INDICATORS TO COMMUNICATE LINKS BETWEEN NO-TILL AND SOIL FUNCTIONS IN THE MIDDLE AND LOWER BRAZOS RIVER WATERSHED

A Dissertation

by

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ABSTRACT

Adoption of no-till is low in the Lower and Middle Brazos River Watershed of Texas, leaving soil vulnerable to erosion, exacerbating flooding, and contributing to high nutrient and sediment levels in surface waters. To aid in the adoption of no-till, changes in soil health need to be measured and related to things that both clearly and directly matter to farmers and stakeholders, yet soil scientists are grappling with which indicators to measure when assessing soil health. We investigated which indicators of soil health were meaningful to farmers using qualitative analysis of transcripts from focus groups. We also measured whether these indicators were changing as a result of no-till adoption in farmers' fields. We collected soil health measurements in perennial fields as a benchmark to compare both no-till and conventional tillage. Farmers were concerned about profitability and influenced by social interactions, but soil health remained an important concern for them when making management decisions. Organic matter and "water management" were the indicators of soil health farmers found most meaningful. Organic carbon was significantly higher in no-till compared to conventionally-tilled fields. Conventional fields had significantly lower saturated hydraulic conductivity than perennial fields. Saturated hydraulic conductivity was 1.3 cm h^{-1} higher in no-till than in conventional fields. Soil structure measured from 10- to 30-cm depth was significantly improved in no-till compared to conventional fields. These improvements in organic matter and hydraulic function are meaningful indicators of soil health that can be used to promote no-till adoption and provide ecosystem services to off-site stakeholders who are impacted by erosion and sedimentation resulting from conventional tillage.

DEDICATION

For Morgan Lane and a Wolfpen loamy fine sand.

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Contributors

This work was supervised by a dissertation committee consisting of Professors Cristine Morgan and Paul De Laune of the Department of Soil and Crop Sciences, Professor Alex McIntosh of the Department of Sociology, and Professor Richard Woodward of the Department of Agricultural Economics.

The focus group data in chapter 2 were collected by Cristine Morgan of the Department of Soil and Crop Sciences, Alex McIntosh and Marissa Cisneros of the Department of Sociology, Richard Woodward and Michael Black of the Department of Agricultural Economics, and Erin Kiella of the Texas A&M University Real Estate Center. The soil structure scanning data analyzed for Chapter 3 were partly collected in collaboration with Sarah Vaughan of the Department of Soil and Crop Sciences. The slaking index data in Chapter 3 were collected and analyzed in collaboration with Kade Flynn of the Department of Geology. All other work conducted for the dissertation was completed by the student independently.

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1. INTRODUCTION AND LITERATURE REVIEW

Soil supports human life and wellbeing by contributing to the production of goods and also to ecosystem services, such as provision of food, wood and fiber; flood mitigation; provision of physical support; filtering of nutrients and contaminants, carbon storage and greenhouse gas regulation; and detoxification and recycling of waste (Dominati et al. 2010; Dominati et al. 2014). Soil management affects soil function and therefore both the provision of ecosystem services and the production of goods. Consequently, decisions made by soil managers affect all people who benefit from the ecosystem services that result from soil functions.

Soil is used for agriculture on three quarters of the acreage in the state of Texas (National Agricultural Statistics Service, 2018). Production of the row-crops corn, cotton, sorghum, and wheat occupies a combined 24% of the 171 million acres in Texas (National Agricultural Statistics Service, 2018). Conventional tillage practices for these and other row-crops involves frequent tillage, which leaves the soil bare, increases the risk of soil erosion, reduces surface soil organic matter, reduces soil water content by exposing subsurface soil to evaporation, and breaks naturally-formed soil structural units (Palm et al., 2014). Soil structure is defined as the hierarchical organization of the soil solid phase in to soil structural units, which are called peds (Tisdall and Oades, 1982). The soil solid phase is made up of primary particles (sand, silt, and clay) and organic matter that aggregate to form peds under the influence of soil wetting and drying, microbial exudates, and root influences (Bottinelli et al., 2015). Soils with little structure have fewer peds and therefore fewer pores between peds, allowing less water to infiltrate into the soil, and more water to run off the soil surface. Surface runoff of rainfall and the subsequent soil erosion that it causes are a source of sediments, nutrients, and other contaminants in water systems.

In the Middle and Lower Brazos River Watershed of Texas, sediment loading is a concern for several reasons. Sediment is affecting the numerous flood control reservoirs managed by the Brazos River Authority (Brazos River Authority, 2017) and the Army Corps of Engineers. For example, sedimentation at Lake Granger is filling the reservoir faster than anticipated and reducing the reservoir’s storage capacity. Also, excess nutrients and pesticides are concerns in the river (Brazos River Authority, 2017). Finally, flooding is a persistent concern in the Lower and Middle Brazos River Watershed (Rice, 2016). These problems are exacerbated by increases in heavy precipitation events in Texas (Karl, et al. 2009; Mishra and Singh, 2010) that overwhelm the soil’s ability to infiltrate water, leading to larger proportions of water running off agricultural fields, entering water bodies, and causing flooding.

Each of these problems is rooted in the degradation of soil condition due to agricultural practices. To address this problem, the effects that tillage practices have on soil functions must be measured and communicated to decision makers. We propose that the needed links between soil condition and ecosystem services are selected biophysical metrics that will be specific to the study region and communicate value to stakeholders, termed “linking indicators.”

BACKGROUND

Soil management practices that improve rainfall infiltration and reduce runoff can be implemented to increase the provision of ecosystem services in the Lower and Middle Brazos River Watershed. One such management practice is conservation tillage, which is an alternative to conventional tillage practices. Conservation tillage was first introduced to combat erosion in response to the US Dust Bowl (Joel, 1937). Conservation tillage was widely adopted between the 1982 and 2002, and this resulted in average rates of erosion on cropped lands dropping from 9 to 6 Mg ha^{-1} yr^{-1} (Nearing et al., 2017). Nearing et al. (2017) also found that converting cropped land to perennial systems had the potential to reduce average erosion rates to 1 Mg ha^{-1} yr^{-1} or less. Conservation tillage is a broad term and may refer to a spectrum of practices ranging from reducing plowing events per season to complete elimination of plowing. No-till is a form of conservation tillage that eliminates soil plowing by simply opening and closing a slit in the soil for planting seeds, which is a minimal disturbance of soil structure. No-till was the conservation tillage practice that this study focused on, because the minimal disturbance it causes has the potential to increase soil ecosystem services by allowing soil structure to develop.

No-till

The concept of no-till was suggested in 1943 by Edward H. Faulkner in his book, *Plowman's Folly*, but was not widely adopted until after chemical weeding technology became commonplace following the second World War, because tillage served as a mechanical means of weed control. Aziz et al. (2013) found that, after 5 yr of no-till, soil quality significantly improved as indicated by increasing soil microbial biomass, basal respiration (a measure of microbial activity), total carbon, total nitrogen, and aggregate stability. A key benefit of no-till is that it allows native formation of soil structure. Soil structure has a major impact on soil hydraulic properties because it changes the arrangement of the soil solid phase that water infiltrates through. The development of soil structure underpins changes in soil hydraulic functions that are critical in the Middle and Lower Brazos River Watershed, which is a dryland cropping region. Improvements in soil structure can increase infiltration rates and plant-available water, and improve drainage in wet springs (de Moraes et al., 2016; Moncada et al., 2014; Mueller et al., 2011).

No-till farming has benefits to the soil manager including reduced energy use, labor, and wear on machinery because fewer passes over the field are required (Allmaras and Dowdy, 1985; Vitale et al., 2011). However, tillage has served many functions in production agriculture, and when a soil manager transitions to no-till, other methods must be found to carry out those functions. The use of chemical weed control has already been mentioned to replace cultivation. A second example is the use of tillage to level rills and gullies caused by erosion; this is not possible when using no-till management. Prolonged use of no-till therefore requires that such erosional features be prevented from developing. A third issue is that machinery traffic during crop production and harvest operations puts weight on soil and may lead to soil compaction regardless of what tillage practice is used (Bakker and Davis, 1995). Compaction can present problems with planting by preventing seed-soil contact. Soil that is compacted has less pore space available for air and for water and has negative effects on crop growth (Hamza and Anderson, 2005). Hamza and Anderson (2002, 2003) found that water infiltrates much faster in soils that have well-aggregated soil relative to compacted soils.

While tillage, such as deep ripping, has been used to temporarily alleviate compaction, alternative practices are available such as the use of cover crops, increasing organic matter, reducing the weight of machinery, controlled traffic, and no-till (Hamza and Anderson, 2005). Controlled traffic is the restriction of soil compaction to the traffic lanes to allow an uncompacted rooting zone (Braunack et al., 1995). Tilling effects compaction immediately, but these alternative practices take time to develop soil structure and reduce compaction and its effects, making them less desirable to a famer.

Farmers rarely link their land management practices to degradation of soil structure because it is not apparent on the soil surface (Hamza and Anderson, 2005) and farmers may not have observed well developed soil structure since fields have been plowed for many years. Though they take time to show results, alternatives to tilling may be more effective in the long run. For example, deep ripping can alleviate soil compaction temporarily, yet it makes soil more susceptible to compaction (McGarry and Sharp, 2001; Spoor, 1995). Also, Ellies et al. (2000) found that in well-aggregated soils, compaction due to traffic was not as deep as in poorly aggregated soils. If compaction is removed and then a controlled traffic, no-till system is adopted, the soil water infiltration rate can be similar to that of soil that has not been plowed (Li et al., 2001).

These discussed issues illustrate that adopting no-till requires the soil manager to find alternative practices for several crop production operations, which is one reason that no-till adoption may have remained low in our study area. Soils in our geography of interest are high in clay and therefore especially subject to compaction and erosion. Despite the complexities of implementation, no-till has spread in North America, South America, and Australia (Derpsch et al., 2010) and its adoption is increasing worldwide (Freidrich et al., 2012). However, in Texas, no-till has only 6% adoption in corn (2007) and 8% in cotton (2010) by land area (Economic Research Service, 2015).

No-till delivers many ecosystem services (Palm et al., 2014), though it presents tradeoffs that require planning to navigate. Higher adoption rates of no-till in the Lower and Middle Brazos River Watershed have the potential to improve soil structure and reduce sedimentation from erosion. Changes in soil structure, and therefore in soil hydraulic properties that result from no-till, need to be quantified and included in hydrology models so that the beneficial impacts can be weighed against the challenges of implementing no-till. Models that predict hydrologic changes resulting from no-till would allow soil managers and off-site stakeholders to make informed decisions about implementing (manager) or supporting (stakeholder) no-till.

Soil Structure

Most widely accepted methods of characterizing water flow through soil assume a structureless, homogenous soil (Beven and Germann, 1982; Wang et al., 1994). The rate at which water flows through a continuous soil matrix is governed by the hydraulic conductivity of the matrix, which is an expression of the ease with which water may move through the soil matrix of particles. Soil texture is primarily used to parameterize models of water flow through soil. This is done either by applying texture class to a look-up table or sand and clay % to a pedotransfer function to estimate soil hydraulic conductivity (Rawls et al., 1982; Saxton and Rawls, 2006). However, it is soil structure, not texture, that responds to management practices, such as no-till, and the impact of soil structure on hydrology has long been recognized (Bouma and Dekker, 1978; Wu, et al., 1990; Chen et al., 1993; Connolly, 1998).

The interfaces between peds can conduct water down the soil profile, bypassing the soil matrix, therefore this flow is not governed by soil matrix hydraulic conductivity. Rather, it responds primarily to gravity and is termed preferential flow. Preferential flow allows water to move faster down the soil profile because the flow is not restricted by soil particles in its path. Well-structured soils have many preferential flow paths because of the continuousness and abundance of soil structural interfaces. Representing water flow in both the soil matrix and preferential-flow domains allows more realistic modeling of water-flow through soil (Connolly, 1998; Šimůnek et al., 2003; Jarvis, 2008; Lepore et al., 2009), but inclusion of preferential flow is not commonly done. The inability of hydrology models to capture how soil structure changes in response to management weakens our ability to quantitatively model soil ecosystem services provided by soil management practices. Soil structure can be integrated into hydrology models (Lepore et al., 2009), but first, soil structure must be quantified.

A recent review on quantifying soil structure concluded that imaging techniques were best suited to quantifying indicators of soil function (Rabot et al., 2018). While imaging has traditionally required removing soil from the field and taking costly, small (< 1 cm^3) scale lab measurements (Rabot et al., 2018), a field method of soil structure scanning has been developed (Eck et al., 2013; Eck et al., 2017) using multistripe laser triangulation (MLT). Bagnall et al. (2019) built on the work of Eck et al. (2013 and 2017) by changing scan-collection methodology to be faster and more practical for the field. The method used by Eck et al. (2017) required preparation of the soil profile by freezing and removing the pit face, which is time consuming and required bringing soil monoliths of profiles into the lab intact (Eck et al., 2013; Hirmas, 2013). Bagnall et al. (2019) reduced preparation time to ~ 1 hr per pit after surface pits were opened for 1 d to dry. The scans were processed in the software created by the manufacturer of the scanner (NextEngine, 2009), point clouds were converted to rasters in R (R Development Core Team, 2018), and Dirichlet tessellations (Stoyan et al., 1992) were computed on the raster surface. The number and size of the Dirichlet tessellation-derived features was found to be related to management (perennial, no-till, or conventional tillage). Multistripe laser scanning holds promise as a method to quantitatively measure soil structure. This quantification would allow the effects of no-till on soil structure to incorporated in to hydrology models, enabling ecosystem service benefits of no-till to be quantified.

Linking Indicators

Social interest in “healthy soil” is growing and businesses and non-profit organizations are pushing for the adoption of soil health practices, such as no-till, to generate downstream ecosystem services (Griffiths, 2016; Miller Coors, 2019). While there is consensus that accounting for ecosystem services, like those provided by no-till, should be done, the methods with which to account for them are not agreed upon. Whether or not to adopt no-till is a management decision made by farmers. Adoption of any new technology has challenges for the adoptee and these challenges are more pronounced for innovations whose benefits are preventative and long-term in nature (Rogers, 2003), as is the case with no-till.

Soil scientists have used valuations such as the damage associated with erosion (Smith, 2014; Duffy, 2012) or partial budgets for new technologies (Townsend et al., 2016) to encourage land managers to change practices. These methods may not have been persuasive because soil managers do not find them credible, salient, and legitimate (Ingram et al, 2016) and also because the metrics and language used to communicate was not understood by farmers (Reimer et al, 2014). Also, since some benefits of no-till are experienced by people other than the soil manager, those benefits may not be considered by the soil manager.

Non-market valuation of ecosystem services has been used since at least the 1960s (deGroot et al., 2012) and is another way to account for ecosystem services. Valuation estimates have been made for many ecosystem services, including, more recently, soil ecosystem services (McBratney, 2017). While the sums that result from such valuations are impressive, non-market valuations of soil ecosystem services are values that are not experienced by decision makers and perhaps not by anyone at all (Toman, 1998) and this may explain why they have not resulted in higher adoption rates.

Another option to value soil ecosystems services is to use biophysical measurements that convey value to a particular audience, in our case, farmers in the Middle and Lower Brazos River Watershed. The metrics needed to convey the value of soil ecosystem services to farmers are termed “linking indicators” (Boyd et al., 2014) or “benefit relevant indicators” (Olander et al., 2018). Such indicators would show changes in soil function that result from changes in soil management, be measurable, and have clear and direct value to their target audience (Boyd et al., 2014). Linking indicators may be visualized as elements in a causal chain (Fig. 1.1). The causal chain in Fig. 1.1 shows a conceptualization of how no-till may be important to farmers because it affects their income. A measurement of how no-till changes soil structure is unlikely to be clearly valuable to a farmer. The capture and storage of water resulting from that change in soil structure may be more important, but it is not until it is converted to the amount of water that would be available for crops in a given year that a farmer can value the change. A particular farmer may value that amount of water a great deal in a dryland situation and much less if irrigation was available and not too costly. Whether a given amount of water is valuable (results in increased yield) would depend on other variables such as the type and variety of crop and the weather. The linking indicator in this example is water for crops because it is quantitative and farmers are likely to know how much it is worth to them. It does not require assumptions that would restrict its use as would the next step in the causal chain (crop yield) because of the situation-specific variables.

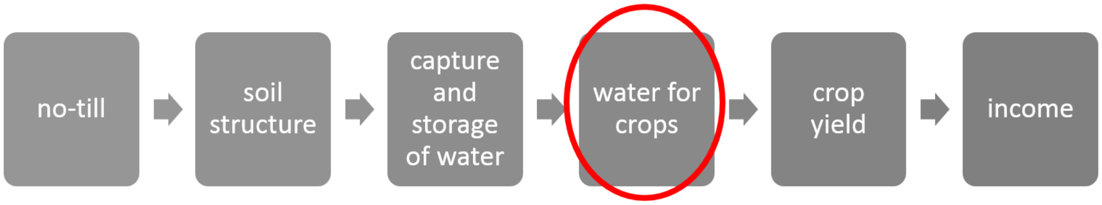

Figure 1.1 A causal chain linking no-till to metrics that farmers value. Water for crops is the linking indicator in this causal chain and is marked with a red oval.

Reducing the reliance of indicators on situation specific variables makes such indicators more broadly applicable because different people evaluate innovations differently based on their needs and abilities (Goodhue, 1995). Even so, linking indicators are audience-specific (Boyd et al., 2014). It has been shown that researchers who gain meaningful experience with conservation tillage practices in the local context are more effective at promoting successful adoption (Bossange et al., 2016). The fact that the benefits and challenges of no-till, as well as the predisposition of farmers to adopt it, are unique to our study area motivated this research project to measure soil function directly in farmer's fields in the Middle and Lower Brazos River Watershed. The overall goal of this study was to identify linking indicators that quantify the value of improved soil functions resulting from no-till to things that clearly and directly matter to farmers in the study area. In order to do so, we used focus groups of farmers who had adopted no-till and farmers who had not adopted no-till to understand which indicators of soil health and function they perceived as meaningful. We also measured changes in soil function in farmer's fields with a suite of soil health measurements and compared how these measurements were different in no-till, conventional, and perennial fields.

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2. COMMON GROUND: DEVELOPING MEANINGFUL, MEASURABLE INDICATORS OF SOIL HEALTH FOR THE BRAZOS RIVER WATERSHED IN TEXAS

INTRODUCTION

Social interest in healthy soil is growing, and businesses and non-profit organizations are pushing for the adoption of soil health-promoting practices (SHPP) to generate downstream ecosystem services (Griffiths, 2016; Miller Coors, 2019). Soil scientists are grappling with which indicators of soil health to measure (Stewart et al., 2018), but ultimately the decision to adopt a SHPP is a management decision made by farmers. For this reason, changes in soil health must be presented to farmers in a manner that is credible, salient, and legitimate (Ingram et al., 2016) and using language that farmers understand (Reimer et al., 2014). Adoption of any new technology has challenges for the adoptee. These challenges are more pronounced for innovations which have preventative benefits and are long-term in nature (Rogers, 2003), as is often the case for SHPPs. People evaluate innovations based on their own needs and abilities (Goodhue, 1995), complicating the search for meaningful indicators of soil health. Useful indicators of soil health should (i) show changes in soil function that result from changes in soil management, (ii) be measurable, and (iii) have clear and direct value to their target audience. Such indicators are termed “linking” or “benefit relevant” indicators (Boyd et al., 2014; Olander et al., 2016). They may be useful tools for promoting the adoption of soil health, as they communicate benefits of soil health that farmers find meaningful.

In Texas, the adoption of SHPP is low. For example, no-till has only 6% adoption in corn (2007) and 8% in cotton (2010) by land area in Texas (Economic Research Service, 2015). The Brazos River Watershed in Texas is a region that would benefit from widespread adoption of SHPP. In the watershed, significant off-site consequences of soil management include sediment loading which affects storage capacity of flood control reservoirs managed by the Brazos River Authority (BRA) and the Army Corps of Engineers. For example, sedimentation in Lake Granger is filling the reservoir faster than anticipated and reducing the reservoir's storage capacity (Brazos River Authority, 2017). Sedimentation is also impacting aquatic animal species in the river, disrupting habitat for endangered species (pers. comm., Tiffany Morgan, BRA) and fish sought by anglers (pers. comm., Brian Van Zee, Texas Parks and Wildlife Department). Excess nutrients and pesticides are also concerns in the river (Brazos River Authority, 2017). Low adoption rates of SHPP leave soils vulnerable to erosion in agricultural fields, exacerbate flooding, and contribute to high nutrient and sediment levels in surface waters. Therefore, conventional soil management in Texas row-crop agriculture has negative consequences for off-site ecosystem services. This problem will grow as extreme weather events continue to become more common (Mishra and Singh, 2010).

To increase adoption rates of SHPP by farmers in the Brazos River Watershed, linking indicators of soil health can be identified using selection guidelines. The first principle that Boyd et al. (Boyd et al., 2014) list for linking indicator selection is that ecological production functions should be used to link biophysical outcomes and their indicators. This is done using input-output frameworks that describe causal relationships between inputs, like SHPP, and outputs, like changes in soil health or ecosystem services. Chains of causal relationships allow us to differentiate between inputs (e.g., using no-till) and outputs (e.g., changes in soil structure) as well as the degree to which outputs are closer (proximal) to or farther (distal) from a stakeholder’s welfare. For example, after implementing no-till, a change in soil structure is a distal indicator compared to increased plant-available water for crop production, which is a more proximal indicator.

A second principle for identifying linking indicators is to measure biophysical changes that matter as directly as possible to social welfare. These are changes valued as ends in themselves (Johnston and Russell, 2011). In the example above, the farmer values an increase in yield (resulting from increases in plant-available water) as an end unto itself, whereas an increase in plant-available water is not an end unto itself.

The final principle is that, because stakeholders are heterogeneous, linking indicators are expected to be stakeholder specific (Johnston and Russell, 2011; Reimer et al., 2014). This specificity means that indicators are useful only when presented to the appropriate audience. Indicators which matter to larger numbers of stakeholders are preferred, but a balance must exist between how specific (and therefore meaningful) linking indicators are and how broadly applicable they are. Boyd et al. (2014) stated that people’s perceptions of what matters directly to their welfare is an empirical question. Answering this empirical question requires engagement with stakeholders, and it has been shown that researchers who gain meaningful experience with SHPP in the local context are more successful at promoting SHPP adoption (Bossanage et al., 2016).

GOAL AND RESEARCH QUESTIONS

Successful promotion of SHPP requires that farmers perceive that changes in soil health are meaningful. We differentiate between two primary types of decisions farmers make regarding soil health: 1) paying to purchase or lease land because they prefer healthy soil and 2) engaging in management practices that promote soil health. The goal of this study was to discover which (if any) changes in soil health farmers perceive as being meaningful to their welfare. This qualitative content analysis of focus group transcripts provided a foundation for the creation of ecological production functions linking the adoption of SHPP biophysical outcomes that farmers perceive are meaningful. The qualitative nature provided deep insights into how farmers describe soil health and to what degree (if any) soil health was a factor in their decisions to buy or lease land and their management practice decisions. The analysis was guided by four specific research questions (RQs):

- RQ.1 How do farmers assess soil health?
- RQ.2 Does soil health play a role in farmer decisions about land purchase or leasing?
- RQ.3 Does soil health play a role in farmer decisions to adopt, or continue to use management practices?
- RQ.4 What are the other major factors in farmers’ decision-making and how does soil health interact with those factors?

METHODS

Population

This study used semi-structured group interviews, referred to as focus groups, to address our research questions. Potential participants for the focus groups were identified through Texas Natural Resource Conservation Service (NRCS) and AgriLife Extension Agents and Specialists. These potential participants were contacted by phone and email. We notified them that they would be paid for their travel to the location, provided lunch, and given a stipend of $50. Participants self-identified as either adopters or non-adopters of SHPP. Adoption of no-till was particularly emphasized. Each participant was given a demographics questionnaire asking about their farm land: 1) the county in which they farmed, 2) the total number of acres they farmed, 3) percent of acres rented, 4) soil types, 5) crops grown, 6) tillage type(s) used, and 7) whether or not they used cover crops.

All focus group participants were males who farmed in the Lower and Middle Brazos River Watershed of Texas. The adopters focus group had seven participants and the nonadopters group had eight. On average, farmers in the focus groups rented 75% of the land they farmed. The minimum area of land farmed was 303 ha (750 ac), the mean was 1618 ha, (4,000 ac) and the maximum was 3682 ha (9,100 ac). The area of land farmed and the percentage rented was not substantially different between adopters and non-adopters. The crops farmed were corn, cotton, wheat, oats, grain sorghum, and pearl millet. One adopter also raised yearling calves. Every farmer grew at least two crops. All participants in the adopters group described their soils as clayey Blackland soils. The non-adopters also described their soils as clayey with two exceptions – one farmer described his fields as having some portions of sandy loam and another described his soil as loamy. In the adopters focus group, all but one farmer indicated that they used no-till or strip till extensively, if not exclusively. The remaining adopter described his tillage as "semi-conventional." The non-adopters group had one participant who reported using some strip-till and one who reported using some no-till. The remainder of non-adopters described their tillage practices as minimum-till or conventional. Four of the adopters and one of the non-adopters said they used cover crops on some or all of their fields.

Procedures

Each focus group lasted about three hours with a 30-minute break at 90 minutes. A semi-structured interview process was used. After participants introduced themselves, a moderator prompted the group with questions regarding their soil management practices, their observations about soil health, and how they obtain information about farming practices. The list of questions used by the moderator are in Appendix A. In addition to the moderator, researchers specializing in sociology, economics, and soil science were present and asked follow-up questions to gain clarity. Five researchers were present at the adopters focus group and six at the non-adopters group. All participants spoke during the focus groups, though some spoke more often. As an example, A6 spoke up most often in the adopters group and had roughly eight times as many speaking events as A4, who spoke least often (Table 2.1).

Table 2.1 Count of speaking events by participants for both focus groups

Adopters	**Events**	**Non-adopters**	**Events**
A1	65	N1	163
A2	47	N2	73
A3	155	N3	38
A4	18	N4	161
A5	53	N5	129
A6	158	N6	164
A7	72	N7	43
		N8	201

Each participant signed a consent form for audio and video recording. These recordings were transcribed, yielding separate transcripts for the adopters and non-adopters groups. Each farmer was assigned a code consisting of a letter based on the focus group (A for adopters and N for non-adopters) and a number. The transcripts were analyzed using content analysis (Berg and Lune, 2012). Content analysis is a systematic examination and interpretation of a body of material, including written documents, designed to code the content as data that can be used to address research questions. Researchers immersed themselves in the data by both watching video recordings and writing field notes on farmers' non-verbal communication and interactions with one another, as well as reading transcripts thoroughly to familiarize researchers with the concepts they contained. The transcripts were then open-coded (Strauss, 1987; Charmaz, 2006) using words, phrases, and paragraphs as the units of analysis. The linking indicator theory outlined in Boyd et al. (2012) was used as a sensitizing concept (Charmaz, 2006) during coding. After open coding, a codebook was created to define codes and note significant incidents related to each code. Focused coding was used to develop emergent themes and memos were written on emerging themes to develop concepts (Charmaz, 2006). Thematic development was based on memos and the constant comparative method (Glaser, 1965) was used to compare thematic incidents between and among focus groups.

FINDINGS AND DISCUSSION

With respect to RQ.1, a theme emerged that soil health was assessed using *indicators* that were largely qualitative and common between the two focus groups. Farmers preferred *agronomic indicators*. Soil health did not play a major role in farmers' decisions about buying and leasing land (RQ. 2). Decisions to buy or lease land were overshadowed by two themes: farmers were *land hungry because of urban growth* and farmers were *confident they could improve soil health* after they purchased or leased land. Soil health was perceived as an aspect of a *stewardship ethic* and did play a role in farmers' decisions about which management practices to adopt or continue to use (RQ. 3). With regard to RQ.4, the *stewardship ethic*, of which soil health is a part, is one of three themes common to both focus groups. The other two common themes were *profitability* and *social interactions*. A *tuition* theme also emerged in the adopters group, relating to the time and expense associated with adopting SHPP.

RQ.1 How do farmers assess soil health?

Farmers in the focus groups initially talked in general terms when questioned about how they knew soil was healthy. Many cited their intuition about what constituted healthy soil. Several variations of the phrase “you can just tell” were used. When pressed with follow-up questions, they shared examples of various indicators describing healthy soil.

Farmers’ indicators of soil health

Farmers were aware of physical, chemical, and biological aspects of soil health (Table 2.2). Some farmers spoke in quantitative terms, such as A5, who said "*[We had] 2% organic matter, now come to find 6%. And those soils are becoming more responsive…”* But overwhelmingly, the indicators were discussed in qualitative terms. Terms like “concrete” were used for compacted soil, which was contrasted to “carpet” for un-compacted soil. The two most consistent indicators described as the goals of soil management practices were water management and organic matter. The discussion of organic matter indicated each farmer had a conceptualization of how their own preferred management practices would change a soil’s health if they were to begin to farm it. The fact that farmers themselves provided mostly qualitative indicators of soil health does not mean that they would not respond to quantitative terms. Farmers’ use of quantitative terms may have been discouraged by the presence a soil scientist and the fear of being “judged” by an expert. Whether or not they use more quantitative terms amongst themselves cannot be tested with the present dataset, but further work could test whether farmers respond more strongly to quantitative or qualitative indicators of soil health.

Table 2.2 Indicators of soil health mentioned by farmers during focus groups.

Indicator	**Description**	**Aspect of Soil Health**
greenness of crops	Described relative to other nearby crops. Greener crops have access to more plant-available water in the soil.	physical
compaction	Words like “tight” and “hard” were used in addition to “compaction." Much of the discussion about compaction related to workability during planting.	physical
soil structure	Soil structure was explicitly referenced and described as being responsible for reduced ponding and increased infiltration.	physical
ponding	Compared to neighboring fields, the lack of, or shorter duration of, ponding was a positive sign.	physical
clarity of runoff	The clarity of water running off fields was evidence of healthy soil.	physical
water management	This was a “catch-all” term that described the partitioning of rainfall between runoff and infiltration. It was discussed in terms of preventing erosion as well as infiltration of water.	physical
erosion	Erosion was detected either when rills or gullies were observed in fields or when drainage ditches filled up with soil.	physical
microbiology	Only A6 mentioned microbiology specifically and stated it was the goal of cover crop planting.	biological
earthworms	Were not often mentioned, though A6 used them as evidence that cover crops were effective.	biological
soil tests	This was in reference to soil fertility.	chemical
organic matter	An often-mentioned indicator, it was consistently presented as desirable. Most farmers did not state what % of organic matter they had or wanted, though a few did.	physical, chemical, biological
yield	Soil health and yield were consistently perceived as being positively correlated.	agronomic
biomass	Presented in terms of above-ground biomass such as stalks and corn cobs. Higher biomass was perceived as positively correlated with soil health.	agronomic

In addition to physical, chemical, and biological indicators of soil health, two agronomic indicators, yield and biomass, were commonly mentioned. Farmers noted they observe their crops more than soil. Yield and biomass were often the “go-to” indicators in both focus groups. For example, A3 said, "*Well but you know the corn- you know enough to know that the corn’s not good if the dirt’s not good.”* Likewise, when non-adopters were asked to list indicators of soil health, N6 said “*Well just productivity in general, I mean healthy soil ought to be more productive.”* and N5 agreed with him, saying, *“That’s the bottom line I guess. Production.”* Compared to the other indicators, yield and biomass are more proximally linked to farmers’ welfare in that they are more closely related to their income.

RQ2. Does soil health play a role in farmer decisions about land purchase or leasing?

In response to whether farmers chose fields to rent or buy based on soil health, both focus groups had widespread agreement that soil health was not an important factor. In the non-adopters group, N5 said*:* “*Yeah, I think as farmers if you're actively farming or aggressively farming, I was like, you gonna take the land regardless [of how healthy the soil is] and try to do what you can with it.*” Similarly, in the adopters group, A5 said: "*But to us, as farmers, it don’t matter what the soil looks like it’s what – there’s other factors too*.” The other factors discussed during the focus groups are given in Table 2.3 along with brief descriptions.

The factors listed in Table 2.3 and soil health were overshadowed by the lack of opportunities to buy land and high land prices. Farmers were not unaware of the benefits of soil health, rather, their demands for land were high, and they perceived that they could improve soil health after they bought or rented a field.

Table 2.3 Factors in decision to buy or rent land.

Factor	**Description**
location	Farmers prefer fields close to their current fields and far from residential housing.
access	Quality of roads and bridges is important. Examples of poor access are narrow dirt roads and bridges that are likely to flood.
topography and field layout	High slopes, hilly land, and fields that are oddly shaped make management time-consuming and expensive.
existence of terraces	Terraces prevent erosion and aid in water capture. They were strongly preferred.
management history	Informal, local knowledge of previous owner's or tenant's use of fertility, yields, and management practices.
presence of rocks	Fields with rocks are not preferred.
length and price of lease	For rented land only. Longer leases are preferred because they provide certainty. All else equal, cheaper leases are preferred.

Land-hungry because of urban growth

In both focus groups, major lines of dialogue developed around urban growth reducing the number of fields for sale and raising the prices of those fields. As an example from the adopters group, A1 said "*I mean everybody in here- we're hungry for land. We want more land."* Further, A5, said "*If [badly eroded land is] cheap enough [I would buy it]- because we're dealing with urban growth"* and A6 agreed *"[Urban encroachment is] our number one thing with buying."* The same theme emerged for non-adopters. For instance, N1 voiced "*Urban pressure is a lot"* and N5 agreed, *"Yeah it's hard to compete and buy land and pay for it with agriculture, you know, production."* As an outcome of urban growth, farmers expressed that when they had the opportunity and financial ability to buy more land to farm, they did so, regardless of the health of the soil.

Confident they can improve soil health

Farmers in our focus groups expressed that if they purchased or rented a piece of land with poor soil health, they could improve it over time. A3 voiced this by saying,

> "*They're asking about what determined that price* of land. *Alright, well if you have done it long enough you know that I could take that piece of ground and I may bring my strip-till program over here and my no till-program… and I can make money with that piece of ground, with the guy that's plowing it all the time he can't."*

He went on to say that improving soil health would take time, a concept repeatedly voiced by other farmers in both groups. Non-adopters also talked about how their practices improved soil health. For example, N8 described the outcome of his manure applications, saying *"…our infiltration rates go up because the soil is so much healthier where we've been putting [manure]."* It was clear that farmers perceived soil health as a dynamic, though slowly changing, aspect of fields. This dynamic nature is one reason why soil health does not factor strongly into their decision to buy or rent land. This was explained by A5, saying:

> *"So yes, we, in the initial phases of this we do [no-till] just to save labor, cut cost and those types of things. But a couple of years into it we start to see what the NRCS, we're seeing with years of work, yes, you can change the quality of that land. In dramatic ways given enough time and patience. But it does not happen in a two- or three-year period."*

RQ.3 Does soil health play a role in farmer's decisions to adopt management practices?

Soil health was a component of a larger *stewardship ethic* for farmers in both focus groups. They were adamant farmers were stewards of the land and a *stewardship ethic* influenced their management choices. For example, the entire non-adopters group voiced verbal and physical agreement when N5 said "*To me- to me as a farmer we're- we're the- the -the least of my desire is to hurt the environment … We're the husbandry-men of the soil, our desire is not to hurt the soil.*"

Stewardship ethic

The idea of a *stewardship ethic* was a part of the identity of both adopter and non-adopter farmers. As an example, N1 said, "*I don't think [any farmer] is ever gonna make a decision that would be a detriment to the land period. It's just the way we are.*" Similarly, A3 said, *"Well you know…If you don't take care of [soil]- it won't take care of you."* Further, A3 asserts not only that farmers are good stewards, but that they are the best equipped to make stewardship decisions about their farms:

> *"You leave the land better than you found it. That's the whole bottom line. And who- who is more capable to take care of a farm than a guy that is investing his life in it? Can somebody out of town, can they come out there and tell you how to manage that farm? What's best for that farm? Just no!"*

Being a good steward was presented as a "win-win" for farmers as explained by A2, "*it seems like taking care of the land makes more money to be honest.*" The core ideas regarding *stewardship* where that 1) it was beyond question that farmers, as a group, would make decisions that were good for the environment and, more specifically, for soil health and 2) that soil health was good for farmers' profits. Both groups were also open about the fact that there were other factors at play, besides a *stewardship ethic* when making management decisions.

RQ.4 In what way does soil health interact with other factors in management decisions?

Other than the *stewardship ethic*, two other themes emerged that were relevant to farmers' decisions in both groups. These themes were *profitability* and *social interactions*. In the adopters group, a *tuition* theme emerged as well.

Profitability

Profitability was a major theme in both focus groups. A definition of *profitability* was offered by A2 that was consistent with the rest of the adopters group. He said, *"So I look at trying to keep profitability in my operation really it's -it's not making the biggest* *yield, but it's making the most economic yield, is what I've been trying to focus on."* In the non-adopters group, N3 gives a similar definition, "*So I'm trying to cut my cost and as well as equipment by going to minimum-till as much as possible."* Four different adopters used the term *profitability* 22 times. Only one non-adopter used the term *profitability*, but the concept was central to discussions in both groups.

Social interactions

In addition to the *stewardship ethic* and *profitably* themes, farmers were influenced by their interactions with other people. Landlords, family, neighboring farmers, non-farming neighbors, and people near farmers' operations all had opinions on how farmers should manage their land. The weight that farmers placed on these opinions varied from farmer to farmer, but farmers were generally similar in their opinion of who was most important.

Older people, including older landlords, were generally said to dislike no-till and cover crops. As A3 explains, older people have a negative perception of no-till: *"[No-till is] not- that's not what a farm is supposed to be. I mean a farm is supposed to be plowed, it's supposed to be. Any time it rains, it's supposed to be plowed and fresh and black- no crust."* The reason given by A6 for why older people do not like cover crops was because they go to seed and look ugly. Landlords had particularly strong influences because of the threat to the farmer of losing the lease on the land. When asked why he did not convert to 100% no-till, A6 offered this explanation *"Cause you'll lose the farm cause the landlord will take it away from you.* In the non-adopters group, N8 and N4 also said landlords didn't like the way no-till looks.

Farmers didn’t always stop a practice because other people disliked it. They were less likely to stop a practice for neighbors than for landlords. For example, A3 related a story about a neighbor disliking no-till:

> *Ah, the other day, I had a neighbor, he come up there and he said, “well sonny I believe you got the prettiest cotton around here you know,” he said, ‘just think what it would have been like if you would have plowed it. :: group laughter:: But they can't, you know, they just can't visualize that they can do that.*

People described as "urban" and younger people were mentioned as complaining or calling authorities in regard to spraying of chemicals or spreading manure. One farmer (N4) experimented with applying manure to fields but quit because of “*everyone calling in cussing*” about the smell. However, N8 used manure extensively even though people complained. He adapted by trying to locate it in his fields where the fewest people would be bothered. Expressing frustration, A6 said, *“Yeah -it's -it can be- it can be harassment. You can have -you can have people that are either vested or not vested either have property or don't, just can be driving by or riding a bicycle, and they can claim that something happened to them if [drift from a sprayer gets] on them.”* In another statement, A6 said one reason he preferred no-till was that he had less equipment on the road traveling between fields, so he had fewer complaints. The farmers did not generally express a willingness to change a practice because of such complaints, but the farmers were irritated by them.

Social interactions that exerted positive pressure to adopt SHPPs were also apparent. For example, A5 started using no-till because of family interactions:

> *So for us, I was forced into [adopting no-till] to some degree. My father-in-law bought a piece of land, and he said "only way you can rent it is if you no-till it." And uh, I went to my dad and said "this is what we're going to do" and he said, "You're wasting all our money."*

He noted that his father later encouraged him to continue using no-till after he had started, saying, *"That's a good thing you've done there."*

Tuition

In the adopters group, a fourth factor influenced the decision of whether or not to adopt or continue to use management practices. During the discussion, A3 gave this factor a name when he said "*Yeah, as I was telling my kids, I didn't go to college but I paid a lot of tuition.* The term *tuition* "caught fire" in the adopters group, with four other farmers using the word after him and several using other phrases like "learning curve" for the theme. *Tuition* was used by the adopters to describe the fact that they improved their management skills over time. This was described by A6 who said, in regard to no-till having a yield drag, *"Just being new and just you know you don't know all the tricks you haven't paid the tuition yet… [Yield drag]-It's- it's our screw up. It's not the soil's fault. It's our fault."* Further, in an interaction with A1, A6 asserted that mentorship from other experienced farmers reduced this *tuition*.

> *A1: You're going to sacrifice a yield.*

A6: No. I haven't lost any yield.

A1: Hmm.

A6: But I had an experienced guy help me.

The adopters mentioned informal mentorship as a way to learn from each other. In contrast, non-adopters were more competitive. For example, when asked if their neighbors would tell them about the practices they were using, N4, N5, and N8 had the following discussion:

N4: "Most will tell you, 'I'm putting out more fertilizer' or something."

N5: "Yeah"

N4: "There will be a few that [would share that information with you]"

N8: "Not in my area, they won't tell you how they- it's too competitive."

As a result of the *tuition* concept, adopters were more likely to persevere with a management practice when they got undesirable results. They believed they needed time to learn the technique and that they needed to seek advice from mentors. Under the same circumstances, non-adopters perceived that the undesirable results indicated that the technique was not appropriate for their fields.

Interactions between themes

Soil health, as a component of the *stewardship ethic*, was an important part of farmers' identities, but there were caveats to the operation of the *stewardship ethic*. In other words, the stewardship ethic does not operate in a vacuum; rather, it interacts with *profitability* and *social interactions*. For adopters, the *tuition* theme also comes in to play.

Profitably was a “gatekeeper” factor in making decisions about soil management. As A2 put it, “*If you aren't in business, you know, you don't make it and so there's no – then the conservation doesn't matter*.” Going further with this concept, A6 said:

> *We’re not doing it to save the world, we're not doing it- that's not the purpose. It goes back to your question; we're trying to turn red numbers black at the end of the day. That's the number one reason we’re here - is profitability.*

Despite the centrality of the *profitability* theme, farmers did not view *profitably* to be in conflict with the *stewardship ethic.* For example, A7 says:

> *Motivators are to be more profitable... Now has it made economic advances in my production? Due to the things we’ve done? Actually, that’s, uh the cost of learning that – that we're talking about, so it's- I hope the benefits are out there in my lifetime. Will they be? I dunno.*

In this quote, A7 references the idea that the *tuition* theme modifies the *profitability* theme. He has not experienced improved *profitably* as a result of adopted practices yet, but he accepts the additional cost of the learning curve - his *tuition* - and hopes to see future benefits.

Social interactions also modified the *stewardship ethic*. Specifically, farmers felt "targeted" by urban people and especially younger generations. Both groups expressed frustration that they were not the only people responsible for environmental issues and that they were disproportionally blamed. For example, A3 said, *"I guess that what bothers me the most is… Alright, the farmers get blamed for what's in that creek, but they're cementing all these places in town that water can't soak in…"* The blame demotivated farmers to try to find solutions because they perceived others were not doing their part. As A2 put it:

> *"But I think one of the biggest things is we're seeing a transfer of liability when you start looking at that the urban or even the cities, when they're pushing that water out to the farms, they're telling the farmers 'you've got to manage it, you've got to take care of it' and we're saying 'we're wanting to be good stewards of what we have first, before we take on your liabilities.'"*

Here, A2 expresses frustration that others are not doing their part, and he does not want responsibility forced upon him. The distaste for being forced to use a particular management was widespread in the groups and was expressed by A6 when he said, "*When they start forcing stuff on you, say they forced you to no-till, say they forced you to cover crop, you're gonna fail at it. That's the point."* Here, A6 gives an example of how the *stewardship ethic* is modified by *social interactions* by registering his resentment of the idea of being forced to make management changes. Further, he asserts that the outcomes of those management changes will not have the desired result.

A further caveat of the *stewardship ethic* stems from the nature of the indicators that farmers use to assess soil health. First, the qualitative nature of soil health indicators makes it hard to say when one has healthy soil and when one does not. The notable exception in the groups were the farmers who mentioned organic matter percentages. A second issue raised in the focus groups was the use of agronomic indicators. Yield and biomass indicators may give a "false positive" for soil health when other drivers are truly causing increases in yield or biomass. We questioned farmers about whether they thought their neighboring farmers were good stewards and A6 provided this insight:

> *"Everyone wants to leave the land better than it was, but the ones who are still messing it up, you gotta get in their head. In their head, they're improving it. But it's all relative cause it's better than grandpa had it cause 'grandpa could only raise 60-bushel of corn where I can grow 120-bushel corn.' They think they're improving it so that's where it goes back to."*

The phrase *"In their head, they're improving it"* identifies that A6 perceives that these farmers' soil health is poor, but that the farmer perceives it as good. Further, he asserts that it is their use of yield as an indicator that allows them to believe this. Claiming a causal association between soil health and yield may be an encouragement for farmers to adopt soil health practices, but A6 shows this logic may be a justification for not improving soil health if other factors (like crop genetics or changes in fertility) are not accounted for.

We should not interoperate the false positive that A6 mentions above to mean that he believes the *stewardship ethic* and *profitability* are not linked, conversely, A6 says "*And then also we're going to save the world by accident*" and A3 agrees. The idea put forward in this quote is that in pursuing *profitability*, they will achieve soil health and provide ecosystem services too. This linkage between *profitably* and soil health has examples that both support and detract from it in the focus groups. In the non-adopters group, N1 describes adopting manure application and cover crops, both of which increased his costs relative to conventional practices. He continued using manure, stating that it had improved his yield compared to conventional fertilizers. He also said manure had improved the soil health indicators of soil structure and water management. He stopped using cover crops because they were too costly and had not improved his yield, even though he says they were "*the best thing*" he has seen for erosion control. This example of N1's adoption behavior highlights the "gatekeeper" role of *profitability* in adoption decisions. This "gatekeeper" nature of profitability was present in the adopters focus group as well.

CONCLUSIONS AND RECOMMENDATIONS

Farmers in our focus groups overwhelmingly spoke in qualitative terms when describing indicators of soil health, but we do not make the inference that they would not find quantitative indicators meaningful. Rather we believe that farmers do not measure some indicators of soil health, because those soil health indicators are either replaced by or correlated with agronomic indicators, which are more proximal to farmers' welfare. In addition to being meaningful, agronomic indicators are also usually measured in the process of harvest or sale, so no additional effort is needed to measure them. A problem raised in the groups was that using only agronomic indicators could lead to a “false positive” for soil health and conservation - an increase in yield does not necessarily mean an increase in soil health. This false positive should be considered when promoting the link between agronomic indicators and soil health. One solution may be to stress the idea that agronomic indicators alone are not sufficient measurements of soil health.

Of the non-agronomic indicators discussed, water management and organic matter were most often reported by farmers in these focus groups as the indicators by which they knew SHPP were working. We recommend that future work with farmers in the Blackland Prairie of Texas focus on these two indicators as linking indicators between SHPP and farmers’ welfare. Water management and organic matter are relatively proximal to farmers’ welfare, while not being prone to the false positives that agronomic indicators may cause. Improvement in water management and organic matter not only benefit farmers, but also provide important off-site ecosystem services such as flood prevention, water quality, and greenhouse gas regulation. Future analysis should focus on how farmers value quantitative changes in these two linking indicators and develop ecological production functions that relate SHPP to ecosystem services.

Even though farmers were aware of soil health, it was not the major driver of farmers’ decisions to buy or lease land. The themes of farmers being *land hungry because of urban growth* and that they were *confident that they could improve their soil health* after they bought or leased land overshadowed soil health.

Soil health was important to farmers when considering what practices to use on their land. Specifically, soil health had a place in a larger *stewardship ethic* for farmers in our two focus groups. This *stewardship ethic* was a motivating factor to improve soil health, but was affected by the other themes of *profitability* and *social interaction*. Additionally, the adopters group considered their learning curve, which they called *tuition* when making management decisions. *Profitability* exercised strong influences on the adoption of soil health management practices, acting as a "gatekeeper." *Social interactions* were often the reason adopters initially chose to convert to SHPP like no-till. *Social interactions,* such as a local narrative about a SHPP not working, also kept non-adopters from adopting. These interactions were strongest when they were with family members or landlords. Neighbors and those driving by farms also played a role. The *tuition* concept for adopters described their willingness to forgo immediate improved *profitability* while learning the new practice. The *tuition* was reduced when mentors helped adopters get started with a new practice. Whereas adopters described mentoring one another, non-adopters described more competitive relationships with one another. These themes, and more so their interactions, illustrate the complexity inherent in farmers decisions to adopt SHPP. Researchers and policymakers should be aware of this complexity and farmers' resentment at the idea of being forced to adopt new practices. Therefore, certain efforts to promote SHPP could be negatively perceived by farmers.

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3. QUANTIFYING TILLAGE EFFECTS ON SOIL PHYSICAL PROPERTIES IN THE LOWER AND MIDDLE BRAZOS RIVER WATERSHED OF TEXAS

INTRODUCTION

By avoiding soil disturbance, no-till has the potential to allow soil structure to develop, improving soil health and increasing the provision of soil ecosystem services. For example, compaction due to traffic is shallower in well-structured soils (Ellies et al., 2000) and if compaction is remediated and a controlled traffic, no-till system is adopted, soil water infiltration rate can be similar to that of soil that has never been plowed (Li et al., 2001). Aziz et al. (2013) found that, after 5 yr of no-till, soil health significantly improved as indicated by increasing soil microbial biomass, basal respiration (a measure of microbial activity), total carbon, total nitrogen, and aggregate stability.

Despite its advantages for soil health, no-till was adopted on only fifteen percent of Texas cropland acres in 2017 (Economic Research Service, 2019). The low adoption of no-till practices in Texas may be partly due to the fact that farmers rarely link their land management practices to degradation of soil structure, because soil structure formation is not apparent at the soil surface (Hamza and Anderson, 2005). However, farmers do recognize changes in soil health and consider soil stewardship in management decisions. Bagnall et al. (2019b) studied farmers in the Lower and Middle Brazos River Watershed of Texas and found that they perceived organic matter and “water management” to be meaningful indicators of soil health. The term “water management” was used by farmers in that study to describe partitioning of rainfall between runoff and infiltration, and it was discussed as being important to prevent erosion and to provide water for crops. Linking no-till to organic matter and "water management" may aid in promoting the adoption of no-till in the Lower and Middle Brazos River Watershed of Texas.

The National Resource Conservation Service (NRCS) recommends four principles for soil health promotion. These are 1) keeping soil covered as much as possible, 2) having living roots in the soil at all times, 3) minimizing soil disturbance, and 4) diversifying plant species (The National Resource Conservation Service, 2019). Perennial fields by nature meet the first three recommendations. Some perennial fields (such as a native prairie) may meet the fourth, while others (such as a hay field) may be a monoculture. We collected soil health measurements in perennial fields to provide a benchmark to compare both no-till and conventional tillage. The ***central question*** of our study was "does the adoption of no-till shift the soil health of farmers' fields to be more like that of perennial fields in the Lower and Middle Brazos River Watershed of Texas?" To address this question our ***primary objective*** was to determine whether the indicators that were meaningful to farmers in the region (organic matter and "water management") were different between farmers' fields that were under no-till (NT), conventional-till (CT), and perennial grass (PG). Our ***secondary objective*** was to compare two recently developed soil health measurements to established measurements of soil health. The two recently developed measurements were an *in situ* quantification of soil structure (Bagnall et al. 2019a) and an aggregate stability measurement quantified with a smartphone (Flynn et al. 2019).

Organic matter can be accurately predicted from measurements of organic carbon (OC), but measuring “water management” requires a suite of soil health measurements related to soil hydrologic function. To investigate “water management”, we measured saturated hydraulic conductivity (KS), bulk density (BD), slaking index of soil aggregates (inversely related to aggregate stability), and soil structure. The SLAKES smartphone application was used to calculate a slaking index based on the expansion of soil aggregates in water over time. Soil structure was measured using Dirichlet tessellation area variability (DTAV) of the surface (0-to 30-cm depth) soil structure in CT, NT, and PG fields. The DTAV is calculated using vertical scans of a soil surface horizon *in situ* and higher DTAV are associated with less well ordered soil structure. Bagnall et al. (2019a) demonstrated that DTAV was significantly higher in CT fields than NT and PG fields, indicating that CT fields had less regular soil structural units compared to NT and PG. We used the 3D scans of soil structure taken in farmer’s fields from the Bagnall et, al. (2019a) dataset along with measurements of OC and “water management” taken at the same locations and times as scanning. The Bagnall et al. (2019a) dataset consisted of high-clay, shrink-swell soils that are characteristic of farmland in the Texas Blackland Prairie Major Land Resource Area in the Lower and Middle Brazos River Watershed. Both OC and “water management” depend on both manageable soil properties and inherited soil properties. To better characterize the inherited soil properties in the Watershed, additional 3D scanning data were collected in floodplain soils, which are lower in clay content. These new 3D scanning sites also had OC and “water management” measurements collected and were taken in farmer’s fields.

Together, the Blackland prairie soils and the floodplain soils represent the major row-crop soils of the Lower and Middle Brazos River Watershed. For floodplain soils, only one NT 3D scan site was located. To fill this gap on no-till floodplain soils, measurements of OC and "water management" were taken in a long-term research experiment comparing NT and CT at the plot scale. No 3D scanning data was collected on long-term plots because it would have caused excessive soil disturbance in NT plots.

METHODS

Farmer fields in the Middle and Lower Brazos River Watershed were located based on recommendations by the National Resource Conservation Service (NRCS) and Texas A&M AgriLife Extension. Because few farmers in the area used NT, NT farmers were located first and then neighboring farms that practiced CT or had PG fields were located. Measurements were taken in spring 2017 and winter and spring 2018 for Blackland sites. For floodplain sites measurements were taken in spring 2019. All measurements were taken when desiccation cracks were closed. Study locations and the samples taken at each site are summarized in Table 3.1.

Study Locations

Blackland field locations

Blackland field locations were selected in Falls, Milam, and Williamson Counties, Texas. Six CT, six NT, and six PG fields, each mapped as similar soil series were selected for a total of 18 Blackland fields. The sampled soils are Houston Black (Fine, smectitic, thermic Udic Haplustert) and Branyon (Fine, smectitic, thermic Udic Haplustert). The Houston Black soils originate from calcareous mudstone residuum and the Branyon soils formed in clayey alluvium derived from mudstone (Soil Survey Staff, 2012). Slopes were between 1 and 3 percent for Blackland soils. Three of the NT fields in the Blackland locations had been under no-till for 21 years, and the remaining fields had been under no-till for 3, 7, and 18 years.

Floodplain field locations

Floodplain field locations were selected in Brazos and Milam Counties, Texas. Five CT, five NT, and one PG field were selected for a total of eleven floodplain fields. The soils sampled are Frio (Fine, smectitic, thermic Cumulic Haplustoll), Weswood (Fine-silty, mixed, superactive, thermic Udifluventic Haplustept), and Gaddy (Sandy, mixed, thermic Udic Ustifluvents). Frio soils were formed in calcareous loamy and clayey alluvium, Weswood in calcareous loamy alluvium, and Gaddy in sandy alluvium of Holocene age. Slopes were between 1 and 3 percent for these sites. The NT field had been under no-till for 21 years.

Sampling

Fields

In each Blackland field, three soil pits were dug, and a 25.4-cm wide by 30.5-cm deep section of the surface soil was scanned in 3D using a NextEngine MLT scanner (NextEngine, 2009) set to the wide resolution. Before 3D scanning, soil pits were left to dry for 24 h and then surface horizon was picked to expose soil structural units and remove artifacts of digging. Scanning of each soil took about 15 minutes. The scanning methodology is described in detail in Bagnall et al. (2019a). For floodplain soils, the scan collection methodology was the same as in Blackland fields with the exceptions

Table 3.1 Study locations by tillage type along with the number of saturated hydraulic conductivity (KS) measures, bulk density (BD) cores, and aggregate stability (SLAKES) measures that were collated at each site. Additionally, median and standard deviation for clay, base saturation, and pH are summarized. We also list whether or not 3D scans of soil structure were taken.

	CT	NT	PG	Total	Ks per site	BD per site	3D Scan	SLAKES per site	Clay %	BS %	pH
Blackland Fields	6	6	6	**18**	3	3	Yes	3	38±9	100±1	7.8±0
Floodplain Fields	5	1	5	**11**	3	3	Yes	3	27±9	100±0	8.0±0
Floodplain Plots	8	8	0	**16**	3	1	No	3	32±3	100±0	8.0±0
Totals	**19**	**15**	**11**	**45**							

that the 3D scanned area was increased to a 51.0-cm wide by 30.5-cm deep and only one soil scan per site was made.

For each field in which 3D scans were taken (Table 3.1), soil samples for lab analysis of particle size distribution, total carbon, inorganic carbon, pH, base saturation, and cation exchange capacity were collected. One sample was taken from 0- to 10-cm depth and one from 10- to 30-cm depth after scanning. For Blackland soils, the three samples from each field were bulked so that one soil sample for each depth was analysed for each site. Samples were dried at 60°C, and passed through a 2-mm sieve for lab analysis.

For SLAKES measurements, a separate soil sample from 0 to 10 cm was taken at each pit, bulked by field, and air-dried. For BD measurements, soil cores from 0- to 15-cm depth were collected from each field using a split-core sampler with a 7.7-cm inner diameter. Three KS measurements were made ~2 m away from the scanning site in each field. Single ring, constant head infiltrometers that were 31 cm in diameter were used to measure KS with a 5-cm constant head.

Plots

For each plot in the long-term research experiment, soil samples for lab analysis from 0-10 and 10-30 cm were taken using handheld probes and bulked for the four plots within a treatment. Saturated hydraulic conductivity rings were located ~1 m from the center of the rep. SLAKES and lab soil samples were taken near the outside of KS ring locations after ring removal. Bulk density samples were also taken ~1 m from the center of each replication.

Floodplain long-term plots

Plot data were collected from a trial initiated in 1982 on a Weswood silty clay loam (fine silty, mixed, thermic Fluventic Ustochrept) located at the Texas A&M University Research Farm near College Station, TX (30°32′N, 94°26′W). Two tillage types (NT and CT) and two cropping systems were sampled in our study. The cropping systems were continuous wheat (Triticum aestivum L.); 2) and a rotation of sorghum (Sorghum bicolor L. Moench), wheat, and soybean (Glycine max L. Merr). Plots were 4 by 12.2 m and were replicated four times for a total of 16 plots sampled. Conventional tillage operations consisted of disking (10 to 15 cm depth) after harvest, followed by chisel-plowing (20 to 25 cm depth) with a second disking, and ridging prior to winter. Under the NT treatments, no soil disturbance occurred except for banded fertilizer application to sorghum and planting of crops (González-Chávez et al., 2010). There were no differences in fertility treatments between tillage types in the plots sampled. The 8 NT plots had been under no-till for 37 years.

Laboratory analysis

For all samples, particle size distribution analysis was completed using the pipette method and wet sieving of sands (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 were determined using the NH_4OA_c, pH 7.0 Automatic Extraction method (Holmgren et al., 1977; Soil Survey Staff, 1996). Bulk density was measured using a field moist method (Blake and Hartge, 1986; Soil Survey Staff, 1996). Slaking index was measured using the SLAKES smartphone application for a 10 minute slake (Flynn et al., 2019), and we used the SI600 parameter for slaking index (SLAKES). For each field, three Petri dishes, each containing three soil aggregates, were measured and the 10-minute SLAKES measurements were averaged.

Statistical analysis

A total of 45 experimental units were sampled, 29 fields and 16 plots. When repeated measures were taken in an experimental unit (for example, multiple KS) we report a mean (either arithmetic or geometric, depending on the distribution of the variable) of the repeated measures. For 3D scans of soil structure taken in both the Blackland and floodplain fields, a Dirichlet tessellation area variability (DTAV) was calculated as the standard deviation of the natural log of Dirichlet tessellation features (see Bagnall et al., 2019a). For each soil pit, separate DTAV calculations were performed from 0- to 10- and from 10- to 30-cm deep. The DTAV from the three scans of soil pits in Blackland fields were averaged by depth.

To confirm that our sampling method was successful in measuring similar soils in each of the three tillage types, we conducted ANOVAs for clay percentage, pH, and base saturation that had tillage type as a factor. If we included similar fields in each tillage type, ANOVAs for clay percentage, sand percentage, pH, and base saturation will not show tillage as a significant factor.

To investigate how the soil health measurements related to one another, to tillage practices, and to soil particle size distribution, we performed a principal component analysis (PCA); we included the DTAV, OC, clay, and sand from both 0- to 10-cm and 10- to 30-cm as well as SLAKES, KS, and BD. The PCA was run using the prcomp function in R (R Core Team, 2018) and included all 29 fields that had DTAV measurements. We did not include the 16 plots without DTAV. Because the soil health measurements all had different magnitudes, all units were scaled to have unit variance prior to PCA.

To confirm that removing the measurements taken in the long-term research experiment did not change the interpretation of the relationships between fields, tillage practices, or measurements, a second PCA for all sites (n = 46 fields and plots) was conducted. This second PCA did not include DTAV. Similarly, a third PCA was conducted that included clay and sand from the 10 to 30 cm depths to confirm that their exclusion did not change interpretations. Having confirmed that these changes did not alter interpretations from the first PCA, findings from the first PCA (n = 29) are presented.

To further investigate relationships indicated by the PCA, an ANCOVA was run for each soil health measurement, using tillage type (CT, NT, and PG) as a factor. Each ANCOVA included clay as a covariate and the interaction between clay percentage and the soil health measurement. When the interaction term between clay percentage and the soil health measurement was significant in the ANCOVA, main effects were not tested further. When the interaction term was not significant, and the tillage type was, tillage type was used as the factor in an ANOVA for the soil health measurement. Similarly, when the interaction was not significant and clay was, a linear regression between clay and the soil health measurement was performed. Transformations for normality of the soil health measurements were done when needed and are reported.

To investigate relationships between the two recently developed soil health measurements (DTAV and SLAKES), the established measurements (OC, KS, and BD), and clay, pairs of variables were plotted against one another and tested using simple linear regression. Further, we linearly interpolated the DTAV, SLAKES, KS, and BD measurements over the range of clay and OC in our study to assess whether DTAV and SLAKES responded to changes clay and OC in a similar manner to KS and BD. When needed, we log-transformed the variable to be interpolated so that it had a normal distribution.

For each linear model, plots were used to check for non-linear relationships, quantile-quantile plots were used to check for normality of the residuals, Cook's distance plots were used to check for outliers, and plots of the residual versus fitted values were used to check for heteroscedasticity. The significance level for statistical tests was $\alpha = 0.05$.

RESULTS AND DISCUSSION

To confirm that comparisons between tillage types were appropriate, we used an ANOVA to test whether fields in the three tillage practices were significantly different in regard to measurements of soil capability (inherited soil properties). ANOVA results showed that clay, pH, and base saturation from both depths, 0- to 10-cm ($p = 0.42, 0.44, 0.07$) and 10- 30-cm ($p = 0.46, 0.37, 0.51$), were not significantly different between tillage types.

Relationships between tillage and soil health measurements

A PCA was used to visualize relationships between experimental units that had different tillage types and also to understand how soil health measurements related to tillage type (Fig. 3.1). The first two principal components of the analysis captured 67 percent of the total variability in the dataset, with PC1 accounting for 41 percent and PC2 accounting for 26 percent of the variation. As expected, sand and clay were negatively correlated. The fields in all three tillage practices were evenly distributed along the axis created by sand and clay vectors, supporting our interpretation of the previous ANOVA that soil texture was not different between tillage practices. In the PCA plot, CT and PG fields were almost completely separated, with all CT fields falling above PC2 = -0.05 (dashed line in Fig. 3.1) and all but one PG field falling below PC2 = -0.05. The NT fields were centered on this line, with four fields above and three below. The three NT fields that fell below PC2 = -0.05 had all been under NT for 21 years, while those above the line had been under NT for 21, 18, 7, and 3 years. Our central question was “does the adoption of no-till shift the soil health of farmers’ fields to be more like that of perennial fields in the Lower and Middle Brazos River Watershed of Texas?" The placement of NT fields relative to PG and CT fields in principle component space indicates that that NT does shift soil health toward PG fields and away from CT fields. Evidence in Fig. 3.1 also suggests that time under NT is a factor as well.

In regard to the soil health indicators, CT fields were associated with low aggregate stability (large SLAKES) and irregular soil structure (large DTAV) as well as lower KS and surface (0 to 10 cm) OC. The remaining soil health measurements, BD and OC from the 10- to 30- cm depth, have vectors that are roughly parallel with the diving line between CT and PG fields and so do not relate strongly to tillage type. While PG fields had relationships with soil health measurements that were opposite that of CT fields, the NT fields occupied the middle of the principal component space for both PC1 and PC2 and were never the most extreme fields in the direction of a soil health measurement vector.

The DTAV from 0- to 10- cm depth and SLAKES were highly positively correlated with each other in the PCA and their vectors were roughly perpendicular to the line that separated CT and PG fields, demonstrating that they may be highly sensitive to tillage type. Both DTAV from 0- to 10- cm depth and SLAKES were negatively correlated with KS and OC in the 0- to 10- cm depth. They were positively correlated with clay as we expect (Fajardo et al., 2016 and Bagnall et al., 2019) and independent of BD measured from 0 to 15 cm. In agreement the PCA interpretation, Flynn et al. (2019) found that SLAKES was significantly greater in CT fields than in NT fields and significantly greater in NT fields than PG fields. Similarly, Bagnall et al (2019a) found that CT fields has larger DTAV values than both NT and PG fields. Previous studies support the findings that NT improves soil structure and aggregate stability relative to CT (Aziz et al., 2013; Dalal, 1989). In agreement with the PCA results, Foster et al. (2018) and Dalal (1989) both reported that the use of NT on a Vertisol significantly improved surface soil carbon but not bulk density. While the PCA indicated that KS was smallest for CT and largest for PG, effects in the literature are inconsistent (Blanco-Canqui et al., 2017), with some studies finding significant effects of NT on KS (Li et al., 2001, Palm et al., 2014) and others finding none (Castellini et al. 2019; Blanco-Canqui, 2017; Blanco-Canqui, 2004).

The loading scores (weights for each standardized soil health measurement) for PC1 (Table 3.2) showed that BD and OC from 0 to 10 cm were the two factors that had the strongest impact on PC1. The loading scores for PC2 (Table 3.2) show that DTAV from 0 to 10 cm and SLAKES were the factors that explained the most variability in that component, further supporting the concept that these two measurements may be especially sensitive to changes in tillage type. Overall, soil health measures of the PC1 axis were correlated with clay content, or influenced by inherited soil attributes, while PC2 was related most strongly to the dynamic soil properties of soil structure formation associated with management.

Significance of the effect tillage type on soil health measurements

Tillage type was a significant factor for all of the soil health measurements except bulk density in ANCOVAs, and no interaction terms between tillage type and clay percentage were significant (Table 3.3). Clay was a significant covariate for all

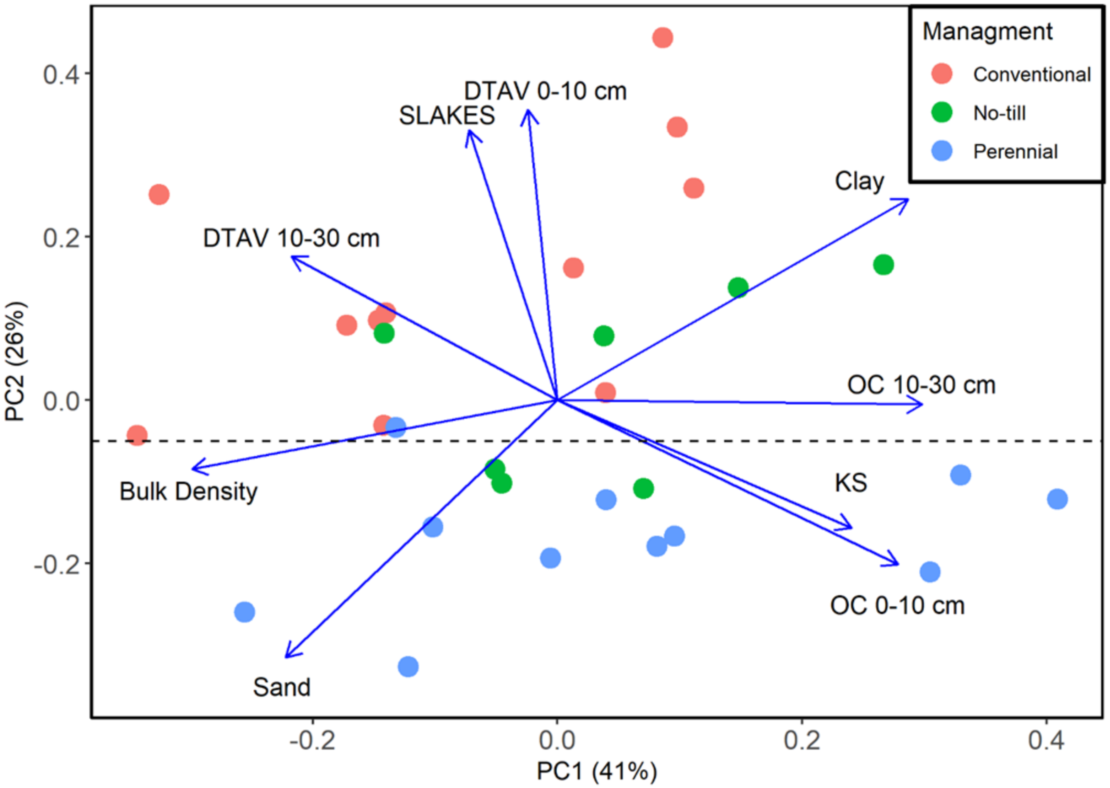

Figure 3.1 Principle component analysis for n = 29 fields with three tillage types. The soil health measurements plotted are Dirichlet tessellation area variability (DTAV) from 0- to 10- and 10- to 30-cm depths, slaking index (SLAKES), clay and sand from 0- to 10-cm depths, organic carbon from both 0- to 10- and 10- to 30-cm depths, saturated hydraulic conductivity in cm h^{-1} (KS), and bulk density from 0- to 15-cm depth (Mg m^{-3}).

Table 3.2 Loading scores for principal component analysis for n = 29 fields using the Dirichlet tessellation area variability (DTAV) from 0- to 10-cm and 10- to 30-cm, slaking index (SLAKES), clay percentage from 0- to 10-cm, sand percentage from 0-to 10-cm organic carbon (OC) from both 0- to 10- and 10- to 30-cm, saturated hydraulic conductivity in cm h-1 (KS), and bulk density from 0 to 15 cm (Mg m-3).

Principal Component 1								
BD	**OC 10-30**	**Clay**	**OC 0-10**	**KS**	**Sand**	**DTAV 10-30**	**SLAKES**	**DTAV 0-10**
-0.42	0.42	0.41	0.39	0.34	-0.32	-0.31	-0.10	-0.03
Principal Component 2								
DTAV 0-10	**SLAKES**	**Sand**	**Clay**	**OC 0-10**	**DTAV 10-30**	**KS**	**BD**	**OC 0-10**
0.50	0.46	-0.45	0.35	-0.29	0.24	-0.22	-0.12	-0.01

measurements, except SLAKES and DTAV from 0- to 10-cm depth. This contradicts our observations in the PCA, based on which we expected SLAKES and DTAV from the 0 to 10 cm depth to be positively correlated with clay percentage. The p-values for linear regressions (Table 3.3) showed that clay was only a significant predictor of soil health measurements in the cases of BD and the two depths of OC. Tillage type was significant measurements, plotted by tillage type along with ranks from Tukey's HSD are shown in Figure 3.2. The Tukey's HSD showed significant differences between CT and PG for all cases in which tillage was significant in an ANOVA (Table 3.3), which supports results from the PCA. Perennial grass and CT had the largest differences between their populations. As we would expect from the PCA, clay and BD were not different between the three tillage types (Fig. 3.2A and 3.2C), but KS values were significantly larger in PG fields compared to CT fields (Fig. 3.2B). Measurements of KS in NT were not statistically different from either PG of CT fields, though the median KS in NT fields was double that of CT fields (2.4 and 1.1 cm3 h-1, respectively) and this may be practically significant for ecosystem service provision.

SLAKES values were only slightly less sensitive to tillage type than OC from 0 to 10 cm (Fig. 3.2D), and if the level of significance were raised to 0.10, SLAKES would have detected differences between all three tillage types (Table 3.3). While shallow OC (0 to 10 cm) was significantly different between all three tillage types, deeper OC (10 to 30 cm) was not significantly different, showing that NT and PG tillage types only increased OC in the top 10 cm (Fig. 3.2E and 3.2F). The DTAV values at both depths were significantly larger in CT fields than in PG fields, which was consistent

Table 3.3 P-values for the significance of predictor variables for tillage type for analysis of covariance (ANCOVA), analysis of variance (ANOVA), Tukeys' honest significant difference (HSD), and linear regressions. Analysis that included DTAV included 29 experimental units, and all other analysis included 45 experimental units.

	P-values for tests of significance of tillage type							
	ANCOVA			**ANOVA**	**Tukeys' HSD**			**Regression Slope**
Predictor variable	Tillage	Clay	Interaction	Tillage	CT-NT	CT-PG	NT-PG	Clay
Log(KS)	0.02*	0.03*	0.33	0.03*	0.31	0.02*	0.38	0.12
BD	0.51	<0.001***	0.09	-	-	-	-	<0.001***
Log(SLAKES)	<0.001***	0.18	0.67	<0.001***	0.06	<0.001***	<0.001***	-
Log(OC 0-10 cm)	<0.001***	<0.001***	0.134	<0.001***	0.03*	<0.001***	0.002**	0.02*
Log(OC 10-30 cm)	0.008**	<0.001***	0.25	0.07	-	-	-	<0.001***
Log(DTAV) 0-10 cm	0.009**	0.18	0.15	0.01**	0.16	0.01*	0.65	-
Log(DTAV 10-30 cm)	0.002**	0.005**	0.07	0.009**	0.03*	0.02*	0.99	0.01

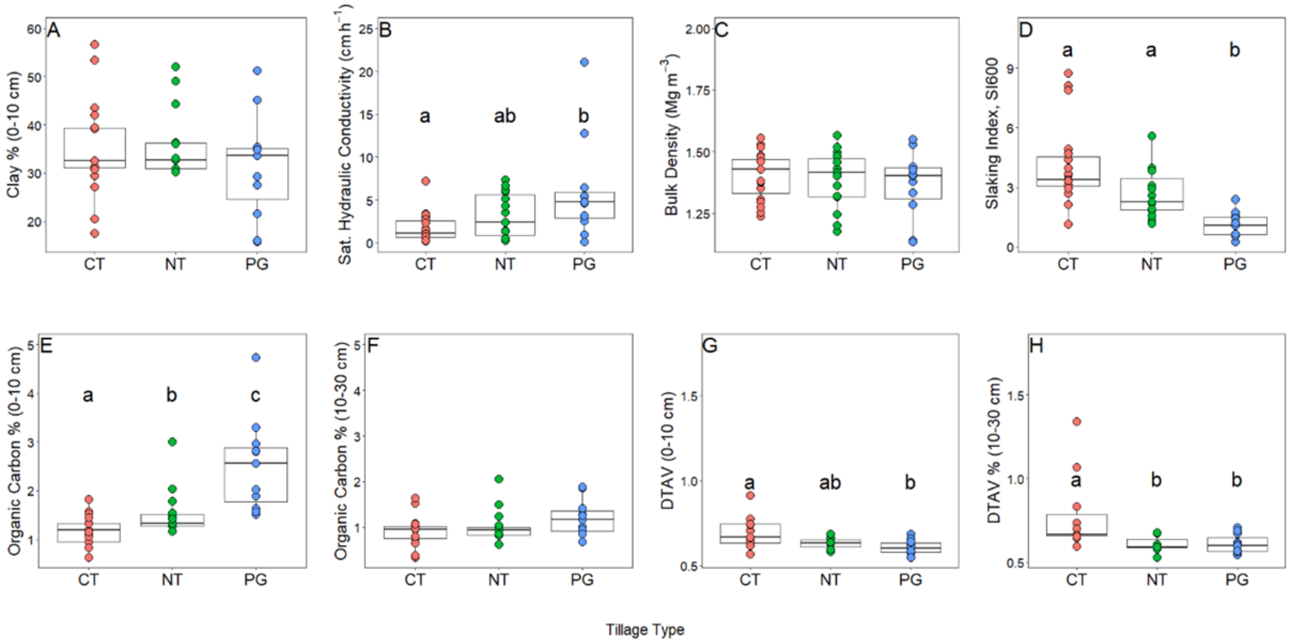

Figure 3.2 Boxplots of clay (A), saturated hydraulic conductivity (B), bulk density (C), SLAKES smartphone application slaking index (D), organic carbon from 0- to 10-cm depth (E), organic carbon from 10- to 30-cm depth (F), Dirichlet tessellation area variability (DTAV) from 0- to 10- cm depth (G), and DTAV from 10- to 30- cm depth (H) each by tillage type. For tillage type, CT = conventional tillage, NT = no-till, and PF = perennial grass. For A-F there are 19 CT fields, 19 PG fields, and 7 NT fields shown. For G and H there are 11 CT fields, 11 PG fields, and 7 NT fields shown. Ranks in A-H are Tukey's HSD with $\alpha = 0.05$.

with our interpretation of the direction of the DTAV vectors in the PCA (Fig. 3.1). Additionally, DTAV values from the 10- to 30- cm depth were significantly larger in CT than in NT. The higher sensitivity of DTAV to tillage at the lower of the two depths was unexpected because a previous (Bagnall et al., 2019a) study found that DTAV was more sensitive to tillage when measured shallower in the profile. With the exception of BD, the soil health measurements used all showed some effects of tillage type. Aggregate stability, soil structure, and OC were the three manageable soil properties that are were the most useful for detecting difference between NT and CT.

SLAKES and DTAV compared to other soil health indicators

SLAKES was only linearly related to OC in the 0- to 10-cm depth ($p<0.001$, Table 3.4). The DTAV from 0- to 10-cm depth was not linearly related to any other soil health measurements taken in this study (Table 3.4). The deeper DTAV (10 to 30 cm) was only linearly related to OC at the same depth (Table 3.4). These results contradict the apparent correlation between SLAKES and DTAV in the PCA, though the PCA and ANOVA indicated that DTAV and SLAKES were both sensitive to tillage type. Based on the results of the PCA and from prior studies, we expected both SLAKES and DTAV values to increase with increasing clay content. However, clay percentage was not a significant covariate for SLAKES or either depth of DTAV in the ANCOVAs (Table 3.3).

To further investigate the behavior of SLAKES and DTAV, we linearly interpolated the log-transformed DTAV and SLAKES measurements over the range of clay and OC to assess how DTAV and SLAKES responded to these soil attributes associated with

Table 3.4 P-values, sample size (N), and r-squared values for thirteen separate linear regressions with 1) slaking index (SLAKES) , 2) Dirichlet tessellation area variability (DTAV) from 0- to 10- cm depth and 3) DTAV from 10- to 30- cm depth as response variables and saturated hydraulic conductivity (KS), organic carbon (OC), bulk density (BD) as predictor variables. Log transformations were used when variables were log-normally distributed.

Response variable	**Predictor variable**	**Regression p-value**	**r-squared**	**N**
Log(SLAKES)	*Log(KS)*	0.06	-	45
	Log(OC 0-10 cm)	<0.001***	0.24	45
	Log(OC 10-30 cm)	0.44	-	45
	BD	0.78	-	45
Log(DTAV) 0-10 cm	*Log(KS)*	0.24	-	45
	Log(SLAKES)	0.15	-	29
	Log(OC 0-10 cm)	0.18	-	29
	BD	0.89	-	29
Log(DTAV) 10-30 cm	*Log(KS)*	0.08	-	29
	Log(SLAKES)	0.30	-	29
	Log(OC 10-30 cm)	<0.001***	0.42	29
	BD	0.12	-	29
	Log(DTAV) 0-30 cm	0.04	0.14	29

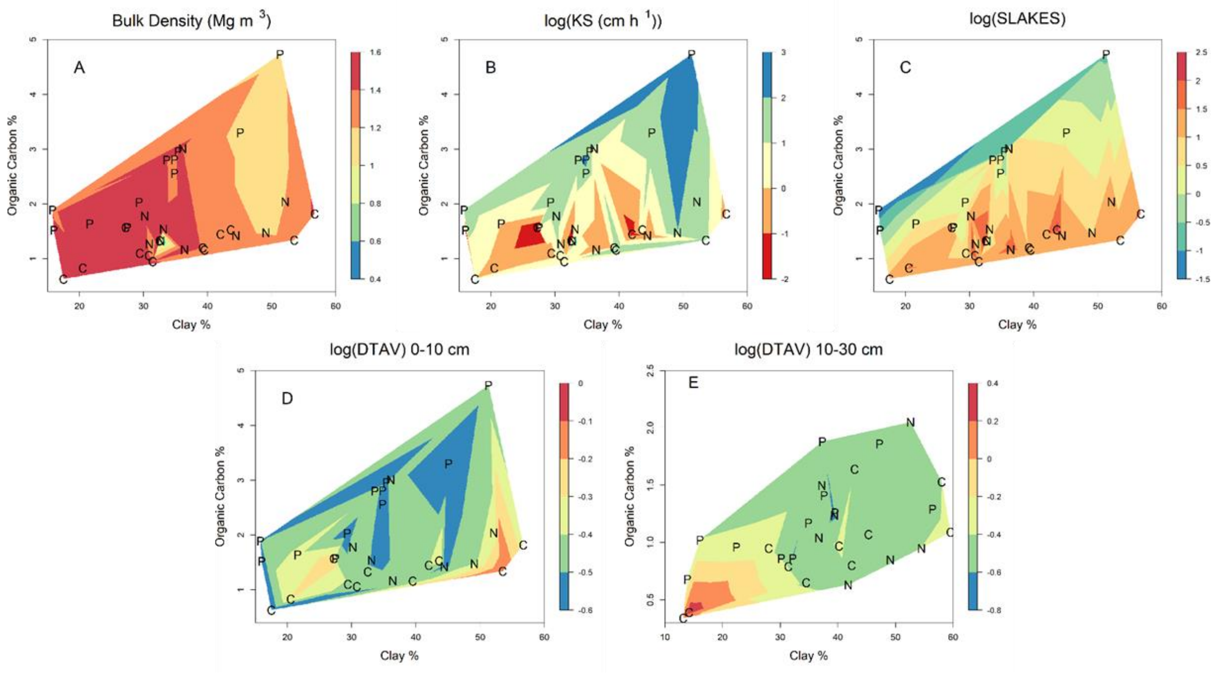

Figure 3.3 Linear interpolations of bulk density, saturated hydraulic conductivity (KS), slaking index (SLA KES), and Dirichlet tessellation area variability (DTAV) for 0- to 10-cm depth across clay and organic carbon for 0- to 10-cm depth as well as linear interpolation of DTAV for 10- to 30- cm depth across clay and organic carbon for 10- to 30-cm depth. Variables to be interpolated were transformed for normality. Red indicates poorer soil health and blue indicates better soil health. Points for OC and clay are labeled C, N, and P, representing sampling locations under conventional, no-till, and perennial tillage systems, respectively.

inherited and manageable soil properties. We also linearly interpolated BD and KS across clay and OC for comparison. Bulk density values were negatively related to clay (Fig. 3.3A), likely due to increasing macroporosity from structure formation at higher clay percentages. Though an ANOVA showed that BD did not respond significantly to tillage type, some relationship is seen in Fig. 3.3A. For example, the area at ~50% clay content shows that, for that clay percentage, PG and NT had smaller BD values than CT. However, at lower clay percentages, this relationship between tillage and BD did not hold, illustrated by the fact that all three tillage types are represented in red (large BD). None of the measured bulk densities were above the critical level for root growth given by Brady (1990) for their particle size class.

Tillage was a significant factor in the ANOVA for KS (Table 3.4), and this is apparent in Fig. 3.3B, which shows that the largest KS values are associated with PG and the smallest KS values are associated with CT. The largest KS values are also found in clayey soils with large more OC. As with bulk density, improvements in KS in clayey soils are likely because of better soil structure formation. Comparing KS in Fig. 3.3B and SLAKES in Fig. 3.3C shows a similar overall pattern of desirable (high KS or low SLAKES) and undesirable (low KS or high SLAKES) values. The pattern of SLAKES shows that low slaking indexes are promoted by increasing OC for any given clay percentage. Also, clayey soils require more OC to achieve a particular slaking index. The implication for management is that a particular amount of OC may result in different aggregate stability depending on the clay percentage of the soil. Thus, both clay content, which is an inherent property, and organic carbon, which is manageable, impact soil health as measured by aggregate stability.

DTAV from 0 to 10 cm had no consistence with clay and OC (Fig. 3.3D). The red and orange colors occur where around CT fields. This behavior of DTAV was also observed by Bagnall et al. (2019). The color values in Fig. 3.3D group around the tillage types rather than any particular area of the OC-clay percentage plane. This suggests that the map (Fig. 3.3D) is likely not useful for predicting DTAV from 0-10 cm because it lacks some information about the occurrence of high or low DTA values. This is not surprising given that neither the clay in our ANCOVA nor OC from 1 to 10 cm in the linear model were significant. The fact that tillage, rather than these other variables, relates strongly to DTAV from 0 to 10 cm supports the interpretation that DTAV from 0 to 10 cm carries information about the arrangement of soil structure and is related to disturbance caused by tillage.

Note that the range of organic carbon from 10 to 30 cm is roughly half that from 0 to 10 cm depth (Fig. 3.3E). The DTAV from 10 to 30 cm has a stronger and clearer relationship with both OC and clay percentage, but less so with tillage type, than the DTAV from 0 to 10 cm. The regression of DTAV (10 to 30 cm) showed that OC at the same depth explained 42 percent of the variation in DTAV. Clay percentage was also a significant main effect in the ANCOVA for DTAV. The DTAV from 10 to 30 cm was not as related to the tillage type as was the DTAV from 0 to 10 cm depth, as demonstrated by CT fields being represented in almost the entire range of DTAV values for the 10 to 30 cm depth. The highest DTAV values, which are associated with the poorest soil structure, are found in the low clay and low carbon range for the 10- to 30-cm depth. Our interpretation is that while management has some direct effect on the arrangement of soil structure in the 10 to 30 cm depth, clay and OC content are driving the DTAV values. The DTAV from 0 to 10 cm depths serves as a better indicator of management on soil structure than does the DTAV from 10 to 30 cm. The 0 to 10 cm DTAV relates more to the effect of tillage per se, rather than either a soil's inherited attributes (clay percentage) or other management effects of tillage (OC).

SUMMARY AND CONCLUSIONS

The central question of this study was "does the adoption of no-till shift the soil health of farmers' fields to be more like that of perennial fields in the Lower and Middle Brazos River Watershed of Texas?" The PCA showed that CT and PG fields were different from one another and that NT fields were in between the two. Older NT fields were more like PG fields compared to younger NT fields. Four of the five soil health measurements showed differences between PG and CT, supporting the findings of the PCA that CT and PG fields in our study are different from one another. Organic carbon at the surface (0 to 10 cm) and soil structure (DTAV from10-to 30-cm) were significantly different between NT and CT (Fig. 3.2E and 3.2H) while surface OC (0 to 10 cm) and aggregate stability (SLAKES) were significantly different between NT and PG (Fig. 3.2D and 3.2E). Additionally, for KS and DTAV from 0 to 10 cm, NT fields were not different from PG fields, but CT fields were, demonstrating that NT was shifting the system to be more like PG fields.

Surface OC (0 to 10 cm) was the soil health measurement that was most sensitive to tillage practice, and the only one that detected significant differences between all three tillage types. Overall, NT fields have significantly higher surface OC and significantly improved soil structure (measured by DTAV) compared to CT fields (Fig. 3.2). Also, NT fields had significantly lower surface OC and significantly lower aggregate stability (higher slaking index) compared to PG fields (Fig. 3.2).

While some differences in soil health measures between tillage practices were not statistically significant, they may be practically significant. For example, median KS was 1.3 cm h^{-1} larger in NT fields than CT fields, and this may be important for ecosystem service provision. Further investigation should make use of this on-farm data to model the differences in on-field and offsite ecosystem service provision between NT and CT fields. This would provide data to evaluate the value of adoption of NT in the Lower and Middle Brazos River Watershed of Texas.

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4. SUMMARY AND FUTURE WORK

Farmers in the Lower and Middle Brazos River Watershed of Texas balance the need to remain profitable, social interactions, and a stewardship ethic when making decisions about which soil management practices to adopt or continue to use. Soil health is a part of the larger stewardship ethic for farmers. Additionally, farmers who self-identified as adopters of no-till had mentorship networks that helped them persist in using soil health practices. Our analysis of focus group transcripts revealed that farmers use indicators of soil health to make decisions about which management practices to adopt or continue to use. Farmers used organic matter, “water management”, and agronomic indicators to assess soil health. The term “water management” described partitioning of rainfall between runoff and infiltration, and it was discussed as being important to prevent erosion and to provide water for crops. We found that the exclusive use of agronomic indicators for soil health could lead to a false positive in which soil was assumed to be healthy if yields were good. Including the other two indicators that farmers found meaningful, “water management” and organic matter, is important to avoid this false positive. The relationships between farmers’ concern for soil health, their social interactions, and their need to remain profitable are complex, but are important for policy makers and scientists to consider when promoting no-till adoption in the region.

Soil health measurements in farmers’ fields showed that organic matter (measured by organic carbon from 0 to 10 cm) was significantly higher in no-till fields compared to conventional fields. Soil structure (measured as the Dirichlet tessellation area variability from 10 to 30 cm) was also significantly improved in no-till fields relative to conventional fields. It may be this change in soil structure that resulted in the saturated hydraulic conductivity in no-till fields being more than twice that of conventional fields; median hydraulic conductivity was 1.1 cm h^{-1} for conventional fields and 2.4 cm h^{-1} in no-till fields. This change in hydraulic conductivity manifests itself in farmers' fields as the indicator "water management". For offsite stakeholders who are negatively impacted by run-off from farm fields, the increase in saturated hydraulic conductivity may reduce flooding events and the amount of sediment that enters water bodies.

Biophysical changes in farmers' fields that result from no-till adoption should be incorporated in biophysical and hydrology models so that the benefits to farmers (such as additional plant-available water) and the benefits to off-site stakeholders (such as reduced flooding and sedimentation) can be quantified. These models will serve as ecological production functions, linking changes in soil tillage with biophysical outcomes. Economic and social analysis should investigate how valuable these biophysical outcomes are to stakeholders. Our work shows that soil health and ecosystem service provision exist in tension with social and economic priorities of decision makers. Future avenues to explore the real-world pros and cons of no-till include market and non-market valuation of biophysical outcomes as well as social investigation that reveal why farmers and stakeholders may make choices that are not explained by economic models.

APPENDIX A: FOCUS GROUP QUESTIONS

Focus Group Questions for Adopters

1. If you could change anything about your soil, what would you change?
2. Suppose you are considering buying a piece of land, what factors do you think are most important? What soil conservation practices do you use?
3. What made you adopt the conservation practices you’re using?
4. Before you adopted soil conservation practices, what risks did you see with the practices? Did you feel that you would lose money; that your neighbors would criticize you?
5. Before you adopted soil conservation practices, did anyone encourage you to adopt these practices? Did anyone discourage you? Why did they encourage/discourage you? Who were these people? Neighboring farmers? Family members?
6. Did you receive any government cost-share or incentive payments for adopting conservation practices?

7. What sources of information do you use to make decisions about your farming operation? Are there some sources you trust a lot? Are there some sources you mistrust?

8. Did you notice any improvement in soil performance on your farm after adopting soil conservation practices? If so, what changes did you notice?

9. Does the soil on your land affect your neighbors or the broader community?

10. Some people worry that soil erosion hurts people downstream. Do you think this is important? Do you think adoption of soil conservation practices on your farm affect the chances of flooding downstream? How do you measure downstream effects?

Focus Group Questions for Non-Adopters

1. If you could change anything about your soil, what would you change?
2. Suppose you are considering buying a piece of land, what factors do you think are most important?
3. Have you tried or considered adopting no-till/strip-till/cover crops? Why did you, in the end stop using or not adopt these practices?
4. What risks do you see inherent in these practices? Did you feel that you would lose money; that your neighbors would criticize you?

5. Has anyone ever encouraged you to adopt these practices? Did anyone discourage you? Why did they encourage/discourage you? Who were these people? Neighboring farmers? Family members?
6. Are you aware of government programs that pay farmers to adopt soil conservation practices? Have you ever applied for funding from EQIP or some other program that supports soil conservation practices?
7. What sources of information do you use to make decisions about your farming operation? Are there some sources you trust a lot? Are there some sources you mistrust? Other farmers; family members; crop advisors; the extension service; USDA conservation information service.
8. In the past few years, have you noticed any change in soil performance on your farm? If so, what changes did you notice? What do you do to improve your soil function over time?
9. What does your soil do for your neighbors or the broader community?
10. Some people worry that soil erosion hurts people downstream. Do you think this is important? Do you think adoption of soil conservation practices on your farm affect the chances of flooding downstream? How do you measure downstream effects?