors currently used in classifcation of soil structure. Separate tessellation analyses were completed on the A horizon and below the A horizon to a depth of 30 cm for each scan. Statistical analysis was performed in R. Tukey's 'Honest Significant Difference' method (α=0.05) was employed using the "TukeyHSD" function (R Development Core Team, 2014) to identify significant differences in land managements and horizons. Tukey's method was also used in the analysis of volumetric water content, bulk density, and organic carbon content by management.

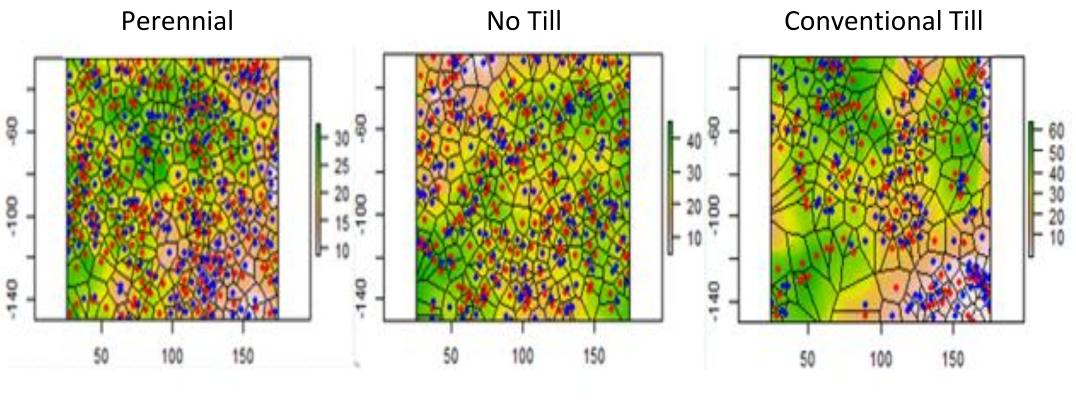
Sampling and Lab Analysis

At each scan location, soil samples were collected for lab analysis of particle size distribution, total carbon, inorganic carbon, organic carbon, pH, base saturation, cation exchange capacity, and bulk density. Six samples from each field were taken for the analysis: one sample was pulled from 0 to 10 cm and one from 10 to 30 cm for each scanning pit. The samples from each of the three pits in a single field were combined by depth, dried at 60°C, and passed through a 2-mm sieve for lab analysis. Particle size distribution analysis was completed using the pipette method (Steele and Bradfield, 1934; Kilmer and Alexander, 1949). Total carbon was determined using the dry combustion method (Soil Survey Staff, 1972; Nelson and Sommers, 1982). Inorganic carbon was analyzed using the modified pressure calcimeter method (Sherrod et al., 2002). Organic carbon was calculated by subtracting inorganic carbon from total carbon. Soil pH was measured in a 1:1 water dilution (Soil Survey Staff, 1996). Base saturation and cation exchange capacity was determined using the NH_4OA_c, pH 7.0 Automatic Extraction method (Holmgren et al., 1977; Soil Survey Staff, 1996). For measuring bulk density, soil cores were collected in triplicate from 0 to 13 cm depth with a 7.7-cm diameter split core sampler. Bulk density was determined using the field moist method (Blake and Hartge, 1986; Soil Survey Staff, 1996). The triplicate measurements were averaged for each site.

RESULTS AND DISCUSSION

Objective 1: Obtain Quantitative Metrics from 3D Scan Data That Can Be Used to Identify Structural Properties

As an example of the polygon output from the dirichlet tessellation analysis, results from a selected pit for the three fields in Falls County can be seen in Fig. 8. The polygon output overlays an elevation raster of the topography of the soil face. The tessellation results from each of the fields are visually different. The differences in the identified polygons, or structural features, follow what was expected. The scan from the P field shows smaller and more numerous polygons than those in the NT field and the CT field. CT also shows larger elevation distances in the topography of the soil face, supporting that CT has larger structural features.


Perennial

No Till

Conventional Till

Figure 8: Tessellation results from the Falls County Fields on top of an elevation raster (elevation in millimeters) with high points in blue and low points in red. All dimensions are in millimeters.

A parameter that effects the output of the tessellation is the elevation raster resolution used in creating the polygons. The data were processed several times using different elevation raster resolution settings in R for the tessellations. Inputing a higher resolution setting in R produces a larger pixel size within the raster and yields a lower overall raster image quality. Using a lower quality raster image produced larger polygon areas in the tessellation analysis. Figure 9 shows the results using R raster resolution settings of 1, 2, and 3. While all resolutions created the same overall trend between different managements, raster resolution 1 showed statistical differences between the managements. Based on this result, raster resolution 1 is used for data processing for comparisons to management and soil properties in the following sections.

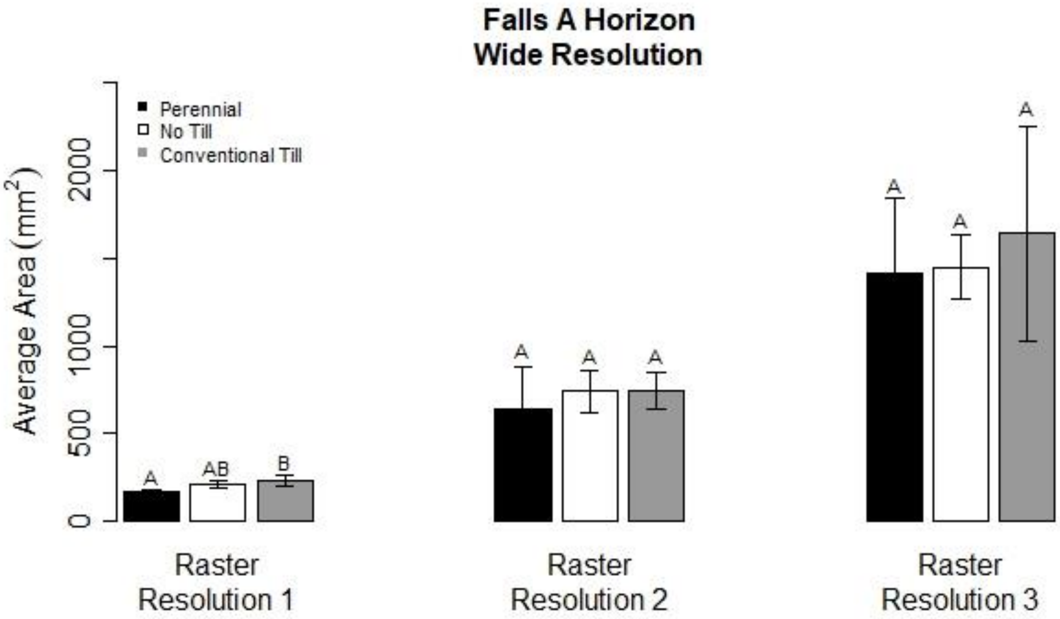


Figure 9: Average polygon areas from Falls County A horizons processed at different tessellation raster resolutions.

Objective 2: Develop a Robust, Rapid Field Method for Using a MLT Scanner to Rapidly and Precisely Capture Quantitative Structural Data

Tessellation counts and average areas were used for comparison between the Macro and Wide scans. Macro tessellation counts were statistically greater ($p < 0.001$) than wide counts. However, Macro and Wide counts followed the same trends with changes in structural conditions and land management. A plot of Macro and Wide counts showed a positive linear relationship (Fig. 10) with a regression slope that is not significantly different than 1 (p=0.09), meaning that the use of either resolution should produce a similar result for comparison purposes.

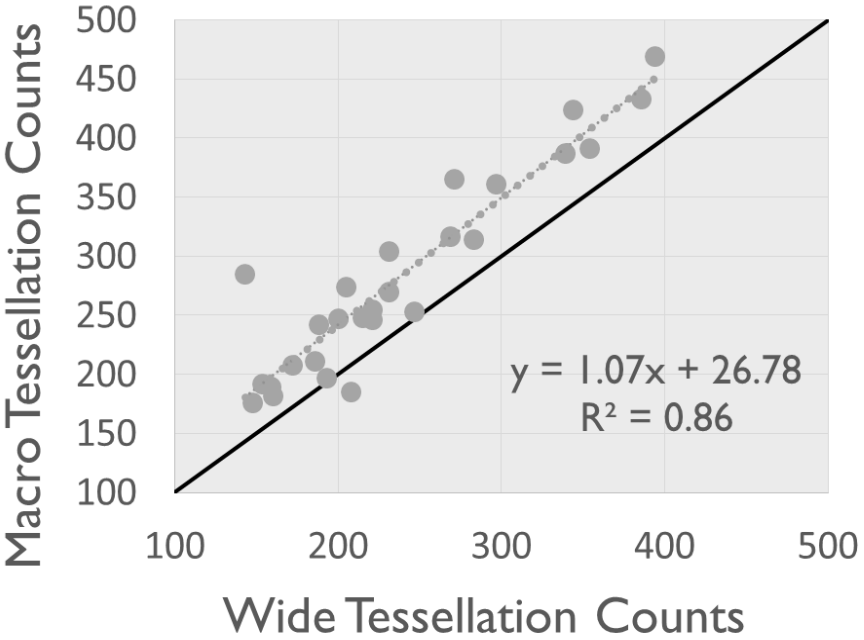


Figure 10: Tessellation counts of the Macro and Wide resolution scans had a positive linear relationship. The one to one line is solid and the regression line is dashed.

Tessellation analysis on both the Macro and Wide scans also produced similar average polygon areas in each of the replications within each management in the Falls County fields (Fig. 11). The results from comparing tessellation counts and areas from both resolution settings suggest that Wide resolution scans produced repeatable and comparable tessellation outputs within replications compared to Macro. Because they present the same trend compared to each other and there is only a bias for more count in Macro, we can choose to use Wide for the field method, eliminating 45 minutes for the measurement method and 25 minutes from the processing.

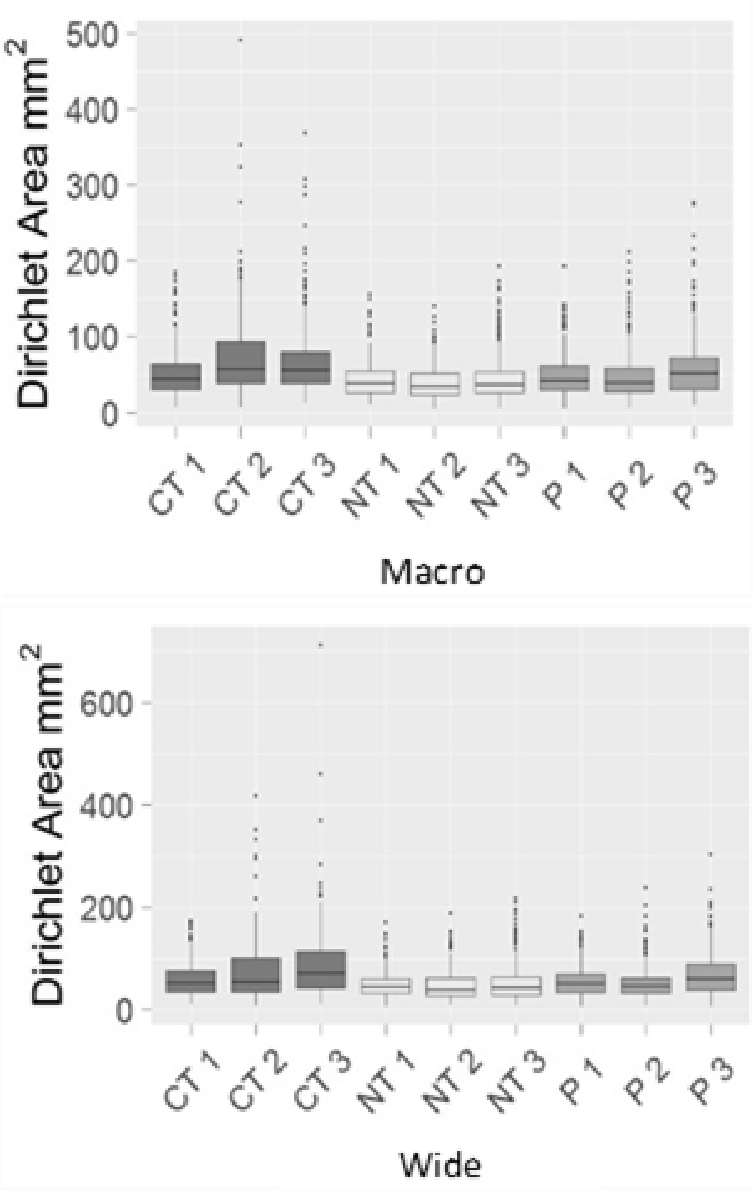


Figure 11: Boxplots of dirichlet tessellation areas for each scan and each field in Falls County, a) Macro and b) Wide resolutions are shown.

Objective 3: Link Scanning Metrics to Land Management and Soil Properties

Field descriptions the A horizon depths and soil structure of the scanned pits are summarized in Table 1. Differences in physical soil properties between managements were visually apparent (Fig. 12). While visible difference within a field of the same management did exist, there were some overarching trends. The P fields, especially the native Falls County one, appeared to have better soil health. The surface soils in these fields were soft and moist to the touch, had smaller more granular to subangular structure and were much darker in color. Complex root systems and high biological activity (ants, worms, etc.) were also common in the soils of the P fields. In striking contrast to the P fields, the CT fields were generally very dry and had little to no apparent natural structure. In the pits that did have structure, the peds were generally very angular and firm. The surface soils were lighter in color and lacked apparent biodiversity. The soils in the NT fields seemed to fall somewhere in between as we would expect. While they were not exactly like the soils in the P fields, they did have some properties that resembled them. The soil was less firm and structure was smaller and more subangular than that of the CT fields, closer to that of the P fields. Roots and biological activity were also more common in the NT fields than the CT fields.

Figure 12: Photos of surface soils from the a) Falls County Perennial field and b) Milam County Conventional Till field

Table 1: Summary of Field Soil Description Data.

Area	Management	Pit Number	Master Horizon	Depth (cm)	Type[1]	Grade[3]	Size[4]
Falls County	Perennial	1	A	0-19	GR	2	CO
			B	19-30	ABK	2	M
		2	A	0-21	GR	2	CO
			B	21-30	ABK	2	M
		3	A	0-16	SBK	1	M
			B	16-30	ABK	1	M
	No Till	1	A	0-18	SBK	2	CO
			B	18-30	PR	3	M
		2	A	0-14	ABK	2	CO
			B	14-30	PR	3	M
		3	A	0-12	SBK	2	M
			B	12-30	PR	3	M
	Conventional Till	1	A	0-21	MA[2]	0	-
			B	21-30	PR	3	CO
		2	A	0-11	MA[2]	0	-
			B	11-30	ABK	3	CO
		3	A	0-21	ABK	1	CO
			B	21-30	PR	3	CO
Williamson County	Perennial	1	A	0-15	SBK	2	M
			B	15-30	SBK	2	CO
		2	A	0-14	SBK	2	M
			B	14-30	SBK	2	M
		3	A	0-18	SBK	2	M
			B	18-30	SBK	2	CO
	No Till	1	A	0-10.5	SBK	2	M
			B	10.5-30	ABK	3	CO
		2	A	0-12	ABK	2	M
			B	12-30	ABK	3	CO
		3	A	0-10	SBK	1	M
			B	10-30	ABK	3	CO
	Conventional Till	1	A	0-10	SBK	1	M
			B	10-30	ABK	3	M
		2	A	0-10	ABK	2	M
			B	10-30	ABK	3	CO
		3	A	0-9	ABK	1	M
			B	9-30	ABK	3	CO
Milam County	Perennial	1	A	0-12	SBK	2	M
			B	12-30	PR	3	M
		2	A	0-13	SBK	2	M
			B	13-30	PR	3	M
		3	A	0-15	ABK	3	M
			B	15-30	ABK	3	CO
	No Till	1	A	0-15	ABK	2	M
			B	15-30	ABK	3	CO
		2	A	0-17	SBK	2	M
			B	17-30	ABK	3	CO
		3	A	0-15	ABK	2	M
			B	15-30	ABK	3	CO
	Conventional Till	1	A	0-8	MA[2]	0	-
			B	8-30	ABK	2	VC
		2	A	0-12	ABK	2	CO
			B	12-30	ABK	3	VC
		3	A	0-13	ABK	2	CO
			B	13-30	ABK	3	CO

Notes:
1) GR- Granular; ABK- Angular Blocky; SBK- Subangular Blocky; PR- Primastic; MA- Massive
2) A horizons showed evidence of platy structure but were overall massive
3) 0- Structureless; 1- Weak; 2-Moderate; 3-Strong
4) M-Medium (Gr: 2-5 mm; ABK,SBK: 10-20 mm; PR: 20-50 mm);
CO- Coarse (Gr: 5-10 mm; ABK,SBK: 20-50 mm; PR: 50-100 mm);
VC- Very Coarse (Gr: >10 mm; ABK,SBK: >50 mm; PR: 100-500 mm)

Lab data from soil samples taken from each field are summarized in Table 2. Particle size distributions for the soils were similar, as anticipated since the fields were mapped as similar soil series. Organic matter percentage in P fields was greater than NT and NT higher than CT, following the expected trends. The lab data support the idea that similar soils under Perennial management have soil health conditions superior to No Till Management and Conventional Till management.

Table 2: Summary of Soil Lab Data

Area	Management	Depth (cm)	Total Sand (%)	Total Silt (%)	Total Clay (%)	Texture Class	Organic Matter (%)	Base Saturation (%)
Falls County	Perennial	0-10	10.6	38.1	51.3	Clay	8.14	100
		10-30	10.3	33.3	56.4	Clay	2.22	100
	No Till	0-10	10.3	37.6	52.1	Clay	3.51	100
		10-30	10.4	37	52.6	Clay	3.53	100
	Conventional Till	0-10	7.4	35.9	56.7	Clay	3.13	100
		10-30	6.1	35.9	58	Clay	2.63	100
Williamson County	Perennial	0-10	26.9	38.3	34.8	Clay Loam	4.40	100
		10-30	24	36.5	39.5	Clay Loam	2.17	100
	No Till	0-10	17.6	38	44.4	Clay	2.44	98
		10-30	15.6	35.3	49.1	Clay	1.46	100
	Conventional Till	0-10	20.9	39.6	39.5	Clay Loam	2.00	100
		10-30	19.1	38.5	42.4	Clay	1.38	100
Milam County	Perennial	0-10	10.8	36.3	52.9	Clay	3.72	100
		10-30	8	35.6	56.4	Clay	2.20	100
	No Till	0-10	9.1	41.8	49.1	Silty Clay	2.55	100
		10-30	6.7	38.8	54.5	Clay	1.63	100
	Conventional Till	0-10	6.2	8.2	53.5	Silty Clay	2.30	100
		10-30	4.9	26.8	59.5	Clay	1.87	100

The laser scanner provides a visual picture of each scanning surface. The image includes a visible red green blue image overlain on the 3D laser scan. Figure 13 shows a summary of these images, one image of the soil surface is shown for each site. Scan gaps show up in the image as white. Theoretically, these scan gaps are representative of gaps between structural units or cracks in the soil. The visible difference seen in the field can also be seen in scan images from differing land managements (Fig. 13). Scans of the soil surfaces in perennial grass management are all darker and appear to have smaller and more granular structure. The scans of soils under conventional till management appear to have more massive structure. As described in Table 1, the scans of soils under no till management seem to fall somewhere in between with structure that is more coherent and smaller than the conventional till managed soils but not granular like the perennial grass managed soils. This difference in structure is similar to the visible difference that showed up in tessellation outputs from the Objective 1 results (Fig. 8), with P sites showing smaller more numerous structural features than NT or CT. Differences within a management category itself are visible in the scans as well. For example, the P field from Milam county group is visibly different than the other two P fields. The soil from the P field from the Milam county group appears to have more compact and slightly larger structure.

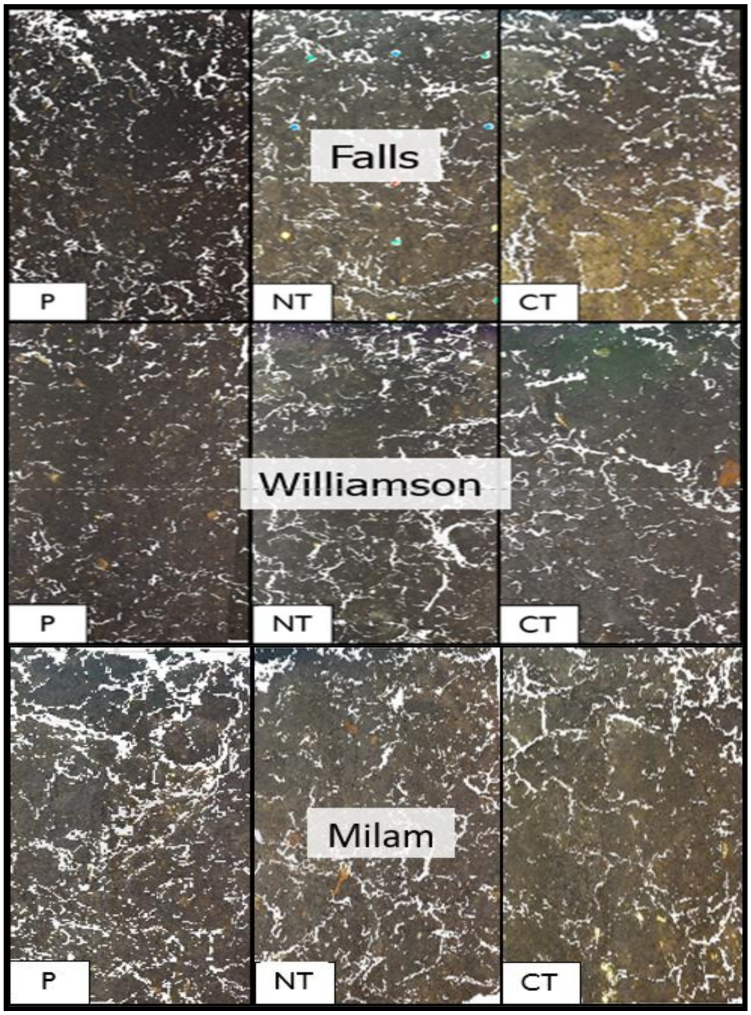


Figure 13: A comparison of Wide resolution scans of Perennial (P), No till (NT), and Conventional till (CT) sites in Falls County, Williamson County, and Milam County. Each scan is 33 cm tall and 25.4 cm wide.

Figure 14 shows the average tessellation areas from the A horizons of the differing land managements in each county from the Macro scans and Fig. 15 shows the same from the Wide Scans. For both Macro and Wide, the only county to show statistical differences between the average tessellation polygon areas in the A horizons was Falls County. Wide and Macro scanning resolutions produce similar outcomes (Figs. 14 and 15). This is expected because the regression line between them has a slope of 1.

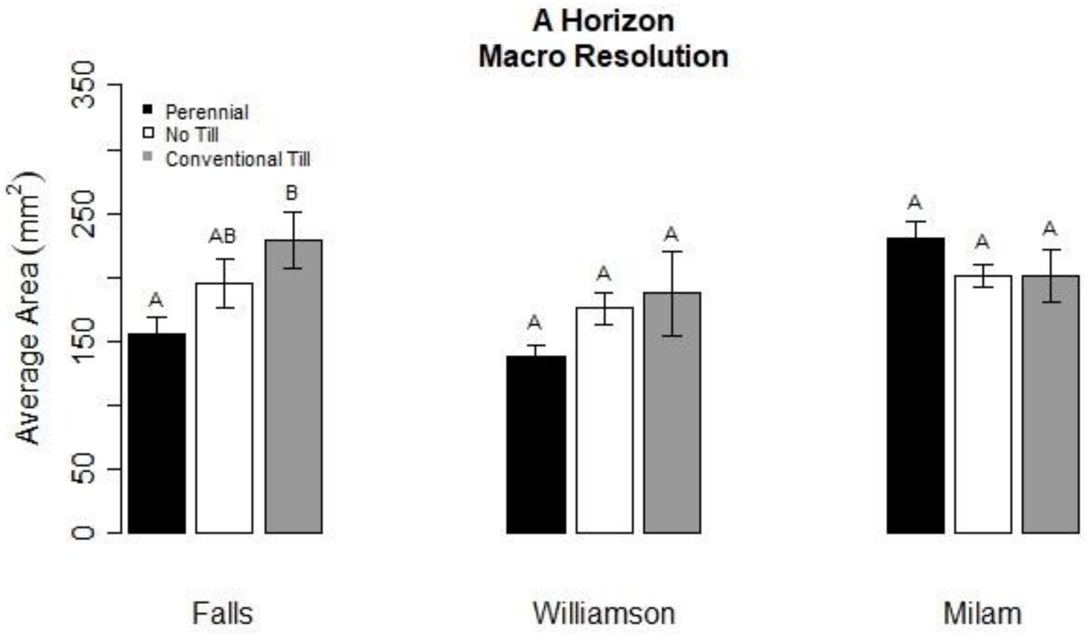


Figure 14: The average tessellation areas from Macro scans of the A horizon from all sites and management types.

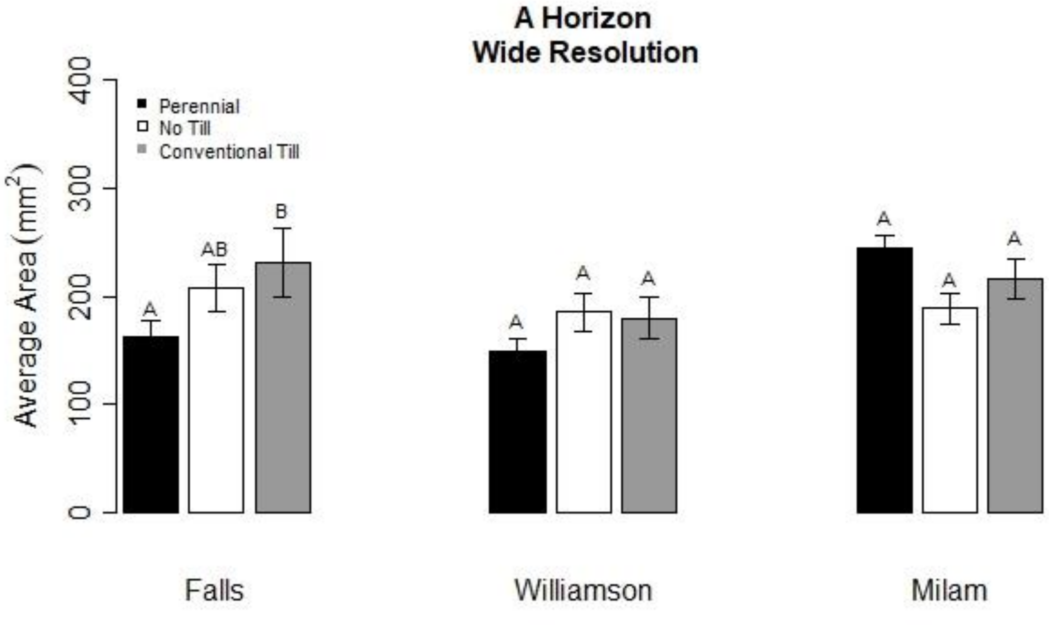


Figure 15: The average tessellation areas from Wide scans of the A horizon from all sites and management types.

Because the Wide resolution is proven to be as effective as Macro scanning, the rest of the presented and discussed results are only from Wide resolution scans. Falls County average tessellation areas from the CT field were statistically different from NT and P fields (*p* = 0.03). Though not statistically significant continuously, the Falls county results follow the expected trend of tessellation areas with management CT > NT > P. This aligns with what was seen and described in the field and what can be seen visually in the scans. In Williamson County, the average area in the P field was numerically less than NT and CT fields, but the NT was slightly greater than the CT field. This also aligns with what was described in the field as the NT and CT field had similar structure (Table 1). This Williamson county NT field had not been under NT management very long and so it could be expected that the structure would still resemble that of a CT field. In Milam County, the P field had greater tessellation areas than expected compared to NT and CT. Comparing this to what was described in the field, the Milam P field had larger and more angular structure than the other P fields. Also as noted in the scan images it appeared visually to have larger more compact structure. Though the differences in tessellations are not showing the trend we anticipate (and that soil scientists would like to demonstrate) based on management, they are picking up on visual observations of soil structure (Table1).

The Williamson and Milam county results do not exactly follow the expected trends from a management standpoint, but this could be attributed to factors other than the measurement alone. Our experimental approach was developed to look at the scanning procedure rather than testing differences in soil structure with management.

The focus when selecting sites was mainly on finding fields with soils that were as similar as possible, not on aligning all management factors. In Falls and Williamson counties, all three managements were under the control of one person. In Milam county, all three fields were under different landowners. Additionally, our management categories are very broad and undifferentiated. For example, among the perennial fields, the Falls County field was in native prairie that has never been plowed and both Williamson and Milam P fields are pastures that are grazed were historically plowed. We do not have the stocking rates or grazing history. Another example is that the fields under NT management have been so for different amounts of time. We do not have the exact amounts of time for each field, but the NT fields in the Falls and Milam groups have been under NT conditions longer than the NT field in the Williamson group. Taking into consideration possible differences within the management categories themselves, the variation in the above results are reasonable and resemble what was seen in the field.

Differences in structure and scan results can also be seen from one horizon to the next. Tessellation areas from the A horizon as described in the field were compared to tessellation areas from the bottom of the A horizon to a depth of 30 centimeters and there was a statistical difference ($p = 0.002$). Meaning that using this analysis on Wide scans can be used to pick up on differences in structural conditions at depth, between horizons. To see if differences between land managements could be seen below the A horizon, subsurface tessellation areas were compared (Fig. 16). The only statistical difference between managements at a subsurface level was in Milam County where the P field average area was larger than the NT ($p = 0.003$) and CT fields ($p = 0.007$). In Falls County the subsurface average area was smaller in the P field than then NT and CT fields. The smaller average area is expected as the P field has never been plowed and both the surface and subsurface have natural structure intact. In Williamson County, all the average areas were similar. At this stage, it is unclear if land management differences are not affecting the subsurface or if the different managements have not been in place long enough to see effects on subsurface horizons.

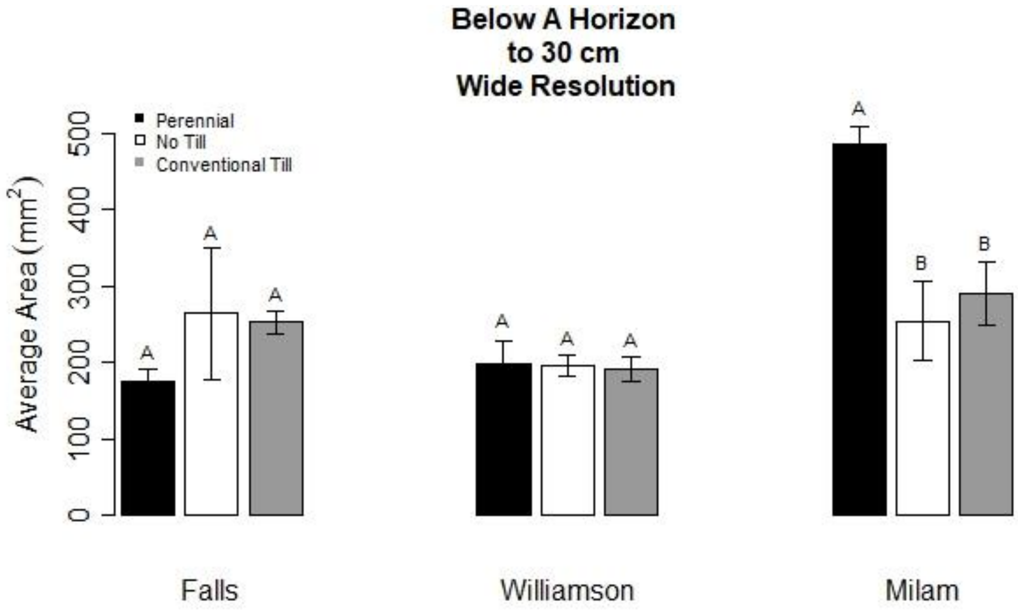


Figure 16: The average tessellation areas from Wide scans of below the A horizon to 30 centimeters from all sites and management types.

The average tessellation areas of the A horizons were also compared to results from the lab analysis of other soil properties related to soil structure. Average area is compared to volumetric water content in Figure 17a. There was no strong correlation between tessellation area and volumetric water content. Figure 17b is a plot of the average areas against the bulk densities. Even though we did see higher bulk densities in mainly CT fields as expected, there was no strong correlation between tessellation area and bulk density. Finally, in Figure 17c there is a comparison of average areas and organic carbon content. While again there is no strong correlation between tessellation area and organic carbon content, the two P fields with the lowest average areas had the highest organic carbon contents as expected. None of the properties of volumetric water content, bulk density, or organic carbon content were significantly different by management ($\alpha = 0.05$). In theory there should be a correlation between soil structure, these properties, and management. It is likely that no correlation of these soil properties exists as a function of management because of multiple reasons 1) each management is implemented by a different person (this was not a replicated experiment with one person performing the soil management), 2) the managements may not be in place long enough for a significant difference, 3) the managements selected may not be capable of presenting significant differences in these mangements.in these soil properties, and 4) the laser measurement of soil structure focuses on the size component of structure and not type or grade. Further refinement of analytical methods used to process the 3D laser data may provide more useful soil structure indices and hence better correlation to soil properties in Fig. 17. The lack of correlation between the tessellation analysis results and lab analysis results suggest that the analysis is measuring something independent of the other soil characteristics we measured. Considering this and the correlation found with land management and what we can physically see in the field as a whole, the results of this study affirm that a quantitative soil structure metric could provide important information that we are not already getting from other soil field measurements.

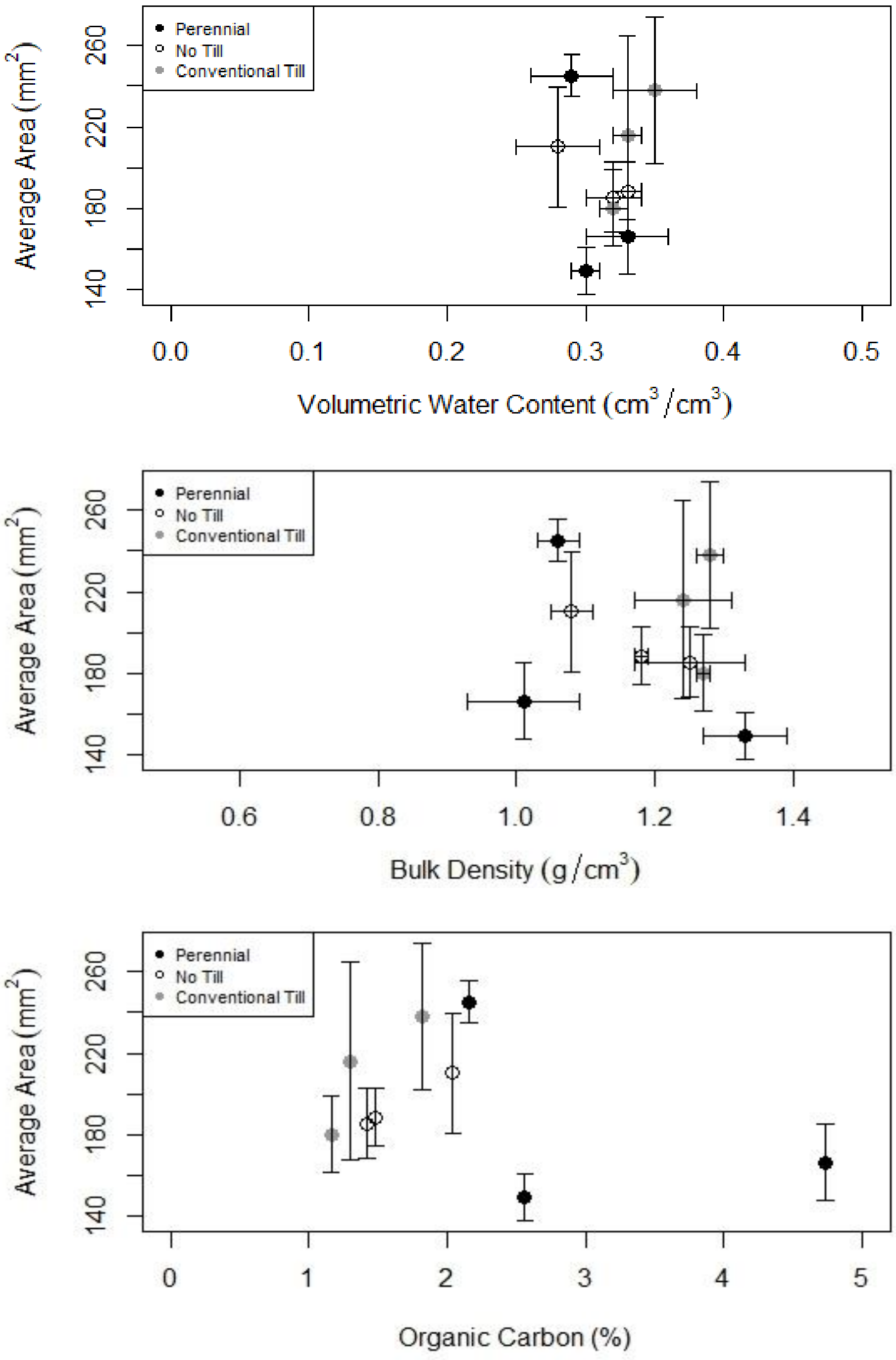


Figure 17: Average tessellation area versus a) volumetric water content, b) bulk density, and c) organic carbon from all sites and management types.

CONCLUSIONS

Practicality of 3D Scanning in Quantitative Structural Analysis

MLT scanning can be used in the field to quickly capture useful quantitative soil structure data. The field method presented used two resolutions, Wide (0.4 mm) and Macro (0.1 mm) resolutions. Scan collection and processing on the Wide scans required 20 minutes and was 70 minutes quicker than that of Macro scans, yet both are capable of producing comparable and repeatable results. Analysis of scans using dirichlet tessellations in the R “polygon” function (R Development Core Team, 2014) gave quantitative information about polygon count and size. A regression of Wide and Macro polygon counts showed a positive linear slope not significantly different that 1 (p = 0.09) and bias towards higher polygon counts in Macro. Since no significant difference was seen between the results of the two resolutions, the quicker and more easily conducted Wide method is recommended. Scan results from different pits within feet of each other in a field produced similar average polygon count and areas, demonstrating the field method is repeatable.

Visual differences in analysis outputs generally mirrored differences in the field descriptions and visual differences in raw scans, quantifying what we can see in the field. The average polygon area showed a significant difference (p = 0.002) in structural conditions between the described horizons. In Falls County, TX the most notable differences in soil structure between managements were quantified (p = 0.03) between average polygon areas between the P and CT fields. However, at the other locations, no significant differences between land managements were found using the scanning methods. Some of the fields measured in this were likely not under a single land management long enough to develop significant structure differences. Results from this study show that there is a potential, with continued research, that a robust method for quantitative structural analysis could be developed using 3D scan data. With the data collected and analyses completed in this project, it is unclear if 3D laser scanner is measuring actual structural units or roughness patterns. The tessellations are clearly picking up smaller features than a structural unit itself at times (i.e. surface roughness).

While the tessellation data showed no strong correlation with the other soil characteristics such as volumetric water content, bulk density, and organic carbon content, better numerical techniques may be developed to better extract information for the 3D scanning data. However, the absence of correlation with other soil characteristics suggests that the scanning and analysis is providing independent measurements from already existing methods. This affirms that quantitative soil structure information would add to the overall understanding of soil health and function, as structure may be a useful health indicator on its own beyond its link with the other characteristics.

Recommendations

The results of this work are a basis for future work in quantitative analyses of soil structure. Tessellation analysis could be further refined for more precise size parameters. Parameters of the tessellation analysis itself, such as raster resolution, can effect tessellation count and area results. More work could be done to identify ideal raster resolution settings. We noted during the evaluation of different raster resolutions, that a possible solution might be the use of different resolutions for different structure size groups. A different elevation raster image quality might allow the tessellation to pick up on a different sizes of structural units or spatial patterns. A future study on a wide variety of structure sizes may yield more insight on adjusting the tessellation analysis. The results of such a study could give a better understanding of which spatial patterns the tessellations are measuring and what the polygon area is representative of.

An independent variable that greatly influenced the outcome of the data was field conditions. During preliminary work, it was noted that water content of the soil can have a large effect on the outcome of the scans, especially in the Vertisols that were investigated in this study. Just as there are obvious differences to an observer in soil structure in the field from a wet soil to a dry soil, the scans can see those differences as well.

The time that a field has been under a particular management and differences in managers also affects the ability to accurately compare results. Perhaps eliminating these variables and performing a long-term study on one field that is undergoing a change in management would provide more useful results in tracking structural changes as a result of land management.

Finally, further work on contour analysis to identify shape parameters and distinctness parameters for use in conjunction with size parameters would be useful.

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