EFFECT OF LONG-TERM TILLAGE PRACTICES ON SOIL PHYSICO-CHEMICAL PROPERTIES AND WEED POPULATION DYNAMICS IN A 36-YEAR OLD EXPERIMENT

A Dissertation

by

PRABHU GOVINDASAMY

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Chair of Committee,	Muthukumar Bagavathiannan
Committee Members,	Jason Mowrer
	Frank M Hons
	Tony L Provin
	Nithya Rajan
Head of Department,	David Baltensperger

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ABSTRACT

Changes to tillage practices can influence soil physico-chemical properties and weed population dynamics. Experiments were conducted in 2016 and 2017 in a 36-year long tillage experiment at Texas A&M University, College Station, TX to study the impact of tillage regimes on soil physio-chemical properties and weed population dynamics in monoculture grain sorghum (*Sorghum bicolor*), and weed dynamics alone in monoculture soybean (*Glycine max*). The tillage systems studied include conventional-tillage (CT) and no-tillage (NT). Results showed that tillage did not affect soil bulk density, total porosity, air filled porosity, water-filled pore space and volumetric water content. However, water holding capacity, soil organic carbon, and cumulative carbon mineralization were 25, 43, and 16% greater in the NT system, compared to CT, at the 0 to 5 cm soil depth. Conversely, cumulative water infiltration and CO_2 emission were greater in the CT system (23.66 cm hr^{-1} and 7.28 g m^{-2}) than NT (3.98 cm hr^{-1} and 5.19 g m^{-2}) in 5 and 24 hrs study. The long-term tillage regimes also influenced weed population dynamics and seedling emergence in grain sorghum and soybean. Greater densities of Johnsongrass (*Sorghum halepense*), prostrate spurge (*Chamaesyce humistrata*), tall waterhemp (*Amaranthus tuberculatus*), henbit (*Lamium amplexicaule*) and shepherd's purse (*Capsella bursa-pastoris*) were recorded in the NT system, compared to the CT system in both crops. The long-term NT system was characterized by greater weed diversity (Shannon-Wiener's index, $H = 0.8$) and species richness ($S = 6.2$) compared to CT ($H = 0.6$; $S = 4.2$) in sorghum; however, no differences were found in weed species diversity in soybean. Moreover, a greater proportion of the viable seedbank was located in the top 5 cm soil depth in the NT system (24 to 96% depending on the weed species) compared to the CT system

(22 to 61%). Overall, results illustrated that long-term NT practices can provide environmental benefits and are more sustainable than CT. However, growers shifting to NT practices should consider potential changes to weed population dynamics and adjust the management programs accordingly.

DEDICATION

Dedicated to my daughter “Amildha Sri Prabhu”

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CHAPTER I

INTRODUCTION

Tillage is an important soil management practice to provide a suitable environment for the germination of crops (Phillips et al. 1980), control weeds (Teasdale et al. 1991), increase water infiltration (Lipiec et al. 2006), and improve soil aeration (Schjonning and Rasmussen 2000). Tillage could influence the physical, chemical and biological properties of soil and it is essential to adopt a proper tillage practice to avoid soil degradation, loss of soil organic carbon and environmental pollution (Naresh et al. 2016). In this context, one of the major advances in tillage in world agriculture has been the adoption of conservation tillage systems (Awada et al. 2014). Conservation tillage refers to tillage practices where soil disturbance is prevented or kept to a minimum, including minimum tillage (MT) and no-tillage (NT) systems.

Conservation tillage can reduce top soil loss and associated economic and environmental effects. A report by the Conservation Technology Information Centre (CTIC) reveals that conservation tillage systems have reduced sediment losses over the past two decades by about 60 to 85% across different regions (CTIC 2011). Conservation tillage systems are defined as systems that cover at least 30% of the soil surface with crop residue after planting (Koller 2003). Among the conservation tillage systems, NT systems are particularly promoted throughout the US for reducing top soil erosion, nutrient loss, and associated environmental effects, while encouraging crop residue accumulation on the soil surface. Crop residue retention in NT systems provide several benefits. It has been shown that crop residues maintained on the soil surface can improve soil water infiltration and retention (Thierfelder et al. 2009). Rasmussen (1999) found that retention of crop residue on the soil surface was the reason for increased soil water content, through a reduction in evaporative water loss. The absence of soil disturbance or inversion in NT systems allows for maintenance of a higher density and diversity of microspores and greater accumulation of organic carbon compared to the conventional tillage (CT) systems. Increases in the number of soil microspores and organic carbon content appear to improve the water holding capacity of soil (Franzluebbers et al. 1999; Singh et al. 2014; Busari et al. 2015). Further, residue cover and stable aggregates in NT systems protect the soil surface from the kinetic impact of raindrops, decrease runoff, and increase water infiltration (Ehler 1997; Cantero-Martinez 2006).

I.1: Soil microorganisms and soil organic carbon

The NT system influences the activity of soil microbial communities and soil carbon dynamics. Retention of quality residue at the soil surface provides an adequate carbon and nitrogen substrate to microbial population. Fungi are the predominant heterotrophic microorganisms present in undisturbed soil that decompose plant residues and help with C recycling (O' Halloran et al. 1986; Frey et al.1999). They produce long, filamentous vegetative structures called hyphae, which remain undisturbed under NT systems (Sharma-Poudyal et al. 2017). Compared to bacteria, fungi are efficient consumers of low quality (high carbon to nitrogen ratio) residues such as that of corn, sorghum and wheat (Condron et al. 2010). Tiunov and Scheu (2005) found that fungal species richness was positively associated with rate of organic matter decomposition in respect to a single resource of substrate (powdered cellulose) availability. A type of Arbuscular Mycorrhizal (AM) fungi contributes to the formation and maintenance of macroaggregates through the secretion of a soil protein called glomalin and in turn improve soil organic carbon (SOC) status in NT systems (Dai et al. 2015). Further, retention of crop residue at the soil surface can also increase SOC due to direct addition of C from crop residues (Kushwah et al. 2001).

I.2: Soil carbon mineralization (C-mineralization)

Soil carbon mineralization (C-mineralization) is enhanced in the NT systems due to the accumulation of quality crop residue at the soil surface (Kheyrodin and Antoun 2009). Franzluebbers et al. (1996) found that NT plots had greater C-mineralization activity than CT plots as soon as the second year after changing to NT. C-mineralization is determined by the rate of soil organic matter decomposition and ultimately affects nutrient supply and CO_2 emission (Kandeler et al. 1999; Govaerts et al. 2005; Ngwira et al. 2012). The rate of C-mineralization depends on the size of soil C and N pools (Zak et al. 1993). However, Ngwira et al. (2012) reported that increased C-mineralization in NT plots; this is probably because of a high percentage of particulate organic carbon in total soil carbon. The particulate organic carbon is a type of soil carbon which is more easily decomposed by microorganism compared to recalcitrant carbon.

I.3: Soil carbon-dioxide emission (CO_2 emission)

Soil carbon-dioxide (CO_2) emission potential can be influenced by different factors, including but not limited to soil organic matter content, environmental conditions, intensity of tillage practices, soil water content, crop type and fertilization (Moraru and Rusu 2013). Duxbury (1994) reported that excessive tillage, residue burning and excessive fertilizer application can increase CO_2 emission and decrease soil carbon buildup in the CT system. Conversely, high number of microspores and minimal exposure of soil organic matter to the atmosphere result in decreased organic matter decomposition and CO_2 emission in NT systems. Further, a reduction in the air-filled pore space in NT systems is also known to decrease CO_2 emission (Ball 1999). Total soil porosity and pore size are better indicators of CO_2 emission than soil organic matter and microbial biomass carbon (Pengthamkeerati et al. 2005). High soil compaction, high bulk density and reduced soil porosity (by about 33%) in the NT system leads to a decrease in CO_2 emission by 21% (Beare et al. 2009; Mangalassery et al. 2014).

I.4: Weed density and composition

Weeds compete with crops for critical resources. Practices such as conservation tillage and crop residue retention alter the dynamics of soil moisture and nutrient availability to crops and weeds. The reduction of soil inversion and the ability of small-seeded weeds to germinate from the soil surface increased the population of small-seeded annual weeds in NT systems compared to CT systems (Barberi et al. 2001; Dorado et al. 2006). Similarly, the reduced frequency of soil disturbance, a highly stable environment and numerous granivore species have facilitated high dispersal of small-seeded weeds in NT systems (Nichols et al. 2015). In corroboration with this, several studies have found that species richness (more number of weed species) is higher in NT systems than in CT systems (Dorado et al. 2006; Sosnoskie et al. 2006). Further, repeated tillage in the CT systems affect the vertical distribution of weed seeds in the soil profile (Clements et al. 1996; Cardina et al. 2002). Yenish et al. (1992) found that more than 60 % of the weed seeds remained near the soil surface in NT systems due to minimum soil disturbance, whereas only 30% of the weed seeds were found on the soil surface under chisel plowing.

I.5: Limitations of NT system

The NT system also presents some limitations. Wheel traffic produced by machineries during planting, fertilizer injection, pesticide application and harvesting operations and the absence of frequent soil inversion lead to compaction at the soil surface and sub-surface in the NT system. Soil compaction alters the size and structure of pore space and thereby increase the bulk density of the soil. Mapa et al. (1986) reported that soil compaction disturbs the consolidation of soil particles, thus altering the size distribution of pores. Long-term NT systems generally create a minimal disturbance layer just below 20 cm soil depth, where high bulk density and soil resistance affect root penetration and enhance below-ground competition between crops and weed (Shi et al. 2012; Singh et al. 2014). The increase in water retention and soil moisture at compacted soil layers increases water-filled pore space (WFPS), when the range is exceeding that directly influences microbe regulated N-transformation in the soil, which includes organic matter decomposition, ammonification, nitrification and denitrification (Stanford and Epstein 1974; Craswell and Martin 1974; Pal and Broadbent 1975; Linn and Doran 1984). Linn and Doran (1984) reported that maximum microbial N–transformation occurs in 60% WFPS, whereas denitrification occurs in 70% WFPS. NT systems typically have higher WFPS than CT systems due to higher sorption of water by soil organic carbon and increased bulk density. However, improved earthworm activity and root channels in NT systems may counteract the effects created by soil compaction (Ankeny et al. 1990). For example, Logsdon and Allmaras (1991) reported that increase in SOC in the NT system promotes earthworm activity; which will burrow the soil to 2-meter depths. Burrows created by earthworm activity increases water infiltration and root penetration.

NT systems are generally known to be more beneficial to soil, environment and crops compared to CT systems, but there are some inconsistencies on the reports documenting the impact of tillage practices on soil physical, chemical and biological properties. Because the impact on soil physiochemical properties are depending on the location, climate, soil type, cropping system, time and depth of tillage, duration of tillage and quality of crop residues (Mosier et al. 1991; Fernandez et al. 1993; Lauren and Duxbury 1993; Lal 1994; Osozawa and

Hasegawa 1995; Yavitt et al. 1995; Al-Kaisi and Yin 2005). Therefore, more detailed studies are required to fully understand the impact of tillage practices on soil physical and chemical properties in a specific environment. Further, very little research has focused on the impact of both soil physical and chemical properties on weed population dynamics in conservation tillage systems (Benech-Arnold et al. 2000; Gaston et al. 2001). In this study, we aim to understand the impact of changes in soil physical and chemical properties on weed community composition, seedling emergence and seedbank dynamics in two (CT, NT) different tillage systems. Our specific objectives were to determine the impact of long-term tillage practices on:

1. Soil physical properties
2. Soil C sequestration and CO_2 emission
3. Weed population dynamics (seedbank distribution, seedling emergence pattern, and species diversity) in a continuous sorghum production system, and
4. Weed population dynamics (seedbank distribution, seedling emergence pattern, and species diversity) in a continuous soybean production system

The hypotheses underpinning the project objectives were:

1. Long-term NT practices improve soil physical properties more than CT practices **(objective 1)**
2. NT system improves soil quality characteristics and minimize CO_2 emission compared to CT **(objective 2)**, and
3. Weed species diversity, emergence pattern, and seedbank distribution in the NT system is different than in CT **(objectives 3 and 4)**

CHAPTER II

INFLUENCE OF LONG-TERM (36 YEARS) TILLAGE PRACTICES ON SOIL PHYSICAL PROPERTIES IN A CONTINUOUS SORGHUM EXPERIMENT IN SOUTHEAST TEXAS

II.1: Introduction

Soil physical properties, such as soil texture, structure, permeability, penetration resistance, and infiltration significantly influence crop growth and yield (Singh et al. 2014; Indoria et al. 2016). These properties, however, can be altered by repeated tillage operations depending on the type of force exerted by the tillage machinery, and the intensity and depth of tillage operations (Fabrizzi et al. 2005; Osunbitan et al. 2005). For example, periodic tillage can destroy stable soil aggregates, and alter pore size, structure and distribution (Huwe 2002). Moreover, tillage can also increase soil dispersion, water and wind erosion, and soil crusting (Licht and Al-Kaisi 2005; Olson et al. 2016). Intensive tillage operations can also negatively impact soil fertility and quality by accelerating soil erosion, carbon loss and greenhouse gas emissions (Johnson et al. 2007).

Conservation tillage practices such as no-till (NT), on the other hand, can provide several agronomic and environmental benefits, such as increased soil water content, water stable aggregates, soil carbon storage and improved activities of soil microflora and fauna (Triplett and Dick 2008). NT systems can also improve soil physical properties such as bulk density (BD), water infiltration rate, mechanical impedance or root penetration (MI), porosity, and water holding capacity (WHC) (Patel and Singh 1981; Ankeny et al. 1990; Radke and Berry 1993). In particular, increased in BD (about 3 to 16% greater) has been widely reported with NT compared to conventional tillage (CT) (Balesdent et al. 2000; Zuber et al. 2015; Halvorson et al. 2002). Also, improvements in WHC have also been widely reported with NT. For example, Bescansa et al. (2006) reported that NT plots had greater soil water retention at – 33 kPa water potential (11% greater) compared to tilled plots.

The effect of tillage on soil physical properties is largely dependent on the frequency and depth of tillage, original soil texture, cropping system practiced, crop residue management, and climate (Lal et al. 1994; Seiko and Hasegawa 1995; Yavitt et al. 1995; Al-Kaisi and Yin 2005). An integration of conservation tillage and sound crop residue management can have a significant impact on soil properties. For instance, Dao (1996) reported a 6% decrease in soil BD under wheat residue retention (0.1 Mg ha^{-1}) in a NT system, compared to moldboard plowing. Shaver et al. (2002) reported that retention of more crop residues by wheat-corn-fallow decreased BD (6% lower), increased soil porosity (4% greater), and enhanced soil aggregation (19% greater), compared to a wheat-fallow system in a fine loamy soil in Colorado. Similarly, in a study conducted in Spain, Lampurlanes and Cantero-Martinez (2003) reported a higher BD in continuous-crop plots (1.32 Mg m^{-3}) compared to fallow and crop-fallow plots (1.26 Mg m^{-3}). The authors have attributed this difference to tillage operations that were performed in the fallow years to control weeds, compared to continuous-crop plots.

In Texas, the majority of soils are low in fertility with low water holding capacities, and prone to wind and water erosion (NRCS-USDA 2017). Conservation tillage practices such as NT or some form of reduced tillage can provide tremendous benefits to these marginal environments

(Baumhardt et al. 2011). Grain sorghum (*Sorghum bicolor*) is an important row-crop in Texas. A popular crop especially in marginal soils in limited rainfall areas. However, knowledge is limited on the impact of long-term conservation tillage practices on soil physical properties in sorghum production system. At Texas A&M University, a long-term tillage experiment has been ongoing for over 36 years under sorghum monoculture and this experiment can provide valuable insights the long-term (36 years) impact of the soil physical properties. Thus, we hypothesized that long-term NT practices improve soil physical properties more than CT practices. Therefore, the objective of this study was to assess the effect of long-term (36 years) NT and CT systems on soil physical properties such as BD, total porosity (TP), air filled porosity (AFP), water filled pore space (WFPS), Θv, WHC, MI, and infiltration in the long-term (36 yr) sorghum experiment being carried out in the sub-humid, sub-tropical region of Texas.

II.2: Materials and Methods

II.2.1: Study Site

A long-term grain sorghum experiment was initiated in 1982 at the Texas A&M field research farm near College Station, Texas (30.46ºN, 96.43ºW). The mean annual rainfall in the study location was 102 cm (HPRCC, 2018). The soil was a Weswood clay loam (fine-silty, mixed, superactive, thermic Udifluventic Haplustepts) with 29% sand, 42% silt and 29% clay. The treatments include CT and NT arranged in a randomized complete block design (plot size: 4 m × 12 m) with four replications. The observations on soil physical properties presented here were recorded during fall seasons of 2016 and 2017. The CT plots were disk harrowed (10 to 15 cm depth) annually after crop harvest, followed by chisel plowing (20 to 25 cm depth) prior to winter. The NT plots were not disturbed. Sorghum was planted during mid- to late-March in 1-m wide rows and harvested during late July to early August. The plots were fertilized with nitrogen (135 kg ha^{-1}) as a band application prior to sorghum planting. In all plots, atrazine (2-chloro 4-ethylamino-6-isopropylamino-1, 3, 5-trithemazine) was applied preemergence at 680.4 g ai ha^{-1} immediately after sorghum planting.

II.2.2: Measurement of Soil Physical Properties

Soil cores (2.5 cm diameter and 20 cm deep) were randomly collected at five spots in each plot immediately after sorghum harvest (a month after disking) and each core was divided into three sub-samples based on depth (0 to 5, 5 to 10, and 10 to 20 cm). The total soil volumes obtained were 101 cm^3 for the 0 to 5 and 5 to 10 cm depths, whereas it was 202 cm^3 for the 10 to 20 cm depth. Penetration resistance was recorded under field conditions immediately after sorghum harvest. Furthermore, in spring 2018, a combined observation of BD, Θv and MI were carried out at three depths (soil surface, 20 and 30 cm) to evaluate potential relationships among these variables.

II.2.3: Soil Texture

Particle size analysis was carried out for soil texture determination using a hydrometer method. This method quantitatively determines the proportions of sand, silt and clay particles by measuring the settling rates in an aqueous solution using the hydrometer. Forty gram of air dried soil was transferred into a 600 ml beaker containing 100 ml of Calgon® solution and 300 ml of distilled water. The samples were allowed to soak overnight, and were then transferred to a cylinder and distilled water was added to bring the volume to 1000 ml. A plunger was used to mix the content thoroughly. The hydrometer was calibrated in a solution containing 100 ml of Calgon® solution and 900 ml of distilled water (R_L). The calibrated hydrometer was slowly lowered into the suspension and the readings were recorded at 40 s (R_{40s}) and 7 hrs (R_{7h}).

Simultaneously, the oven-dried weight of the soil sample was determined by placing 10 g of soil in an oven at 105°C until constant weight (Day 1965). The proportions of sand, clay and silt were determined using the equations 1 to 3, as shown below:

$$\text{Sand (\%)} = 100 - (R_{40\,s} - R_L) \times 100/\ \text{oven-dried soil (weight in grams)} \quad \text{(II.1)}$$

$$\text{Clay (\%)} = (R_{7\,h} - R_L) \times 100/\ \text{oven-dried soil (weight in grams)} \quad \text{(II.2)}$$

$$\text{Silt (\%)} = 100 - (\%\text{sand} + \%\text{clay}) \quad \text{(II.3)}$$

II.2.4: Soil Bulk Density, Total Porosity, Air Filled Porosity, Water Filled Pore Space and Volumetric water content

Collected soil cores were dried in an oven at 105ºC for 72 hours until constant weights were reached (Jemai et al. 2013). The BD was determined by estimating oven-dry mass of the samples divided by the respective sample volume (Blake and Hartge 1986). Gravimetric moisture content (%) was calculated by subtracting the soil dry weight from the fresh weight. The BD and gravimetric soil moisture values were used to derive AFP, Θv, and WFPS values following the procedure described by Haney and Haney (2010).

II.2.5: Water Holding Capacity

WHC was determined by modifying the method described by Bernard (1963). Disturbed soil samples (100 ml in volume) were placed in a funnel with a filter paper at the bottom. The funnel was placed on top of a graduated cylinder. Then, exactly 100 ml of water was measured and added to each sample and allowed to drain for 72 hours. The water collected in the measuring cylinder was recorded to calculate water holding capacity, which was expressed as a percentage of total water added to each sample.

II.2.6: Penetration resistance

The penetration resistance or mechanical impedance (MI) was measured using a dynamic cone penetrometer [Sleeve Drive Hammer, S-20000, Durham Geo Slope indicators (DGSI)] after sorghum harvest. The observations were recorded at four soil depths (soil surface, 20, 40 and 60 cm) and three random spots in each plot. The number of droppings required to completely bury the cone (length: 3.5 cm) of the penetrometer into the soil was recorded using the following formula (Herrick and Jones 2002) (equation 1):

$$MI\ (J\ cm^{-1}) = ND\ \times 33.31/3.5 \qquad \text{(II.4)}$$

where the ND is the number of disc drops required to push the tip into the soil; length of cone penetrometer tip is 3.5 cm; and the kinetic energy required to push the tip is 33.31 J.

II.2.7: Water Infiltration

Cumulative water infiltration was measured after sorghum harvest using a double-ring infiltrometer (IN7-W-Turf-tec, Turf-tec international, FL) with two rings of 15 and 30 cm diameters. Three infiltrometers were placed in each treatment, and the measurements were carried out for 6 hrs. The amount of infiltration was recorded at 15-min intervals in the first hour, 30-min in the second hour, and 60-min during the remainder of the period (Johnson 1963 and Huang et al. 2015).

II.3: Statistical Analyses

Statistical analyses were performed using the Statistical Analysis Software (SAS v 9.4, SAS Institute Inc., Cary, NC). Data were subjected to ANOVA using the GLIMMIX procedure in SAS. Year, block (nested within years), and all interactions containing either of these factors were considered as random effects in the model, whereas tillage treatment and soil depth were considered as fixed effects. Prior to conducting ANOVA, normality of the dataset was tested using the Shapiro-Wilk test (PROC UNIVARIATE). Multiple comparisons of treatment means were performed using the Least Square Means method ($P < 0.05$). A cubic function (equation 2) was regressed on cumulative water infiltration data using SigmaPlot (v 13.0, Systat Software Inc., San Jose, CA), which took the following form:

$$Y = Y_0 + A^*X + B^*X^2 + C^*X^3 \tag{II.5}$$

where Y is cumulative infiltration (cm) at time X; Y_0 is the overall intercept; A, B and C are coefficients of the cubic function; X is time (minute).

II.4: Results and Discussion

This study is among the few studies published so far that report long-term impacts of tillage practices on soil physical properties. The interaction effects of year-by-treatments were not significant ($P \geq 0.05$) for the soil physical properties BD, TP, AFP, WFPS, Θv, WHC, MI, and cumulative infiltration; therefore, data from both the years were pooled. Monthly average temperature (ºC) and a total rainfall (mm) in 2016 and 2017 is presented in Table 1.

II.4.1: Soil Particle Size Analysis

The proportions of sand, silt and clay in three soil depths (0 to 5, 5 to 10 and 10 to 20 cm) are presented in Table 2. The mean sand, silt and clay contents of the CT and NT systems were similar because of their comparable particle size distribution. The soil texture at the three depths were clay loam, except in the NT system at 10 to 20 cm soil depth where it was a silty clay loam. Overall, the sand, silt and clay content of the experimental plot was 290, 430 and 280 g kg^{-1} of soil and the soil texture was a Weswood clay loam (fine-silty, mixed, superactive, thermic Udifluventic Haplustepts).

II.4.2: Soil Bulk Density

Tillage had no effect on soil BD ($P = 0.42$) (Table 3). It is believed that alternate freezing and thawing during winter months, and cracking during summer months might have ameliorated any soil compaction resulting from farm machineries. In this study, soil cracking was more commonly observed in the NT system, compared to the CT system.In a long-term corn and rye rotation experiment in Kentucky, Blevins et al. (1983) reported that the BD of a silty-loam soil was similar (1.25 to 1.28 g cm^{-3}) between the CT and NT systems, corroborating the findings of this study. Several other studies have also found similar BD values between CT and NT systems (Voorhees and Lindstrom 1984; Ferreras et al. 2000; Singh et al. 2014). Soil BD levels are generally expected to increase in NT systems due to a lack of soil disturbance to overcome wheel-track compaction caused by farm machineries. In our experiment, it is believed that freezing during winter months, and cracking during summer months might have ameliorated any soil compaction resulting from farm equipment. In this study, soil cracking was more commonly observed in the NT system, compared to the CT system.

Soil BD values, however, differed with soil depth. The BD value for the 5 to 10 cm soil depth was lower (1.22 Mg m^{-3}) than that of the 0 to 5 cm (1.38 Mg m^{-3}) and the 10 to 20 cm depths (1.40 Mg m^{-3}) (Table 1). The lower BD value at the 5 to 10 cm depth can be explained by an increased pore space caused by root penetration and earthworm activities, which were not documented in this study. Similar findings were also reported by Follett and Peterson (1988), where a lower BD was observed at the 5 to 10 cm soil depth (1.07 Mg m^{-3}) in comparison to the 10 to 20 cm soil profile (1.34 Mg m^{-3}). The authors attributed this difference to greater pore space in the 5 to 10 cm profile than in the 10 to 20 cm profile. BD is a good indicator of soil compaction, wherein low BD levels may indicate increased soil porosity, infiltration, and rooting capacity. The low BD values observed in this study at the 5 to 10 cm depth indicate for a potentially better environment for aeration and root penetration.

II.4.3: Soil Porosity

Soil porosity parameters (TP, AFP, and WFPS) were not affected by the tillage treatments ($P \geq 0.05$). Similar results were reported by Nkakini et al. (2008) wherein no significant differences were observed in the porosity values between NT and CT. Greater plant (weeds and sorghum) root densities in NT and tillage in CT might have resulted in comparable porosity levels in this study.

Soil porosity parameters, however, differed with soil depth (Table 3). The TP (52.39%) and AFP (52.20%) values were greater at the 5 to 10 cm soil depth, than that of the 0 to 5 and 10 to 20 cm depths (≤ 47.5%). Negative correlations (Pearson correlation coefficient $r = -0.20$; $P = 0.06$) between soil BD and porosity parameters (TP and AFP) were observed in this study (Table 2). Glab and Kulig (2008) also reported an inverse relationship between BD and TP in a silty loam soil in Poland. Greater soil porosity corresponds to a looser soil, which eventually leads to low BD levels. However, the WFPS showed an increasing trend with depth. The WFPS values were greater at the 10 to 20 cm soil profile (57%) compared to the 0 to 5 (43%) and 5 to 10 cm depths (38%). Wang (2014) also reported a similar finding wherein the WFPS values were greater at the 10 to 20 cm soil profile, compared to the 5 to 10 cm depth. In general, sub-surface layers (e.g. 10 to 20 cm) are more compacted and have less aggregation as well as poor root penetration, thus higher WFPS compared to the surface layer (0 to 10 cm). When the WFPS values are above 60%, soil respiration and microbial activities may be severely impacted (Linn and Doran, 1984). The high WFPS value (57%) obtained in this study at the deeper profile was still under the critical level (60%) to impact important soil biological processes such as nutrient cycling and microbial respiration.

II.4.4: Volumetric Water Content

A trend similar to the BD and soil porosity was observed with Θv, where, Θv was not affected by tillage systems, but by the soil depth. The Θv was greater (0.25 cm^3/cm^3) at the 10 to 20 cm soil depth compared to the 0 to 5, and 5 to 10 cm depths (0.20 and 0.19 cm^3/cm^3, respectively) (Table 3). In a study conducted on a silty loam soil, Blevins et al. (1971) observed 24% greater Θv at 30-40 cm depth compared to 15 to 30 cm. Similarly, Lampurlanes et al. (2001) reported that Θv was 4% greater at 25 to 50 cm soil depth than the upper half (0 to 25 cm) of the soil profile. The lower Θv values up to the depth of 10 cm, in comparison to 10 to 20 cm, could be attributed to the depletion of soil moisture by plants during the growing season. Results suggest that an effective strategy for soil moisture management is rotating a deep rooted crops with grain sorghum for efficiently utilizing the stored soil moisture in deeper layers in the rotational years.

II.4.5: Water Holding Capacity

The WHC was 25.8% greater in the NT plots compared to the CT plots (Table 3). Our findings support several previous studies that reported considerable increase in soil WHC under NT management (Lal 1976; Dao 1993; Lal 2006; Gozubuyuk et al. 2014; Mahboubi et al. 1993). In our study, the WHC declined with depth, with the lowest values (63.37%) recorded at the 10 to 20 cm soil depth (Table 3). This trend was consistent with a decline in soil organic carbon content at deeper soil profiles (data not shown). It has been shown that there is a positive relationship between soil organic carbon and micro-pores (and consequently WHC), explaining the trends in WHC observed in this study (Lal et al. 1989; Lipiec et al. 2006; Gozubuyuk et al.

2014). Greater WHC in the NT system could enhance water productivity and crop yield, compared to the CT system.

II.4.6: Correlation among Soil Physical Properties

A correlation analysis was performed to evaluate the relationships among different soil physical properties recorded (BD, Θv, TP, AFP, and WFPS). The Θv was positively correlated with soil BD (*r* = 0.47) and WFPS (0.86) (Table 4). The WFPS also showed positive correlation with the BD (0.49); however, it had negative relationships with TP (–0.50) and AFP (–0.51). AFP and TP had close association (*r* = 0.99) between them. Our findings are consistent with Archer and Smith (1972) who found positive relationships between BD and soil moisture content/available water capacity. Soil BD is an important soil physical property that influences soil water content and aeration. Thus, production practices that reduce BD could indirectly enhance crop production.

II.4.7: Infiltration

The cumulative infiltration was 23.66 cm in the CT system, whereas it was only 3.98 cm in the NT system, 6 hrs after initiation of the experiment (Figure 1). Greater soil infiltration levels in CT than NT have also been reported by Lipec et al. (2006). It is believed that initial soil dryness, roughness, and lesser consolidated soil surface in the CT system could have resulted in the greater cumulative infiltration than in the NT system. The recorded soil moisture content also indicated that the CT system had lower soil moisture and temperature levels compared to the NT system, which might have increased soil infiltration (Table 6). Further, it is likely that the temporary macropores developed by tillage could have promoted greater infiltration in the CT system (Gomez et al. 1999). Soil infiltration is dictated by conditions near the soil surface and can be greatly altered by management practices. In this study, we also observed a lateral movement of water after 5.5 hrs of infiltration in the CT system, which showed that the CT system had poor macropore connectivity due to repeated tillage. Though the rate of infiltration was lower in the NT system, the macropore connectivity was greater in that system as evidenced by deeper water infiltration, though in this experiment the depth difference in infiltration was not measured.

II.4.8: Penetration resistance

Tillage systems did not affect MI (P=0.24); however, tillage-by-depth interaction was significant (not shown). The highest penetration resistance (51.81 J cm^{-1}) was observed at the 60 cm soil depth in the NT system, which was comparable with the values obtained at the same depth in CT (48.11 J cm^{-1}) (Table 5). No resistance was observed at the surface in the CT system. Our findings corroborate the report by Gozubuyuk et al. (2014) on a loamy soil in Turkey, wherein about 2 MPa greater penetration resistance was observed in NT compared to CT at the soil surface. The lack of plowing along with soil compaction due to wheel traffic over the period might have resulted in the higher MI at the surface in the NT system (Grant and Lafond 1993; Causa et al. 2010). Further, penetration resistance had a positive correlation with BD and volumetric moisture content in both the systems at 0 to 40 cm soil depth (Figure 2). These observations were in agreement with the previous findings reported by Imaz et al. (2010) and Gozubuyuk et al. (2014). In this experiment, the observed increase in MI in both the tillage systems are related to changes in BD and Θv. The decrease in soil macropores at farther depths might have increased the proportion of micropores in total porosity, causing soil strengthening. This response may inhibit crop rooting beyond 60 cm depth.

II.5: Conclusions

This experiment assessed the impact of long-term (36 yr) tillage practices on soil physical properties in a continuous sorghum production system. Results suggested that BD, TP, AFP, WFPS, Θv, and WHC were affected by soil depth. Unlike several other studies, which have reported that long-term NT system increased BD and impacted soil aeration, our study suggested that tillage systems did not influence soil physical properties except for WHC and cumulative infiltration. Greater WHC observed with the NT system may facilitate soil moisture conservation and favor improved germination of crop seeds and stand establishment. Further, increased BD and MI in the 0 to 5 cm soil layer could increase the ratio of microporosity in the total porosity. Overall, long-term NT practice benefits improved soil moisture and provides an opportunity for growers to include a winter crop after grain sorghum harvest.

Table 1: Mean monthly temperature (°C) and rainfall (mm) data for the growing season (May to September) in 2016 and 2017 at College Station, TX[a].

Month	Mean temperature			Total precipitation		
	2016	2017	36 yr average	2016	2017	36 yr average
May	26	27	24	347	129	123
June	31	31	28	68	125	99
July	33	34	29	9	9	53
August	32	32	30	159	582	79
September	30	30	27	51	39	86
Annual	21	22	20	1188	1325	1024

[a] Air temperature and precipitation data were obtained from HPRCC, the High Plains Regional Climate Center (2018).

Table 2: Soil texture compared between conventional tillage and No-Till at different depths in the long-term (36 years) continuous sorghum experiment in Southeast Texas.

Depth (cm)	Conventional tillage				No tillage			
	Sand	Silt	Clay	Soil Texture	Sand	Silt	Clay	Soil Texture
	——— g kg^{-1} ———				——— g kg^{-1} ———			
0 to 5	290	430	280	Clay loam	300	400	300	Clay loam
5 to 10	310	370	320	Clay loam	220	510	280	Clay loam
10 to 20	260	390	350	Clay loam	190	430	380	Silty clay loam

Table 3: Soil physical properties as impacted by tillage and soil depth in a long-term (36 years) continuous sorghum experiment in Southeast Texas.

	Soil physical properties†‡					
	BD	TP	AFP	WFPS	Θv	WHC
	— $Mg\ m^{-3}$ —	— % —			— cm^3/cm^3 —	— % —
Tillage						
CT	1.35 a	48.54 a	48.32 a	46.00 a	0.22 a	62.00 b
NT	1.31 a	48.18 a	48.00 a	46.00 a	0.21 a	78.00 a
P-value	0.42	0.83	0.83	0.93	0.81	<0.001
Soil depth (cm)						
0 to 5	1.38 a	47.53 b	47.33 b	43.00 b	0.20 b	75.37 a
5 to 10	1.22 b	52.39 a	52.20 a	38.00 b	0.19 b	71.19 a
10 to 20	1.40 a	45.16 b	45.00 b	57.00 a	0.25 a	63.37 b
P-value	0.001	0.002	0.002	<0.001	<0.001	0.01

† Within each column, means followed by the same letters are not significantly different ($P \geq 0.05$)
‡ BD = bulk density; TP = total porosity; AFP = air filled porosity; WFPS = water filled pore space; Θv = volumetric water content; WHC = water holding capacity

Table 4: Matrix of Pearson correlation coefficients for various soil physical properties including bulk density (BD, Mg m^{-3}), volumetric water content (Θv, cm^3/cm^3), total porosity (TP, %), air filled porosity (AFP, %) and water filled pore space (WFPS, %) in a long-term (36 years) continuous sorghum experiment in Southeast Texas*

	BD	Θv	TP	AFP	WFPS
BD	1.00				
Θv	**0.47**	1.00			
TP	– 0.20	– 0.06	1.00		
AFP	– 0.20	– 0.07	**0.99**	1.00	
WFPS	**0.49**	**0.86**	– **0.50**	– **0.51**	1.00

*Coefficients that are significant ($P<0.05$) are shown in bold text.

Table 5: Penetration resistance (MI) as influenced by tillage and soil depth in a long-term (36 years) continuous sorghum experiment in Southeast Texas.

Tillage	Soil depth (cm)	MI (J cm^{-1})†
CT	surface	0.00 (0)e
	20	28.55 (14.88*) cd
	40	37.01 (17.22) bc
	60	48.11 (20.79) ab
NT	surface	21.67 (7.87) d
	20	27.49 (7.68) cd
	40	29.08 (5.82) cd
	60	51.81 (6.23) a
P-value		0.02

†Means followed by the same letters are not significantly different ($P \geq 0.05$)
* Standard deviation

Table 6: Soil temperature and moisture conditions in the experimental site at the time of the infiltration study.

Tillage[a]	2016		2017	
	Temperature (°C)	Moisture (%)	Temperature (°C)	Moisture (%)
CT	24	32	26	30
NT	22	38	24	37

[a]average of three replications

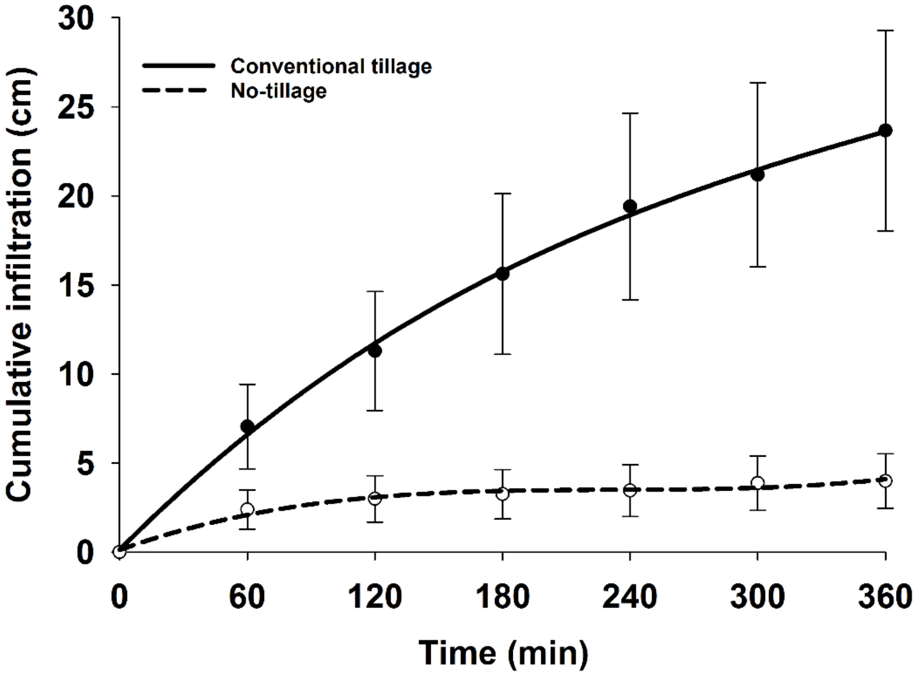

Figure 1: Cumulative infiltration as influenced by tillage in a long-term (36 years) sorghum experiment in Southeast Texas. The model for conventional-tillage is: $Y = 0.12 + 7.17*time –0.77*time^2 + 0.03*time^3$, $r^2 = 0.99$. The model for no-tillage is: $Y = 0.11 + 2.53*time –0.64*time^2 + 0.05* time^3$, $r^2 = 0.98$.

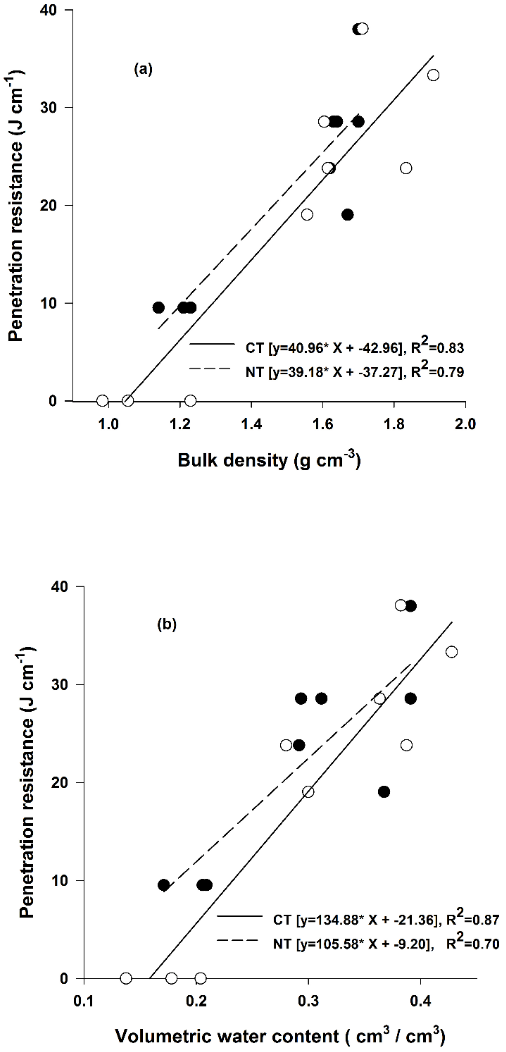

Figure 2: Correlation between penetration resistance and (a) bulk density, and (b) gravimetric water content at the 0-40 cm soil depth as influence by tillage in a long-term sorghum experiment in Southeast Texas.

CHAPTER III

LONG-TERM (36 YEARS) NO-TILLAGE INCREASED SOIL ORGANIC CARBON AND CARBON-MINERALIZATION, AND DECREASED CO_2 EMISSION IN A SORGHUM EXPERIMENT IN SOUTHEAST TEXAS

III.1: Introduction

Soil organic carbon (SOC) contributes positively to soil quality and productivity (Dou et al. 2007; Guimaraes et al. 2013; Wright and Hons 2005a). Carbon content in the soil ecosystem is 3.3 and 4.5 times greater than the atmospheric and biotic pools, respectively (Lal 2004). The rate of SOC accumulation or loss, however, can be influenced by management practices. In particular, tillage can increase the loss of SOC. It is estimated that about 3 to 5 gigatones (Gt) of soil carbon is lost annually in the United States due to tillage (Lal et al. 2004). Intensive cultivation accelerates the loss of fertile top-soil through soil erosion (Lal et al. 1999).

Conservation tillage practices such as no tillage (NT), on the other hand, can favor the assimilation of SOC by both decreasing soil disturbance and increasing crop residue accumulation (Al-kaisi and Yin 2005; Franzluebbers et al. 1995; Gonzalez- Chavez et al. 2010; Wright and Hons 2005b). The duration of conservation tillage, in particular, may influence the amount of SOC accumulation, but it can be confounded by other factors such as soil type, depth, cropping system, and climate (Dou et al. 2007; Paustian et al. 1997). In a 20-year long study conducted in Ohio on a Hoytville silty clay loam soil, Dick (1983) reported that SOC at the top soil layer (0 to 1.25 cm depth) was 2.2 times greater in NT compared to a conventional-tillage (CT) system. Likewise, Wright and Hons (2005a) reported a 27% increase in SOC content in

NT, compared to CT, at the 0 to 5 cm soil depth in a 23-year long experiment in Weswood silty clay loam soil in Southeast Texas.

Residue retention is another important factor that can influence the rate of SOC accumulation. In a study conducted in eastern Kansas, Havlin et al. (1990) found greater SOC in sorghum-soybean rotation, compared to soybean monocropping, and associated the increase in SOC to the high amounts of residue produced and retained on the soil surface in the sorghum-soybean rotation. Similarly, Blanco-Canqui and Lal (2007) reported an increase in SOC with a corresponding increase in crop residue retention, with 16.0 Mg ha^{-1} of SOC in no straw, 25.3 Mg ha^{-1} SOC in 8 Mg ha^{-1} straw, and 104.9 Mg ha^{-1} SOC in 16 Mg ha^{-1} straw.

Tillage can also increase the rate of carbon mineralization (hereafter "C-min") by mixing crop residues in soil and exposing the protected SOC in the aggregates to soil microorganisms. Soil organic matter decomposition initiates C-min, which can directly impact soil nutrient supply and CO_2 emission (Govaerts et al. 2006; Kandeler et al. 1999; Ngwira et al. 2012). In an experiment conducted in Argentina, Alvarez et al. (1998) reported that the rate of C-min was 70% greater in NT than CT in a laboratory incubation study. Franzluebbers et al. (1995) also found that the potential for C-min was greater under NT (80 g m^{-2}) compared to CT (59 g m^{-2}) in a Weswood silty clay loam soil in Southeast Texas.

Accumulation of SOC has a direct positive correlation with the sequestration of atmospheric CO_2. Conversely, oxidation of SOC, favored by practices such as tillage, can contribute to CO_2 emission from agricultural fields. For example, agricultural land-use systems that lead to top soil disturbance, such as CT, are known to increase CO_2 emission by 20 to 30% (Olson et al. 2016; Lal 2018). Bista et al. (2017) reported that CO_2 emission in CT was 29%

greater than NT in a loamy soil. Thus, conservation tillage can both increase carbon sequestration and reduce CO_2 emission (Hernanz et al. 2009).

Because changes to SOC assimilation, C-min, and CO_2 emission are influenced by practices carried out long-term, these variables can be better studied using long-term field experiments. A 36-year long tillage experiment is currently underway at Texas A&M University, College Station that compares NT and CT systems. In this experiment, the most recent SOC accumulation was quantified in 2002 (Wright and Hons 2005a). The changes to SOC in the past 13 years since the last observation, as well as long-term tillage impacts on C-min and CO_2 emission are yet to be determined. The objective of this study was to quantify the impact of long-term NT and CT practices on SOC, C-min and CO_2 emission in the 36-year long tillage experiment.

III.2: Materials and Methods

III.2.1: Study Site

The experiment was initiated in 1982 at College Station, Texas (30.46ºN, 96.43ºW) in a Weswood clay loam soil (8.0 pH, 290 g kg^{-1} sand, 420 g kg^{-1} silt, and 290 g kg^{-1} clay). The study location is characterized by a sub-tropical and sub-humid climate, with an average annual rainfall of 102 cm. Two tillage treatments (NT and CT) were implemented in a continuous grain sorghum production system, and the plots (4 m × 12 m) were arranged in a randomized complete block design with three replications. The CT operations were achieved by disking the soil at 10 to 15 cm depth after sorghum harvest, followed by chisel plowing at 20 to 25 cm depth and bed forming prior to winter. Shortly after harvest (and prior to disking in the CT), sorghum stalks were shredded and spread on the ground in both the tillage systems. The grain sorghum crop was planted at 1-m wide rows during mid-to late-March and harvested during late July to early August. Prior to planting, nitrogen fertilizer was applied in a band to provide 135 kg N ha^{-1}. Atrazine (Atrazine 4L, Helena chemical company, 225 Schilling Boulevard, Suite 300 Collierville, Tennessee 38017) was applied preemergence at 680.4 g ai ha^{-1} at the time of sorghum planting in all plots.

III.2.2: Soil Sample Collection

Soil cores (2.5 cm diameter and 20 cm deep) were randomly collected at five spots in each plot up to a depth of 20 cm, after sorghum harvest in 2016 and 2017, using a motorized soil sampler [AMS, Inc. Main Office, 105 Harrison St. American Falls, ID]. Each core was split into three sub-samples (0 to 5, 5 to 10, and 10 to 20 cm depth categories), and the samples were then placed in plastic bags and stored at 4^0C until further analysis. The soil samples were taken out of cold storage at the time of analysis and air dried for a week to remove excess moisture.

III.2.3: Soil Organic Carbon

The SOC contents in the test samples were determined using the CNHS-O analyzer (EuroEA3000). Two hundred and fifty milligrams of ground soil that passed through a 80-mesh screen was placed in a tin capsule and combusted at 650°C with constant helium flow carrying pure oxygen to ensure complete oxidation of organic materials; CO_2 produced during the combustion was determined using a thermal conductivity detector (McGeehan et al. 1988). Total soil carbon was also measured using a similar procedure described for SOC, but the samples were combusted at 1300°C. Soil inorganic carbon content was calculated as the difference between total soil carbon and SOC (McGeehan et al. 1988).

III.2.4: Carbon Mineralization

A short-term (21 days) incubation study was conducted to measure C-min in the soil samples collected. A sub-sample of 40 g air-dried soil from each sample was placed in a 450 ml glass jar and incubated at a constant temperature of 28°C. The jars (four replications per treatment) were arranged in a randomized complete block design. Soil moisture content was maintained at 50% of the water holding capacity throughout the incubation period (Haney and Haney 2010). A vial containing 10 ml of 1*M* KOH was placed in the jar as an alkali trap to capture the evolved CO_2 from the incubated soil (Haney et al. 2008; Segda et al. 2014; Zhang et al. 2010). Empty glass jars with a vial containing 10 ml 1*M* KOH were used as a blank. The experiment was conducted in dark for 21 days. The alkali traps were retrieved and replaced at 1, 3, 7, 14, and 21 days after the initiation of the incubation. The amount of CO_2 evolved was determined by titrating the KOH solution with 1 *N* HCL solution in an excess of $BaCl_2$ (5 ml) (Paredes et al. 1998). The net CO_2-C was calculated by deducting the value for the control from the treatments, using the relationship provided by Anderson (1982):

$$CO_2 = (B-V)\ NE \qquad \text{(III.1)}$$

where B is the Volume of HCL used to titrate NaOH in blank, V is the volume of HCL used to titrate NaOH in treatment, N is the normality of the acid, and E is the equivalent weight (i.e. 22).

III.2.5: In-situ CO_2–C Emission

An *in-situ* field experiment was conducted to quantify CO_2 –C emission using the titration method (Anderson 1982; Rochette and Hutchinson 2005). Two homemade static chambers (28 cm height and 20.5 cm diameter) with glass vials holding 30 ml KOH were placed on the soil surface in each of the three replications in both tillage systems. Additionally, three chambers containing vials of 30 ml 1*M* KOH were placed without soil contact by covering the bottom of the chambers with a plastic sheet. These chambers were used as a blank while calculating CO_2 emission using Equation 1. The rim of the chamber was pushed into the soil for 5 cm depth to prevent any contact with the atmospheric air. The units were placed in the evening (6 PM) and retrieved after 24 hrs. Soil moisture and temperature conditions were also measured at the time of chamber placement. The amount of evolved CO_2 was determined using the titration method as described above in the C-min experiment. The net CO_2-C emission was calculated using the Equation 1.

III.3: Statistical Analyses

The SOC, C-min, and CO_2 emission data were subjected to ANOVA using PROC GLM in the statistical analysis software (SAS, v 9.4, The SAS Institute, Cary, NC). Prior to ANOVA, normality and homogeneity of variance of the dataset were verified. Mean separations were carried out using the Fishers' protected least significant difference (LSD) test at $\alpha = 0.05$. A double- exponential model was fit to the C-min data to define the amount and turnover rate of two carbon pools (active and intermediate) (Fernandez et al. 2007), using SigmaPlot (v 13.0, Systat Software Inc., San Jose, CA). The model took the following form:

$$Y = C_1(1 - EXP^{-k_1 t}) + C_2(EXP^{-k_2 t}) \qquad \text{(III.2)}$$

where Y is total mineralizable C (μg of $CO_2 - C\ g^{-1}$ of soil); C_1 and C_2 represent the size of active and intermediate pools decomposing at specific rates of k_1 and k_2, respectively; and t is the time (day).

A linear model was also fit to the cumulative C-min data after eliminating the initial burst of carbon observed immediately after the initiation of the incubation study, because the first two days after incubation accounted for 50% of the total mineralized carbon. Given this, the values observed at 7, 14, and 21 days were subtracted by 7 days to obtain the value of C-min per day.

$$Y = B^{*}X + Y_0 \tag{III.3}$$

where Y represents cumulative C-min (µg of CO_2 – C g^{-1} of soil) at time X; Y_0 is the overall intercept; B is the slope; and X is time (day).

III.3.1: Model Goodness-of-Fit

The goodness-of-fit for the double-exponential model (Equation 2) was tested by estimating the root mean square error (RMSE) and the Nash-Sutcliffe model efficiency coefficient (E_f). The evaluation of r^2 is an inadequate measure of model fit for non-linear models (Spiess and Neumeyer 2010). In this regard, RMSE and E_f are considered as better measures (Roman et al. 2000), and are calculated as follows (Nascimento et al. 2012):

$$RMSE = [\ \frac{1}{n} \sum_{i=1}^{n}(P_i - O_i)^2\ ] \tag{III.4}$$

$$E_f = 1 - [\ \sum_{i=1}^{n}(P_i - O_i)^2 / \sum_{i=1}^{n}(O_i - \bar{O}_i)^2] \tag{III.5}$$

where P_i is the predicted value, O_i is the observed value, and n is the total number of observations. Smaller RMSE values indicate better model fit. The Ef values range between -∞ to 1; a value closer to 1 indicates a better fit.

III.3.2: Sum of Square Reduction Test (SSRT)

The differences in cumulative C-min (µg of CO_2 –C g^{-1} of soil) levels between NT and CT were examined using the SSRT (two-curve comparison) method (Schabenberger et al. 1999). For performing this test, full (considering tillage as a factor) and reduced models (without considering tillage as a factor) were developed for cumulative C-min. Model significance was tested based on the test statistic, F_{obs}, which was calculated using the following equation:

$$\mathrm{F_{obs}} = \frac{[(SS\ Residual)_{Reduced-}(SS\ Residual)_{Full}]/[(DF\ Residual)_{Reduced-}(DF\ Resdiual)_{Full}]}{(MS\ Residual)_{Full}} \qquad \text{(III. 6)}$$

where SS is the sum of squares, DF is degrees of freedom and MS is mean square. The calculated F_{obs} value was compared with the cut-offs from an F distribution considering DF $(\mathrm{Residual})_{\mathrm{Reduced}}$-DF $(\mathrm{Residual})_{\mathrm{Full}}$ as the numerator and DF $(\mathrm{Residual})_{\mathrm{Full}}$ as the denominator DF. For cumulative CO_2-C emission data, a quadratic function was regressed using SigmaPlot (v 13.0, Systat Software Inc., San Jose, CA), as follows:

$$Y = Y_0 + A^{*}Time * B^{*}\mathrm{Time}^2 \qquad \text{(III.7)}$$

where Y represents cumulative CO_2 emission (g of CO_2-C m^{-2}) at time X; Y_0 is the overall intercept; A and B are model coefficients; and X is time (day).

III.4: Results and Discussion

The year-by-treatment interactions were non-significant ($P \geq 0.05$) for SOC, cumulative C-min, and CO_2 emission; therefore, data pertaining to both years were pooled. However, tillage-by-depth interactions were significant for SOC and C-min, thus were presented separately by each depth category. Average air temperature and rainfall data for 2016 and 2017 is presented in Table 7.

III.4.1: Soil Organic Carbon

The SOC content at the 0 to 5 cm soil depth was 43% greater in the NT system than CT (10 vs 7 g kg^{-1}) (Table 8). The difference between the CT and NT for SOC content was much greater (13 vs 11 g kg^{-1}) in this long-term study since the last observation 13-years ago (Wright and Hons 2005a). Our findings are also in agreement with Halvorson et al. (2002) wherein 12% greater SOC content was observed in the NT system compared to the CT system at 0 to 7.6 cm soil depth. However, SOC did not differ between the tillage systems beyond the 5 cm depth. Greater crop residue retention in the NT system at the 0 to 5 cm soil profile was believed to have resulted in greater SOC content at this depth, compared to the CT system. In contrary, tillage operations in CT typically incorporate crop residues in the soil, often placing them in favorable moisture conditions (Wander et al. 1998; Yang and Wander 1999), and thereby increasing the rate of decomposition of crop residues and soil organic matter (Halverson et at. 2002). Moreover, intensive tillage operations in the CT system promote the breakdown of macroaggregates, which are known to protect SOC from microbial decomposition (Six et al. 2004). High SOC is often associated with improved soil structure, high water holding capacity, and soil microbial activity.

III.4.2: Carbon Mineralization

In the long-term continuous sorghum production system, tillage impacted cumulative C-min rates (Figure 3). The double-exponential model provided a good fit to the C-min data, with the *RMSE* values ranging between 23 and 59 (Table 9). The model has indicated that total C-min (C_1) at the 0 to 5 cm depth in the NT system was 1,252 μg of CO_2-C g^{-1} of soil, whereas it was 1,069 μg of CO_2-C $g^{-1}$of soil in CT at the same depth (Figure 3a, Table 9). At the 5 to 10 cm soil depth, the NT system had 12% greater cumulative C-min, compared to the CT system (Figure 3b, Table 9). However, no differences were observed between the NT and CT systems at the 10 to 20 cm soil depth (Figure 3c, Table 9).There was 34% difference between CT and NT for mineralized carbon at 0 to 5 cm soil depth. At 5 to 15 cm depth, however, mineralized C was greater in CT than NT in this long-term study since the most recent observation 15-years ago (Dou et al. 2008). Our findings corroborate Alvarez et al. (2000) who found 80% greater C-min rates in NT compared to CT at the 0 to 5 cm soil depth.

The greater cumulative C-min observed with the NT system in this laboratory incubation study was likely due to constant soil moisture, temperature, and breaking of soil structure during incubation. In a similar laboratory incubation experiment, Balesdent et al. (2000) attributed the greater flushes of C-min in the NT system to the destruction of soil aggregates at the time of incubation, which can expose the physically protected SOC to active microbial populations. Moreover, the absence of soil disturbance in the NT system for 36 years has increased SOC storage in that system (Table 9), which also explains greater C-min rates in NT compared to CT. Thus, results of this incubation study are only indicative of high stored carbon in the NT system and not high levels of residue decomposition. In this study, a reduction in the rate of C-min was also observed with increasing soil depth, which is possibly due to high accumulation of crop residues and high SOC content in the surface layer (Table 9), compared to deeper soil profiles. Similar findings were also reported by Balota et al. (2004) and Franzluebbers et al. (1995).

The incubation study also revealed that the rate of C-min was very rapid at the beginning of the study, and declined gradually thereafter (Figure 3). This trend illustrates that SOC is comprised of active (easily mineralizable) and intermediate (slowly mineralizable) components as demonstrated by Fernandez et al. (2007). The rapid initial phase corresponds to the accumulation of labile carbon from recently deposited residues. The model indicates that the intermediate C-min component (slowly mineralizable, C_2) ranged from 68 to 73 µg of CO_2-C g^{-1} of soil in the NT system, whereas it was only 42 to 54 µg of CO_2-C $g^{-1}$of soil in the CT system (Table 9). In general, the rate of decomposition of soil organic matter also decreases with the progression of incubation time. This can be attributed to an increase in the concentrations of lignin and hemicellulose compounds during the latter phases of decomposition; these structural carbohydrates are known to be resistant to decomposition (Jha et al. 2012; Mfilinge et al. 2002).

Further, rapid C-min was noticed during the initial period of incubation therefore, data pertaining to the initial burst (day 1 and 3) were excluded from cumulative C-min. The linear model provided a good fit to the C-min data at 0 to 5 cm ($r^2 = 0.99$ for both CT and NT), 5 to 10 cm ($r^2 = 0.98$ for both CT and NT), and 10 to 20 cm soil depth ($r^2 = 0.99$ for both CT and NT) (Figure 4). However, the observed slopes did not differ between the CT and NT system ($P \geq 0.05$) in all the three depths investigated (data not shown). The initial burst in both tillage systems could be attributed to the breaking of soil structure and addition of water on the dried soil during the incubation study, which might in turn have accelerated the decomposition rate compared to later stages, as indicated by Jackson et al. (2003). The lack of differences in C min between CT and NT could be attributed to similarities in soil texture.

III.4.3: CO_2 Emission

The cumulative CO_2 -C emission observed in this study differed between the NT and CT systems (Figure 5). At 5 days after the initiation of the experiment, the cumulative CO_2 -C emission was greater in the CT system (7.28 g m^{-2}), compared to the NT system (5.19 g m^{-2}). Further, the rate of CO_2 -C emission in the CT system (1.49 g m^{-2} day^{-1}) was greater than that of the rate for the NT system (1.02 g m^{-2} day^{-1}). Greater rates of CO_2 -C emission in CT (3.70 g CO2-C m^{-2} day^{-1}) than in NT (2.82 g CO2-C m^{-2} day^{-1}) were also reported by Ussiri and Lal (2009). The lower CO_2 -C emission in the NT system in this long-term experiment could be partially attributed to the relatively slower decomposition of crop residues maintained at the soil surface in NT, in comparison to the incorporated residues in the CT. Moreover, the CT system facilitates gas emission from the soil by decreasing the partial pressure of CO_2 in the soil air by physically disturbing soil aggregation and soil pore system (Curtin et al. 2000; Rochette and Angers 1999). Furthermore, soil temperature was greater (1ºC greater) in the CT system compared to the NT system (Table 10). The rate of CO_2 emission is directly influenced by soil temperature and moisture because these two factors affect soil microbial processes, influencing the production of CO_2 as suggested by Moore and Dalva (1993). Results from this study confirm the potential of long-term NT practices and the associated accumulation of crop residue on soil surface in reducing soil CO_2 emission.

III.5: Conclusions

Results from this 36-year long experiment have clearly demonstrated that adoption of NT system with crop residue retention increases soil C storage. Though the cropping system studied here was a monoculture sorghum, the benefits of NT on soil C assimilation were obvious. This was particularly evident at the surface soil layer (0 to 5 cm depth) due to residue accumulation. The greater cumulative C-min in NT in the laboratory incubation study illustrates the high levels of C storage in this system, particularly in the surface soil layer. However, actual levels of C-min under field conditions is expected to be low in NT due to a lack of soil disturbance and minimal contact between soil and plant residues. Moreover, among the two carbon pools, the slowly mineralizable, more stable carbon (i.e. intermediate carbon) was greater in the NT system compared to CT, highlighting the greater carbon sequestration potential with long-term NT production. Results also showed that long-term NT systems reduce CO_2 emission, providing tremendous environmental benefits. Combined together, these benefits make the NT systems more sustainable in the long-run over the CT systems.

Table 7: Monthly temperature and rainfall data (mean) of the growing season (May to September) in 2016 and 2017 at College Station, TX[a].

Month	Mean temperature		Total precipitation	
	2016	2017	2016	2017
May	26	27	347	129
June	31	31	68	125
July	33	34	9	9
August	32	32	159	582
September	30	30	51	39
Annual	21	22	1188	1325

[a] Air temperature and precipitation data were obtained from Texas A&M weather station close to the experimental farm.

Table 8: Soil organic carbon (SOC) as affected by tillage and soil depth in a long-term (36 years) continuous sorghum experiment in Southeast Texas.

Soil depth (cm)	Tillage[a]	
	NT	CT
	SOC (g kg^{-1})	
0 to 5	10 (±0.03) a†	7 (±0.03) b
5 to 10	7 (±0.03) b	6 (±0.03) bc
10 to 15	6 (±0.03) bc	5 (±0.03) c
P-value	0.02	

[a] Abbreviations: CT, conventional tillage; NT, no tillage

† means followed by the same letter are not significantly different

Table 9: Parameter estimates and model goodness-of-fit (RMSE and E_f) [a] for the double four-parameter function[b] fitted to cumulative carbon-mineralization data in the 36-year long tillage experiment in Southeast Texas.

Depth (cm)	Tillage[c]	C_1 (±SE) µg of CO_2-C g^{-1} of soil	k_1 (±SE)	C_2 (±SE) µg of CO_2-C g^{-1} of soil	k_2 (±SE)	RMSE	E_f	SSRT[d]
0 to 5	NT	1179±175	0.49± 0.1	73±77	-0.11±0.0	59.61	0.86	$P \leq 0.05$
	CT	1015±204	0.36±0.1	54±74	-0.12±0.0	38.49	0.84	
5 to 10	NT	900±147	0.66±0.1	68±67	-0.12±0.0	50.88	0.85	$P \leq 0.05$
	CT	808±167	0.48±0.1	42±64	-0.13±0.0	23.86	0.85	
10 to 20	NT	710±161	0.51±0.1	71±73	-0.11±0.0	53.07	0.70	NS[a]
	CT	816±163	0.59±0.1	44±68	-0.12±0.0	29.81	0.88	

[a] Abbreviations: E_f, modelling efficiency coefficient; NS, non-significant; RMSE, root mean square error; SE, standard error of the mean; SSRT, sum of square reduction test.

[b] $Y = C_1(1 - EXP^{-k_1 t}) + C_2(EXP^{-k_2 t})$

Y is cumulative C-min (µg of CO_2 g^{-1} of soil); C_1 and C_2 represent the active and resistant pools decomposing at specific rates of k_1 and k_2; t is the time (days).

[c] NT, no tillage; CT, conventional tillage

[d] $F_{obs} = \frac{SS(Residual)_{Reduced} - SS(Residual)_{Full} / DF(Residual)_{Reduced} - DF(Residual)_{Full}}{MS(Residual)_{Full}}$, Where SS is the sum of squares, DF is degrees of freedom and MS is the mean square. The calculated F_{obs} was compared with the cut-offs from an F distribution considering DF $(Residual)_{Reduced}$-DF $(Residual)_{Full}$ as numerator and DF $(Residual)_{Full}$ as denominator DF

Table 10: Soil temperature and moisture conditions observed at the time of the CO_2 emission study.

Tillage[a]	2016		2017	
	Temperature (°C)	Moisture (%)	Temperature (°C)	Moisture (%)
CT	31	27	27	18
NT	30	32	26	26

[a] mean of three replications of the study conducted over five days

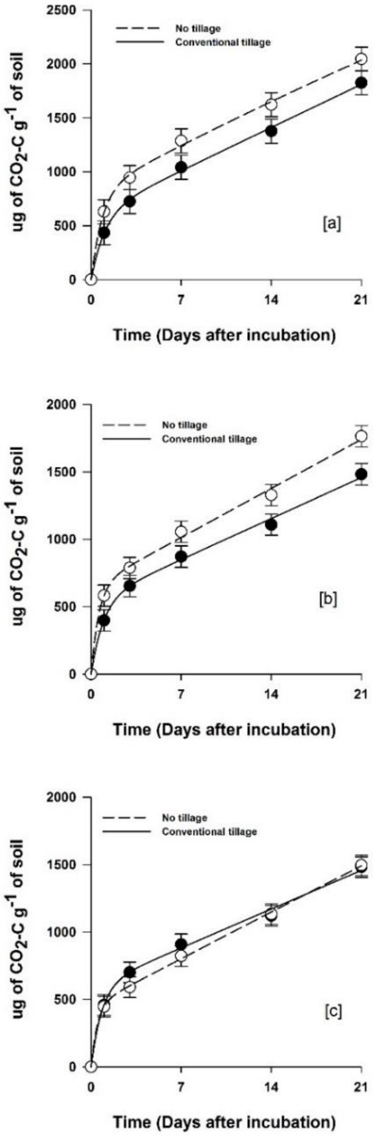

Figure 3: Carbon mineralization as influenced by tillage and soil depth (a = 0 to 5 cm, b = 5 to 15 cm, and c = 15 to 30 cm) in a 36-year long continuous grain sorghum experiment in Southeast Texas.

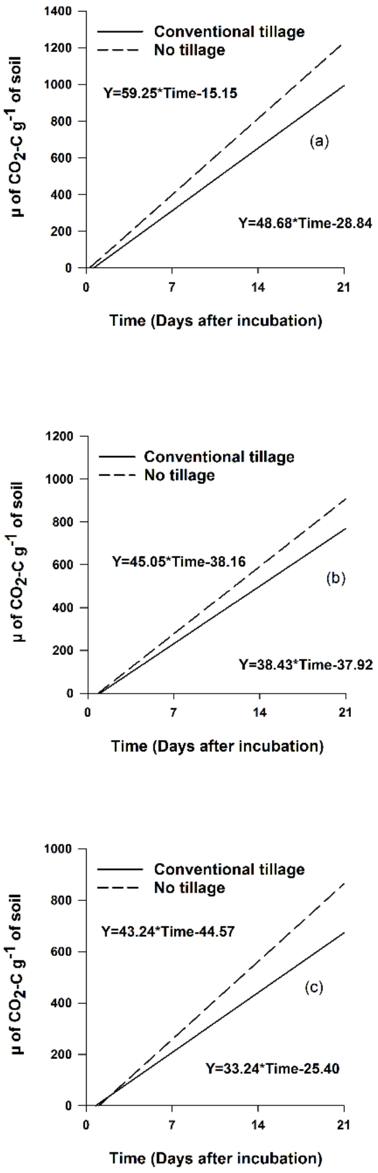

Figure 4: Carbon mineralization as influenced by tillage and soil depth (a = 0 to 5 cm, b = 5 to 15 cm, and c = 15 to 30 cm) in a 36-year long continuous grain sorghum experiment in Southeast Texas (Linear model Y=b*Time-y_0).

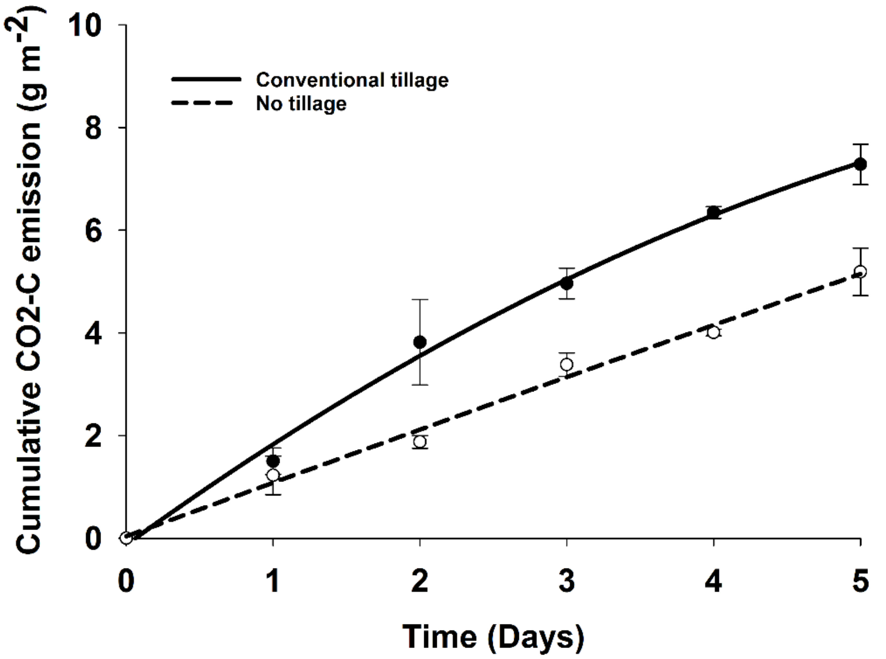

Figure 5: Impact of tillage on CO_2-C emission in a 36-year long grain sorghum experiment in Southeast Texas. The quadratic model for conventional tillage is: Y = -0.12 + 2.07*time * -0.11*time^2, r^2 = 0.99, and for no tillage is: Y = 0.03 + 1.04*time * -0.005*time^2, r^2 = 0.99.

CHAPTER IV

NO-TILLAGE ALTERED WEED SPECIES DYNAMICS IN A LONG-TERM (36-YEARS) GRAIN SORGHUM EXPERIMENT IN SOUTHEAST TEXAS

IV.1: Introduction

A shift from conventional tillage (CT) to conservation tillage [no-tillage (NT) or some form of reduced tillage] can improve the sustainability of soil ecosystems (Lal et al. 1999; West and Post 2002). Studies have demonstrated several advantages of conservation tillage practices, including timely planting of crops, reduction in soil erosion and nutrient loss, retention of soil moisture, increased stable soil aggregate formation, and improved soil organic matter status (Derpsch et al. 2010; Pimentel et al. 1995; Triplett and Dick 2008). As a result, conservation tillage practices have been promoted worldwide to improve soil and ecosystem sustainability. In the US, the area under conservation tillage has been increasing steadily at a rate of about 2.3% annually since 1972 (Dobberstein 2014). According to the most recent estimates, about 39 million ha of the US farmland is under conservation tillage practices (USDA 2012). Kansas has the highest area under conservation tillage (4.21million ha), followed by Nebraska, North Dakota, South Dakota, Iowa and Montana (USDA 2012). In Texas, adoption of conservation tillage is very limited, with only about 0.10 million ha under these practices.

A shift from conventional tillage to practices such as NT can present significant management challenges. In particular, conservation tillage practices have been shown to influence weed population dynamics (Young and Thorne 2004). Specific changes to vertical distribution of weed seeds in the soil profile, weed seedbank persistence, seedling recruitment, weed species dominance, and frequency of occurrence have been reported when shifting to conservation tillage practices (Farmer et al. 2017; Nichols et al. 2015; Gleichsner and Appleby 1989; Mohler 2001; Schafer and Chilcote 1970). The lack of soil inversion in conservation tillage systems may lead to the accumulation of weed seeds in the top soil layer, thus altering their distribution in the soil profile. For instance, Refsell and Hartzler (2009) found a higher (21 seed cm^{-3}) common waterhemp (*Amaranthus rudis* J.D. Sauer) seedbank density at the 0–3 cm soil depth in a NT system, compared to chisel ploughing (10 seed cm^{-3}).

The lack of weed seed burial in the NT system may favor small-seeded annual weeds (Moyer et al. 1994; Swanton et al. 1999) that are able to recruit from shallow depths, such as Palmer amaranth (*Amaranthus palmeri* S.Watson) (Keeley et al. 1987), in comparison to large-seeded weeds that require good seed-soil contact for germination. A study conducted in Iowa revealed a greater seedling recruitment (> 4-fold) of tall waterhemp in the NT system, compared to the CT system, due to differences in seed burial depth (Leon and Owen 2004). In South Australia, Chauhan et al. (2006) reported a greater seedling recruitment of big seeded weeds such as wild oat (*Avena fatua* L.) and rigid ryegrass (*Lolium rigidum* Gaudin) in a NT system, compared to a minimally-tilled system. The authors have also noted greater recruitment of small-seeded weeds (african mustard, *Brassica tournefortii* Gouan and annual sowthistle, *Sonchus oleraceus* L.) in the NT, compared to the minimal-tillage system. Higher seedbank densities in the top soil layer and a selection towards small-seeded annuals may subsequently lead to higher overall weed densities in NT, compared to CT. For example, Barberi and Lo Cascio (2006) reported a greater emergence (60%) of winter annual weeds in the NT system, compared to different conventional tillage practices (≤ 43%). Further, the absence of tillage can also promote greater persistence of perennial weeds in the conservation tillage systems (Taa et al. 2004;

Barberi et al. 2001; Tuesca et al. 2001) because tillage is considered an effective tool for perennial weed management (Esso and Ghersa 1993).

The impact of tillage regimes on weed population dynamics can also be influenced by the specific cropping system in question; moreover, such impacts can be better understood using long-term field studies rather than short-term investigations. At Texas A&M University, a long-term field experiment has been conducted over the past 36 years to understand the impact of NT system on soil properties and health. The specific production systems investigated include a continuous grain sorghum production, among others. However, the impact of long-term NT practice on weed population dynamics is yet to be investigated in this long-term experiment. The objective of this study was to compare the effect of long-term NT and CT practices on weed population dynamics and yield characteristics in grain sorghum, an important agronomic crop in Texas.

IV.2: Materials and Methods

IV.2.1: Study Site and Experimental Design

A long-term field experiment was initiated in 1982 along the Brazos River floodplain at the Texas A&M field Research Facility near College Station (30.46ºN, 96.43ºW). The specific field experiments presented here were carried out during the 2016 and 2017 growing seasons. The soil type of the study site was Weswood silty clay loam (thermic Udifluventic Haplustepts) with 8.0 pH, and 29% sand, 42% silt and 29% clay. Two tillage treatments (CT and NT) were arranged in a randomized complete block design with four replications (plot size: 4 m x 12 m). Each year, grain sorghum was planted in 1-m wide rows during mid- to late-March and harvested during late-July to early-August. Atrazine (Atrazine 4L, Helena chemical company, 225

Schilling Boulevard, Suite 300 Collierville, Tennessee 38017) was applied at 680.4 g ai ha^{-1} at the time of sorghum planting in both NT and CT systems to provide preemergence weed control. In the CT treatments, tillage was performed using a disk harrow (10 to 15 cm depth) after crop harvest, followed by chisel plowing (20 to 25 cm depth) prior to the winter season and beds were formed subsequently. No land preparation was required at the time of grain sorghum planting in spring. However, inter-row cultivation was carried out twice during the early crop growth period for weed control. The NT plots were never tilled. All the plots were fertilized with 135 kg ha^{-1} nitrogen as a band application prior to sorghum planting. Weather data (maximum air temperature, minimum air temperature and precipitation) were obtained from an automatic weather station installed near the research site.

IV.2.2: Weed Seedbank Dynamics and Seedling Emergence

To estimate weed seedbank size and vertical distribution pattern, soil core samples (2.5 cm dia) were collected from each plot up to a depth of 70 cm, using a motorized soil auger [AMS, Inc. Main Office,105 Harrison St. American Falls, ID] a week prior to sorghum planting. Each soil core was divided into 5 different depth categories (0 to 5, 5 to 15, 15 to 30, 30 to 50, and 50 to 70 cm). The soil samples were washed under a gentle flow of water, and the weed seeds were separated using appropriate sieves. The seeds were then counted under a microscope [AM Scope, Irvine, CA], and placed into Petri dishes to determine the germination potential, followed by a viability test (1% tetrazolium chloride test, as shown by Patil and Dadlani 2009) conducted on the non-germinated seeds.

To determine weed seedling emergence patterns, four permanent quadrats per replication (0.5 m × 0.5 m) were randomly placed within each plot between two grain sorghum rows. Weed seedling emergence was recorded at weekly intervals starting at crop planting through the end of

June. At each observation, the newly emerged weed seedlings were identified, counted and removed from each quadrat. The quadrats were covered during herbicide applications to prevent any impact on weed seedling emergence. To estimate total weed densities, four additional quadrats (0.5 m x 0.5 m) were randomly placed in each plot prior to sorghum harvest.

IV.3: Statistical analyses

Data were subjected to ANOVA using the GLIMMIX procedure in SAS (SAS Institute Inc, Cary, NC) and means were separated using the least squares means (LSMEANS) method at $\alpha = 0.05$. Tillage system and year were considered as fixed effects in the model, whereas the blocks (nested within years) were considered as random effects. The year was considered as a fixed effect in the initial model analysis to determine potential treatment*year interactions. Prior to performing ANOVA, normality of the residuals was tested using the Shapiro-Wilk, with PROC UNIVARIATE in SAS.

IV.3.1: Weed Diversity Indices

Different diversity indices were calculated on the data obtained from above ground as well as below-ground weed densities. Species richness was calculated by counting the number of weed species present in a treatment (Clements et al. 1994). Weed diversity, dominance, and evenness values were determined using the Shannon-Wiener index, Simpson’s index, and Pielou’s measure (Equations 1 to 3), respectively. Further, similarity values were estimated using the Jaccard index (Equation 4).

Shannon-Wiener index (Krebs 1985):

$$H = -\sum p_i \ln p_i \tag{IV.1}$$

where H is the species diversity, and p_i is the proportion of individuals in the total sample belonging to the i^{th} species.

Simpson index (Southwood 1978):

$$D = \sum \frac{(n_i(n_i-1)}{(N(N-1))} \tag{IV.2}$$

where n_i is the number of individuals of i^{th} species, and N is the total number of individuals.

Pielou's measure of evenness (Pielou 1966):

$$E = H/\ln S \tag{IV.3}$$

where H is species diversity (from Shannon-Wiener index) and S is the number of species present.

Jaccard measure (Janson and Vegelius 1981; Southwood 1978):

$$C_j = j/(a + b - j) \tag{IV.4}$$

Where j is the number of species common in both the tillage systems, a is the total number of individuals in CT and b is the total number of individuals in NT.

IV.3.2: Seedling emergence data

Seedling emergence data for each of the dominant weed species were converted into cumulative emergence (%) across the entire period of emergence. The cumulative seedling emergence data were regressed over the accumulated growing degree days (GDD) (Equation 5) using a three-parameter sigmoidal function (Equation 6). The GDD is a time-based integral of heat accumulation (C) measured daily, and calculated using the following equation (Gilmore and Rogers 1958):

$$GDD = \left(\frac{T_{max} + T_{min}}{2}\right) - T_b \tag{IV.5}$$

where T_{max} is the maximum air temperature, T_{min} is the minimum air temperature, and T_b is the base temperature for each weed. The base temperature of 8.5 C for johnsongrass (Arnold et al. 1990), 10 C for tall waterhemp (Leon and Owen 2004), and 15 C for prostrate spurge [*Chamaesyce humistrata* (Engelm.) ex A. Gray] (Asgarpour et al. 2015) were selected for calculating respective GDD values.

The three-parameter sigmoidal growth function (Equation 6) was fit using SigmaPlot (V 14.0, Systat Software Inc., San Jose, CA), which took the following form:

$$[Y = A/(1 + exp - [(X - X_0)/B] \qquad \text{(IV.6)}$$

where Y is cumulative seedling emergence (%) at a given value of X (GDD), A is the upper asymptote (theoretical maximum for Y, normalized to 100%), X_0 is the GDD required for 50% seedling emergence, and B is the slope of the sigmoidal function at X_0.

IV.3.3: Model Goodness-of-Fit

The goodness-of-fit for the sigmoidal function was tested by estimating the root mean square error (RMSE) (Equation 7) and the Nash-Sutcliffe model efficiency coefficient (E_f) (Equation 8), respectively. The evaluation of R^2 is an inadequate measure of goodness-of-fit for nonlinear models (Spiess and Neumeyer 2010), but RMSE and E_f could be better suited for such functions (e.g. Sarangi et al. 2016). RMSE and Ef were calculated as follows (Mayer and Butler 1993; Roman et al. 2000):

$$RMSE = [\, \frac{1}{n} \sum_{i=1}^{n} (P_i - O_i)^2 \,] \qquad \text{(IV.7)}$$

$$E_f = 1 - [\, \sum_{i=1}^{n} (P_i - O_i)^2 / \sum_{i=1}^{n} (O_i - \bar{O}_i)^2] \qquad \text{(IV.8)}$$

where P_i is the predicted value, O_i is the observed value, and n is the total number of observations. Smaller RMSE values indicate high degrees of model fit. The Ef values range between $-\infty$ to 1, and a value closer to 1 indicates a better model fit.

IV.3.4: Sum of Square Reduction Test (SSRT)

The differences in cumulative weed seedling emergence (%) between NT and CT were examined through a SSRT (two-curve comparison) as shown by Schabenberger et al. (1999) for herbicide dose-response data, and used in Bagavathiannan et al. (2012) to compare weed fecundity data. For performing this test, full (considering tillage as a factor) and reduced models (without considering tillage as a factor) were developed. Model significance was tested based on the test statistic, F_{obs}, calculated using the Equation 9:

$$\mathrm{F}_{obs} = \frac{[(SS\ Residual)_{Reduced} - (SS\ Residual)_{Full}]/[(DF\ Residual)_{Reduced} - (DF\ Resdiual)_{Full}]}{(MS\ Residual)_{Full}} \qquad [\mathrm{IV.9}]$$

where SS is the sum of squares, DF is the total degrees of freedom and MS is the mean squares. The calculated F_{obs} was compared with the cut-offs from an F distribution, considering DF $(\mathrm{Residual})_{\mathrm{Reduced}}$-DF $(\mathrm{Residual})_{\mathrm{Full}}$ as the numerator and DF $(\mathrm{Residual})_{\mathrm{Full}}$ as denominator DF.

IV.4: Results and Discussion

To our knowledge, this is the first report comparing weed population dynamics between CT and NT systems in a long-term experiment running for over 35 years. The tillage-by-year interaction was non-significant ($P \geq 0.05$) for weed density, weed indices and cumulative seedling emergence; therefore, data from 2016 and 2017 were combined. The monthly maximum and minimum air temperatures were similar during the 2016 and 2017 growing seasons (May to September) (Figure 6). However, mean summer rainfall was greater in 2017 (884 mm) compared to that of 2016 (659 mm).

IV.4.1: Seedbank Distribution

The vertical distribution of viable weed seeds in the soil varied between the two tillage systems (Figure 7; Tables 11 and 12), and in general, the NT system had greater seedbank densities in the top soil layer compared to CT. In the NT system, 27% greater number of total weed seeds were located in the top 5 cm soil profile, compared to CT (Figure 7). This corroborates Clements et al. (1996) who found that 74% of the total weed seeds were present in the top 0–5 cm soil profile in the NT system, whereas only 37% of the seeds were extracted from this depth in the CT system. Total seedbankat the 5 to 15 cm profile in the NT system was still about 80% greater compared to CT (Figure 7b), which could be attributed to potential movement of weed seeds through soil cracking and conduits created by decomposed roots as reported by Hoffman et al. (1998) and Thompson et al. (1993). Data collected using a mini-rhizotron also showed that total root length and area were greater in the NT system compared to CT. In the CT system, 54% of the total weed seeds were distributed within the 5 to 50 cm soil profile (Figure 7a). This depth corresponds to the depth of tillage operations, which explains more uniform distribution of weed seeds throughout this profile. At the farthest depth (50 to 70 cm), only 1 to 2% of the total viable seed were extracted in both tillage systems. With respect to the proportion of viable seeds (out of the total weed seeds extracted), greater proportion (58% greater) of viable seeds were observed in NT, compared to CT at the 0 to 5 cm depth. This is probably due to the minimal seed burial associated with the NT system. Seed viability levels generally declined in both the tillage systems at increasing depths (Table 12). Reduction in seed viability with depth could be attributed to suicidal seed death wherein any germinated seedling could not reach the soil surface and emerge successfully (Conn et al. 2006; Darlington and Steinbauer 1961). High proportion of viable seeds in NT at farther depths could be attributed to seed movement through soil cracking and root channels created by plants (Benvenuti 2007; Chambers and MacMahon 1994).

IV.4.2: Seedling Emergence Pattern

The emergence pattern of johnsongrass and tall waterhemp varied between the CT and NT systems, however that of prostrate spurge was comparable between the two systems (Figure 8; Table 13). Model-predicted GDD values to obtain 50% emergence (X_0) of johnsongrass were 59 and 68 for CT and NT, respectively, whereas for tall waterhemp, it was 63 and 75, respectively. Thus, there was a general delay with the speed of emergence for certain weeds in the NT system. Our findings corroborate Refsell and Hartzler (2009) wherein 50% common waterhemp seedling emergence was achieved at 10 d after planting in CT, whereas it took 35 d in NT. Furthermore, considerable level of johnsongrass and tall waterhemp emergence occurred even during the late season in NT (Figure 8). The higher X_0 values in the NT system can be explained by relatively cooler soil temperatures, particularly during the early season. High residue accumulation reflects the solar radiation and alters the albedo of soil surface in the NT system, leading to a reduction in surface soil temperature (Cox et al. 1990; Fabrizzi et al. 2005). The *RMSE* values for the regression models describing cumulative seedling emergence of johnsongrass, prostrate spurge, and tall waterhemp were generally low (ranged between 5 and 29) (Table 13), indicating a good model fit (Roman et al. (2000). Further, the E_f values for johnsongrass, prostrate spurge, and tall waterhemp cumulative emergence curves were 0.9 (Table 13), also indicating a robust model fit.

IV.4.3: Weed Species Composition

A total of 12 summer and 6 winter weed species were recorded above ground in the 36-yr long NT grain sorghum plots; however, out of these 18 species, 8 were not present in the CT system (Table 14). These include sowthistle (*Sonchus oleraceus* L.), bull thistle (*Cirsium vulgare* (Savi) Ten), common sunflower (*Helianthus annuus* L), crane’s-bill (*Geranium columbinum* L.), cutleaf-evening-primrose (*Oenothera laciniata* Hill), ivyleaf morningglory (*Ipomoea hederacea* Jacq), pitted morningglory (*Ipomoea lacunosa* L.), and sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby]. Johnsongrass was the only perennial weed species observed in this study. Among the 12 weed species observed, johnsongrass, prostrate spurge, common sunflower, and tall waterhemp were the dominant weed species present in both tillage systems.

IV.4.4: Weed Density

IV.4.4.1: Perennial weed

Johnsongrass was the only perennial weed found in the experimental site, which occurred in both the tillage systems; however, average johnsongrass densities were higher (28 plants m^{-2}) in the NT system compared to the CT system (11 plants m^{-2}) (Table 15; Figure 9). Higher densities of johnsongrass in the NT system can be attributed to the lack of tillage and increased availability of soil moisture. Tillage can be an effective strategy for controlling johnsongrass by exposing rhizomes to sunlight and dehydration (McWhorter and Hartwing 1965). Conversely, an absence of tillage can allow the proliferation of perennial structures. Studies have reported higher densities of vegetatively propagated (through rhizomes, bulbs, tubers, runners, etc.) perennial weeds in NT compared to CT, and attributed it to the absence of tillage (Barberi et al. 2001; Hume et al. 1991).

IV.4.4.2: Annual weeds

Prostrate spurge and tall waterhemp were the most commonly found summer annual weeds at the study site, whereas henbit was the predominant winter annual weed species. Higher densities of henbit, prostrate spurge and tall waterhemp (117, 4, and 19 plants m^{-2}, respectively) were observed in the NT system compared to the CT system (45, 2, and 5 plants m^{-2}, respectively) (Table 15). Prostrate spurge, tall waterhemp, and henbit all produce numerous, but small seeds that typically remain on the soil surface in the NT system (Table 16). Because of small seed sizes, they have a better ability to germinate and establish from shallow depths without the need for soil disturbance to provide seed-soil contact. Buhler et al. (1996) and Steckel et al. (2007) have reported that small-seeded annual weeds such as common waterhemp and redroot pigweed (*Amaranthus retroflexus* L.) can be predominant in the NT system. Likewise, Hill et al. (2014) found high densities (10 to 65 plants m^{-2}) of henbit in the NT system due to their ability to germinate readily from the soil surface, supporting the findings from our research.

IV.4.5: Weed Diversity Indices

In both germinable seedbank (GSB) (above-ground weed densities) and extractable seedbank (ESB) (below-ground seedbank densities) evaluations, the Shannon-Wiener index (*H*) and the species richness (*S*) values were relatively greater in the NT system compared to the CT system (Table 17), showing that tillage had an impact on weed diversity and composition in the 36-yr long grain sorghum experiment. The *H* values for CT and NT systems, respectively, were 0.6 and 0.8 for GSB, and 0.2 and 0.4 for ESB (Table 17). Our findings corroborate Legere et al. (2011) who reported the *H* values of 1.8 and 2.1 in CT and NT systems, respectively, in a 18-year rye experiment in Canada. Further, the larger *S* values of 6.2 and 4.0 for GSB and ESB, respectively in NT (vs. 4.2 and 3.0 in CT) in the current study indicate the generally greater weed densities in the NT system.

Both GSB and ESB evaluations have revealed that there were no differences in weed species dominance (Simpson index, *D*) between the NT and CT systems; however, the measure of evenness (Pielou's measure, *E*) differed for ESB, with a greater *E* value (0.3) in CT compared to NT (0.2). The generally lower *E* values ($\leq$ 0.4) in both the systems suggested the dominance of a few weed species at the experimental site due to long-term adoption of monoculture. Additionally, the Jaccard measurement (*Cj*) showed that 77% of weed species were common between both the tillage systems in GSB test, whereas, 82% of species were common in ESB evaluations (data not shown).

IV.4.6: Sorghum Yield

The impact of tillage systems on grain sorghum yield was weather- and weed density-dependent. In 2016, higher grain yield was obtained with CT (7,210 kg ha^{-1}) than with NT (2,090 kg ha^{-1}) (Table 18). Crop establishment was poor in NT in 2016 due to harder soil surface and higher densities of weeds, whereas better crop establishment and lower weed densities were observed in CT. In a modeling study performed in Texas, Ribera et al. (2004) reported greater grain sorghum yields in a CT system (4,600 kg ha^{-1}) compared to NT system (3,940 kg ha^{-1}). In 2017, however, the sorghum grain yields were comparable between the two systems (Table 5). Sufficient rainfall (6.8 mm) the day after planting sorghum resulted in a better crop establishment and grain yield in the NT system in 2017, compared to 2016.

IV.5: Conclusions

Findings from this 36-year long experiment have clearly demonstrated that tillage had an impact on weed population dynamics, with the NT system comprising of greater weed densities and diversity compared to the CT system. In particular, the NT system was predominated with small-seeded broadleaf weeds and perennials, compared to the CT system. The long-term tillage regimes have also influenced the distribution of weed seeds in the soil. Moreover, viable weed seeds were extracted beyond 30 cm soil depth in the NT system even after 36 years of NT, which could be attributed to prolonged viability of certain weed species as well as possible movement of weed seeds through soil cracks. Changes to weed seedling emergence periodicity mean that growers must adjust their weed management practices accordingly. The late-emerging cohorts are less likely to receive any POST application and such escapes can add substantial amount of seeds to the soil seedbank. Coupled with the lack of tillage, weed control thus becomes an increased challenge in NT systems, warranting the development and implementation of robust weed management programs.

Table 11: Total seeds as influenced by tillage and soil depth in a 36-year long grain sorghum experiment in College Station, TX.

Tillage[a]	Depth (cm)	Total seeds	Johnsongrass	Prostrate spurge	Common sunflower	Tall waterhemp
		# seeds m^{-2} cm^{-1} profile[b]				
CT	0 to 5	9710 (46)	883 (66)	68 (80)	475 (39)	8284 (45)
	5 to 15	4312 (21)	102 (8)	0 (0)	204 (17)	4006 (22)
	15 to 30	3010 (14)	158 (12)	0 (0)	204 (17)	2648 (14)
	30 to 50	1511 (8)	68 (5)	17 (20)	288 (24)	1137 (6)
	50 to 70	2343 (11)	136 (10)	0 (0)	51(3)	2156 (12)
NT	0 to 5	13309 (49)	6722(67)	1969 (67)	2377 (63)	2241 (23)
	5 to 15	5534 (20)	1460 (15)	1154 (33)	170 (5)	2750 (27)
	15 to 30	3984 (15)	1381 (14)	362 (10)	588 (16)	1652 (16)
	30 to 50	3718 (14)	289 (3)	85 (2)	170 (5)	3174 (32)
	50 to 70	849 (2)	170 (2)	0 (0)	458 (11)	221 (2)

[a] Abbreviations: CT, conventional tillage; NT, no tillage

[b] Data were normalized for varying soil depth ranges, within each depth category

Table 12: Influence of 36-year long tillage regimes (conventional tillage or no tillage) on the viable seeds of different weed species in a grain sorghum experiment in College Station, TX.

Tillage[a]	Depth (cm)	Total viable seed	Johnsongrass	Prostrate spurge	Common sunflower	Tall waterhemp
		# seeds m^{-2} cm^{-1} profile[b]				
CT	0 to 5	3463 (68)	543 (94)	0 (0)	0 (0)	1901 (54)
	5 to 15	340 (7)	0 (0)	0 (0)	34 (46)	543 (16)
	15 to 30	1109 (22)	0 (0)	0 (0)	23 (31)	770 (22)
	30 to 50	68 (1)	34 (6)	0 (0)	17 (23)	204 (6)
	50 to 70	102 (2)	0 (0)	0 (0)	0 (0)	85(2)
NT	0 to 5	8284 (63)	5975 (74)	475 (37)	815 (92)	1019 (34)
	5 to 15	1732 (13)	781 (10)	475 (37)	0 (0)	475 (16)
	15 to 30	2014 (15)	1064 (13)	272 (21)	68 (8)	611 (21)
	30 to 50	1002 (8)	153 (2)	68 (5)	0 (0)	781 (26)
	50 to 70	136 (1)	51 (1)	0 (0)	0 (0)	85 (1)

[a] Abbreviations: CT, conventional tillage; NT, no tillage

[b] Data were normalized for varying soil depth ranges, within each depth category

Table 13: Parameter estimates and measures of goodness-of-fit (RMSE and E_f)[a] for the three-parameter sigmoidal function[b] fitted to cumulative weed seedling emergence as influenced by different tillage regimes in a 36-year long grain sorghum experiment in College Station, TX.

Weed species	Tillage regime	X0 (±SE)	B (±SE)	RMSE	E_f	SSRT[c]
		— GDD[a] —				
Johnsongrass	CT	59±2	-20±1	5	0.9	$P \leq 0.05$
	NT	68±2	-22± 2	7	0.9	
Prostrate spurge	CT	87± 2	-17±2	13	0.9	NS[a]
	NT	85±2	-19±2	21	0.9	
Tall waterhemp	CT	63± 3	-15±3	29	0.9	$P \leq 0.05$
	NT	75±7	-30±7	6	0.9	

[a] Abbreviations: E_f, modelling efficiency coefficient; GDD, growing degree days (C); NS, non-significant; RMSE, root mean square error; SE, standard error of the mean; SSRT, sum of square reduction test

[b] Y = A/ (1+exp – [(X-X0)/B)], where, *Y* is cumulative seedling emergence (%); A is the upper limit (theoretical maximum for Y normalized to 100%); X0 is the GDD required to reach 50% of the final seedling emergence; and B is the slope of the sigmoidal function.

[c] $F_{obs} = \frac{\mathrm{SS(Residual)_{Reduced}} - \mathrm{SS(Residual)_{Full}} / \mathrm{DF(Residual)_{Reduced}} - \mathrm{DF(Residual)_{Full}}}{\mathrm{MS(Residual)_{Full}}}$, Where SS is the sum of squares, DF is degrees of freedom and MS is the mean square. The calculated F_{obs} was compared with the cut-offs from an *F* distribution considering DF $\mathrm{(Residual)_{Reduced}}$-DF $\mathrm{(Residual)_{Full}}$ as numerator and DF $\mathrm{(Residual)_{Full}}$ as denominator

Table 14: Effect of conventional-tillage and no-tillage on the weed species composition in a long-term grain sorghum monoculture study in College Station, TX.[a]

Weeds	Growth habit[b]	Conventional-tillage[c]	No-tillage[c]
Summer weed species			
Bull thistle [*Cirsium vulgare* (Savi) Ten.]	Annual	×	✓
Common purslane (*Portulaca oleracea* L.)	Annual	✓	✓
Common sunflower (*Helianthus annuus* L.)	Annual	×	✓
Cutleaf evening-primrose (*Oenothera laciniata* Hill)	Biennial	×	✓
Ivyleaf morningglorry (*Ipomoea hederacea* Jacq.)	Annual	×	✓
Johnsongrass [*Sorghum halepense* (L.). Pers.]	Perennial	✓	✓
Pitted morningglorry (*Ipomoea lacunose* L.)	Annual	×	✓
Prostrate spurge [*Chamaesyce humistrata* (Engelm.) ex A. Gray]	Annual	✓	✓
Sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby]	Annual	×	✓
Smellmelon (*Cucumis melo* L.)	Annual	✓	✓
Tall waterhemp [*Amaranthus tuberculatus* (Moq.) J.D.]	Annual	✓	✓
Texas millet [*Urochloa texana* (Buckley) R.Webster]	Annual	✓	✓

Table 14 continued

Weeds	Growth habit[b]	Conventional-tillage[c]	No-tillage[c]
Winter weed species			
Annual sowthistle (*Sonchus oleraceus* L.)	Annual	×	✓
Hoary bowlesia (*Bowlesia incana* L.)	Annual	×	✓
Cutleaf evening-primrose (*Oenothera laciniata* Hill)	Biennial	×	✓
Henbit (*Lamium amplexicaule* L.)	Annual	✓	✓
Italian ryegrass [*Lolium perenne ssp. Multiflorum* (Lam.) Husnot]	Annual	✓	✓
Shepherd’s-purse [*Capsella bursa-pastoris* (L.) Medik.]	Annual	✓	✓

[a] Weed species data were presented from 2016 and 2017.
[b] Growth habit found in Southeast Texas.
[c] ✓= present; × = not present.

Table 15: Impact of tillage regime (conventional-tillage, CT or no-tillage, NT) on the population densities of johnsongrass, prostrate spurge, tall waterhemp, and henbit in a 36-year long grain sorghum experiment in College Station, TX.[a]

Tillage	Johnsongrass	Prostrate spurge	Tall waterhemp	Henbit
	——— (# plants m^{-2}) ———			
CT	11 (± 1.30) b	2 (± 1.01) a	5 (± 4.59) b	45 (±9.23) b
NT	28 (± 6.44) a	4 (± 1.21) a	19 (± 4.59) a	117 (±9.23) a
P value	0.001	0.26	0.04	<0.001

[a] Data were pooled between 2016 and 2017

Table 16: Average seed length and width of major weeds extracted from the soil seedbank in a 36-year long grain sorghum experiment in College Station, TX.[a]

Weed species	Length (mm)	Width (mm)
Common sunflower (*Helianthus annuus* L.)	5.0	2.3
Cutleaf evening-primrose (*Oenothera laciniata* Hill)	1.5	1.0
Henbit (*Lamium amplexicaule* L.)	2.1	0.6
Johnsongrass [*Sorghum halepense* (L.). Pers.]	6.8	1.8
Tall waterhemp [*Amaranthus tuberculatus* (Moq.) J.D.]	1.0	0.85

[a] Measurements were made using AM Scope 40x-800x student microscope-LED

Table 17: Weed indices compared between tillage regimes (conventional-tillage, CT and no-tillage, NT) in a 36-year long grain sorghum experiment in College Station, TX.

Particulars		Index[a]			
	Tillage	*H*	*S*	*D*	*E*
Germinable seedbank[c]	CT	0.6	4.2	0.7	0.4
	NT	0.8	6.2	0.6	0.4
	P value[b]	**0.03**	**< 0.01**	0.39	0.54
Extractable seedbank	CT	0.2	3.0	0.5	0.3
	NT	0.4	4.0	0.5	0.2
	P value[b]	**< 0.01**	**0.01**	0.52	**0.02**

[a] *H*-Shannon-Wiener's diversity index; *S*- richness index, *D*- Simpson dominance index, and *E*- Pielou's measure of evenness

[b] Bolded values are significant ($P \leq = 0.05$)

c Germinable seedbank, aboveground weed species; Extractable seedbank, belowground weed species

Table 18: Sorghum grain yield as influenced by long-term tillage practices in College Station, TX.

Tillage	Sorghum Yield	
	2016	2017
	—————— kg ha^{-1} ——————	
Conventional-tillage	7,210 a	4,130 a
No-tillage	2,090 b	3,950 a
P value	0.02	0.93

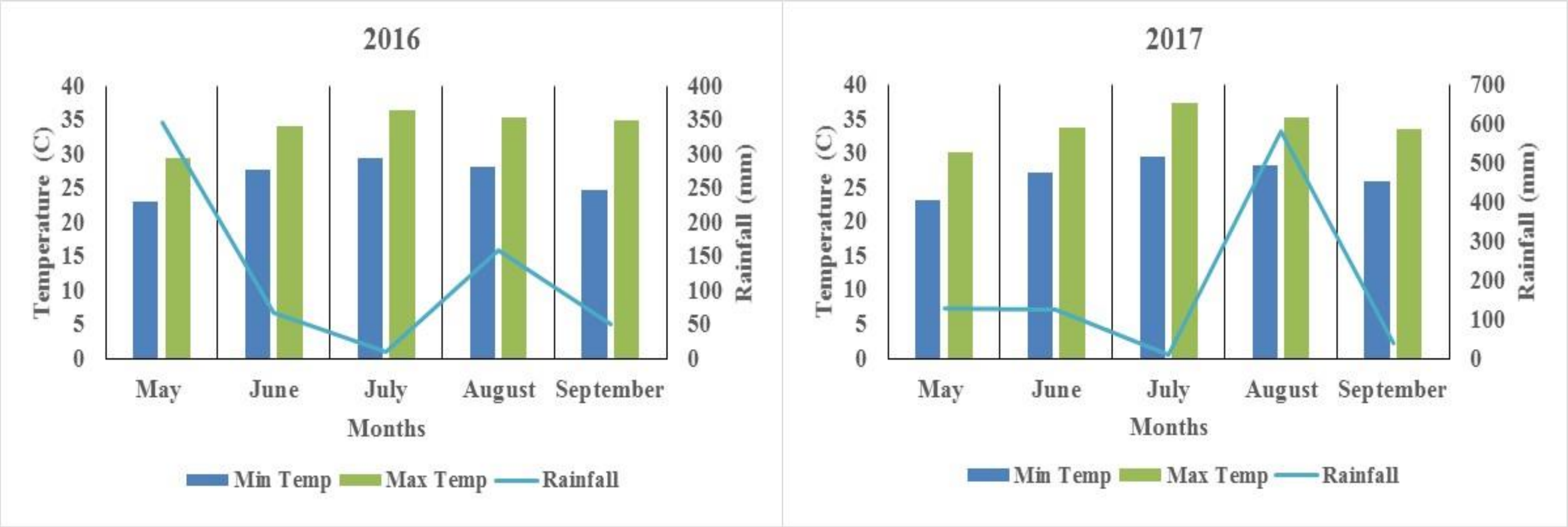

Figure 6: Monthly maximum and minimum temperatures (C) and rainfall (mm) recorded in (a) 2016 and (b) 2017 in a 36-year long grain sorghum experiment at College Station, TX.

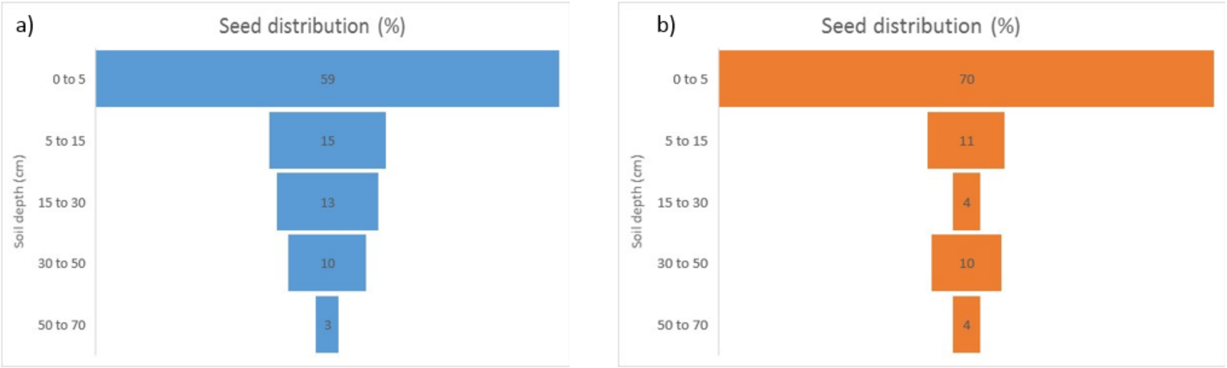

Figure 7: Vertical distribution of total weed seeds as affected by 36 years of conventional tillage (a) or no tillage (b) in a grain sorghum experiment in College Station, TX.

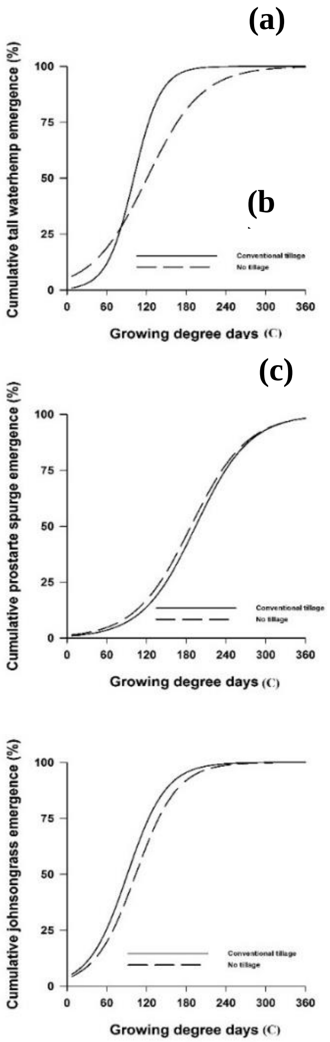

Figure 8: The impact of long-term no-tillage and conventional-tillage practices on cumulative emergence of (a) johnsongrass, (b) prostrate spurge, and (c) tall waterhemp in a 36-year long grain sorghum experiment in College Station, TX.

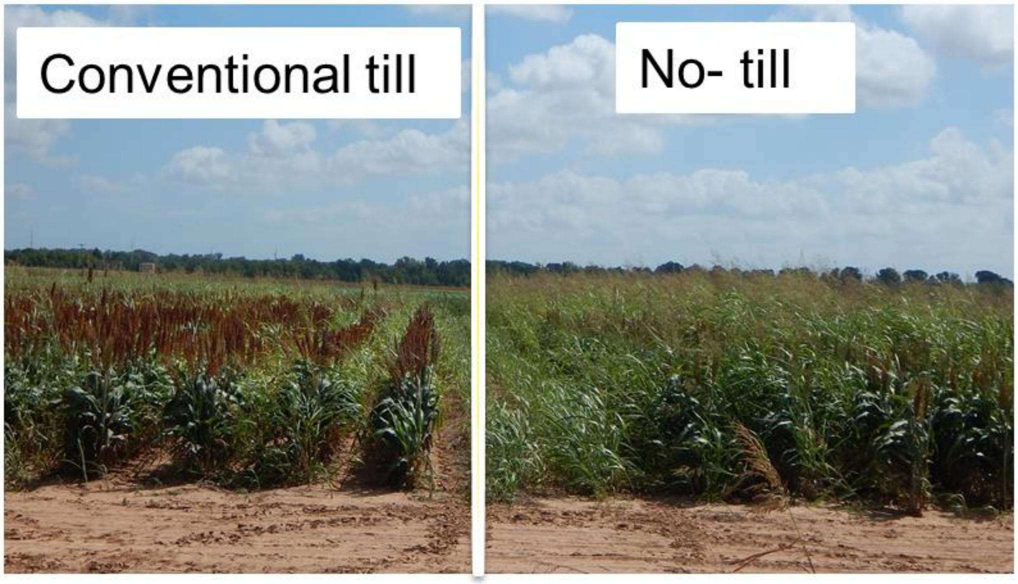

Figure 9: The impact of long-term no-tillage and conventional-tillage practices on johnsongrass density in a 36-year long grain sorghum experiment in College Station, TX.

CHAPTER V

IMPACT OF LONG-TERM (36 YEARS) TILLAGE PRACTICES ON WEED POPULATION DYNAMICS IN SOYBEAN PRODUCTION IN SOUTHEAST TEXAS

V.1: Introduction

Soybean (*Glycine max*), the major oilseed crop in the United States, is primarily grown for both protein meal and vegetable oil. In 2017, the area under soybean production was 121 million ha worldwide (FAOSTAT 2018)the United States ranked first in terms of total soybean area and production in the world, with a share of 31% of the global soybean production (USDA-FAS 2018). Abiotic and biotic factors including low soil fertility, moisture stress, insects, and weed infestations can reduce soybean yield significantly (Burnside 1979; Doss et al. 1974; Oerke 2006). Low soil fertility, which is associated with intensive tillage practices (conventional tillage, CT) and removal of crop residues from the soil surface (Keino et al. 2015; Sepat et al. 2017), often results in low soybean yield. For example, Wilhelm et al. (1986) reported that removal of residues at 1 ton ha^{-1} can reduce soybean yield by 300 kg ha^{-1}.

The introduction of soil residual herbicides in the 1960s has promoted the adoption of conservation tillage practices such as no-tillage (NT) in the United States, which has favored a reduction in soil erosion and soil organic matter depletion, and improved soil physical properties (Hobbs et al. 2008; Triplett and Dick 2008; Sarangi and Jhala 2018). Moreover, the introduction of glyphosate-resistant crops in the late 90’s has dramatically increased the area under NT production in the United States. As of 2013, the combined area under NT and reduced-tillage practices reached 36 million ha in the United States (Friedrich et al. 2005; Kassam et al. 2014).

Adoption of conservation tillage practices can alter weed population dynamics, dominance, species frequency, vertical distribution of weed seeds, and consequently may require a modification to the existing weed management practices (Cardina et al. 1991; Ball and Miller 1993; Barberi and Lo Cascio 2001; Nichols et al. 2015). Weed species shifts are likely to happen due to changes in tillage operations (Buhler 1995). In a long-term (6 yr) tillage study, Tuesca et al. (2001) reported increased densities of *Sonchus oleraceus* and *Carduus acanthoides* (wind disseminated species) in NT system compared to CT. Moreover, the ability of small-seeded annual weeds to germinate rapidly at the soil surface resulted in a greater density of these weeds in NT compared to CT (Frick and Thomas 1992; Swanton et al. 1993). For example, Steckel et al. (2007) observed that the density of common waterhemp (*Amaranthus rudis*), a small-seeded broadleaf weed, was greater (3,940 plants m^{-2}) in NT compared to chisel tillage (2,100 plants m^{-2}). Similarly, Farmer et al. (2017) reported that the density of Palmer amaranth (*Amaranthus palmeri*), another small-seeded annual weed, was 28% greater in NT system than CT system.

Deep burial of weed seeds in CT system can also influence weed seed viability and seedling emergence. For example, in a long-term (21 years) seed burial study conducted in Alaska, Conn et al. (2006) reported that seed viability of shepherd’s purse was reduced by 100% when buried at 20 cm soil depth. Jha et al. (2014) found that Palmer amaranth seeds that were buried at 10 cm soil depth lost their viability by 99.99 % after 4 years of burial in a sandy loam soil. Long-term tillage systems also influence the distribution of weed seeds in the soil seedbank. For example, Swanton et al. (2000) reported that 90% of total weed seeds were present at the 0 to 5 cm soil depth in NT system, whereas 27 and 12% of total seeds were recovered from the top-soil in chisel plow and conventional tillage, respectively. Additionally, Cardina et al. (2002) revealed that NT system had 7,000 germinable seeds m^{-2} in the top 5 cm of soil and the germination declined with increasing soil depth.

Though the literature suggests the potential for shifts in weed species composition and population dynamics in relation to NT, the magnitude of such shifts can be better investigated using long-term experiments. The objective of this study was to determine weed species dynamics in soybean in a 36 year-long tillage experiment currently ongoing at Texas A&M University.

V.2: Materials and Methods

V.2.1: Experimental Site

The long-term field experiment was initiated at Texas A&M University Research Farm (30.54ºN, 96.43ºW) at College Station, Texas in 1982. The soil at the experiment site was Weswood silty clay loam (thermic Udifluventic Haplustepts) with 1.5% organic matter, and 8.0 pH. The experimental plots were laid out in a randomized complete block design with four replications. The CT consisted of disk harrowing at 10 to 15 cm depth after crop harvest, and chisel plowing to about 25 cm depth, followed by ridging prior to winter. Soybean was planted in 1-m wide rows during the first week of June and harvested during late August. Pendimethalin (Prowl® H_20, Helena Chemical Company, 225 Schilling Boulevard, Suite 300 Collierville, Tennessee 38017) was applied pre-emergence (PRE) at 454 g a.i. ha^{-1}, the day after soybean planting.

V.2.2: Weed seedling emergence and seedbank dynamics

Four fixed quadrats per replication (0.25 m^2 each) were evenly placed along and in between two soybean rows to estimate the germinable seedbank (GSB). Weed seedling emergence was recorded at weekly intervals beginning soybean planting through harvest. At each observation, the newly emerged weed seedlings were counted and removed from each quadrat. Additionally, weed densities were estimated at soybean harvest by placing four random quadrats (0.25 m^2 each) in each plot between two soybean rows.

Soil cores (25 samples $plot^{-1}$) were collected randomly a week prior to soybean planting for estimating the extractable seedbank (ESB). The soil probe was 2.5 cm in diameter with a length of 20 cm. Soil cores were divided into depths of 0 to 5, 5 to 15, 15 to 30, 30 to 50, and 50 to 70 cm, and were washed under a gentle flow of water on a stack of 850, 425 and 90µ sieves to separate the weed seeds from the soil samples. The seeds were then identified and counted under a microscope, and placed in Petri dishes to determine the germination potential, followed by a viability test (1% tetrazolium chloride test) of the non-germinated seeds using the method described by Patil and Dadlani (2009).

V.2.3: Weed Diversity Indices

Weed diversity, dominance, and evenness values were determined by estimating the Shannon-Weiner index, Simpson’s index and Pielou’s measure, respectively. Species richness was assessed by counting the number of weed species occurring in a treatment (Clements et al. 1994). Similarity measurement was estimated using the Jaccard index. The weed diversity indices were calculated as follows:

Shannon-Weiner index (Krebs 1985) (equation 1):

$$H = -\sum p_i \ln p_i \tag{V.1}$$

where H is species diversity and p_i is the proportion of individuals in the total sample belonging to the i^{th} species.

Simpson's index (Southwood 1978) (equation 2):

$$D = \sum \frac{(n_i(n_i-1)}{(N(N-1))} \tag{V.2}$$

where n_i is the number of individuals of the i^{th} species and N is the total number of individuals.

Pielou's measure of evenness (Pielou 1966) (equation 3):

$$E = H/\ln S \tag{V.3}$$

where H is species diversity (from Shannon-Weiner index) and S is the number of species present.

Jaccard measure (Janson and Vegelius 1981; Southwood 1978) (equation 4):

$$C_J = J/(a+b-J) \tag{V.4}$$

where J is the number of species common to both the tillage systems, a is the total number of individuals in CT and b is the total number of individuals in NT.

V.3: Statistical analyses

Data were subjected to ANOVA using the GLIMMIX procedure in SAS (SAS Institute Inc, Cary, NC) and means were separated using the least squares means (LSMEANS) method at $\alpha = 0.05$. Tillage and year were considered fixed effects in the model, whereas blocks (nested within years) were considered as the random effects.

Periodic weed seedling emergence data were transformed into percent cumulative emergence and were regressed over the total accumulated growing degree days (GDD) using a four-parameter logistic function (equation 5), using the *drc* package in R (R Core Team, 2016). The logistic function took the following form:

$$Y = Y_0 + \frac{A}{1+\left(\frac{X}{X_0}\right)^{-B}} \tag{V.5}$$

where Y is cumulative seedling emergence (%); Y_0 is the lower asymptote; A is the upper asymptote; X_0 is the GDD required for 50% of the cumulative seedling emergence; and B is the slope of the logistic function at X_0. The X_0 values of NT and CT were compared using the *EDCOMP* function in the *drc* package of R.

Growing degree days (GDD), the accumulated heat unit for determining plant development, was calculated using the equation 6 (Gilmore and Rogers 1958):

$$GDD = \frac{T_{max}+T_{min}}{2} - T_b \tag{V.6}$$

where T_{max} is the maximum air temperature, T_{min} is the minimum air temperature, and T_b is the base temperature for a given weed. The base temperature of 15°C for prostrate spurge (*Chamaesyce humistrata*) (Asgarpour et al. 2015), 10°C for red sprangletop (*Dinebra panicea*) (Benvenuti et al. 2004), 20°C for smell melon (*Cucumis melo*) (Sohrabi et al. 2016), and 10°C for tall waterhemp (Leon and Owen 2004) were used for GDD calculation.

V.3.1: Model Goodness-Of-Fit

The root mean square error (RMSE) and Nash-Sutcliffe model efficiency coefficient (E_f) were estimated to test the model goodness-of-fit for the logistic function. The assessment of R^2 is an inadequate goodness-of-fit measure for the nonlinear model used in this study; therefore, RMSE and E_f were proposed to be well suited for a sigmoid function (Sarangi et al. 2016; Spiess and Neumeyer 2010). RMSE (equation 7) and Ef (equation 8) were calculated as follows (Mayer and Butler 1993; Roman et al. 2000):

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n}(P_i - O_i)^2 \right] \tag{V.7}$$

$$E_f = 1 - \left[\sum_{i=1}^{n}(P_i - O_i)^2 / \sum_{i=1}^{n}(O_i - \bar{O}_i)^2 \right] \tag{V.8}$$

where P_i is the predicted value, O_i is the observed value, and n is the total number of observations. Smaller the RMSE value, and the E*f* value closer to 1 indicate a good model fit.

V.4: Results and Discussion

The tillage-by-year interaction was non-significant for weed density, weed indices, cumulative weed seedling emergence, and seedbank distribution; therefore, data from 2016 and 2017 were combined. Monthly average air temperature and rainfall at the experimental location are presented in Table 19.

V.4.1: Weed species composition

The majority of the weed species observed in this experiment were common between the CT and NT systems (Table 20). Out of the 18 weed species observed in the GSB, two species [common purslane (*Portulaca oleracea*), and parsley-piert (*Aphanes arvensis*)] were not present in the CT system, whereas Italian ryegrass (*Lolium perenne* ssp. *Multiflorum)* was only found in the CT system (Table 20). In general, weed densities were greater in the NT system compared to the CT system, and the majority (90%) of the weeds occurred in the NT system were broadleaf species, whereas it was only 64% in CT (data not shown). Yellow nutsedge (*Cyperus esculentus*) was the only perennial weed observed in this study.

A total of 8 weed species were observed in the ESB study. Wild radish (*Raphanus raphanistrum*) was present only in the CT system, whereas cutleaf groundcherry (*Physalis angulata*) was found only in the NT system (Table 20). Common purslane seedling emergence was observed primarily in the NT system; seeds of this species were found in the soil seedbank in CT, but were rarely noticed in the above ground weed population. This is probably because of small seed size of common purslane that were not able to emerge from deeper soil depths. In a study conducted in Italy, Benvenuti et al. (2001) reported that the germination of common purslane ranged between 5.9 and 12.2% in 0 to 6 cm soil depth, whereas no germination was found beyond the 6 cm soil depth. It has been reported that deep-burial can impact weed seed viability, particularly for the ones that are small in size, due to a lack of light and oxygen supply at these depths (Benvenuti and Macchia 1995). Egley and Chandler (1983) reported that the viability of common purslane reduced from 96 to less than 1% with a change in soil depth from 8 to 38 cm after 5.5 years of seed burial. This indicates that tillage can be an effective tool to reduce the seedbank size of small-seeded weeds.

V.4.2: Weed density

Densities of cutleaf evening-primrose (*Oenothera laciniata*), henbit, and red sprangeltop did not differ between the two tillage systems (Table 21). The densities of prostrate spurge, tall waterhemp and shepherd's purse were 4 and 22 plants m^{-2}, respectively, in the NT system, whereas they were relatively lower (1 plant m^{-2}) in the CT system (Table 21). In addition, total weed density was greater in the NT system (14 and 86 plants m^{-2} for summer and winter annuals, respectively) compared to the CT system (3 and 45 plants m^{-2}, respectively). Our findings are in agreement with Refsell and Hartzler (2009) who reported that the emergence of common waterhemp was three times greater in the NT system than chisel-till. Similarly, Leon and Owen (2006) found that common waterhemp seedling emergence was four times greater in the NT system compared to chisel- or moldboard-plowing. The greater densities of prostrate spurge, tall waterhemp and shepherd's purse in NT could be attributed to the smaller seed size, that allows them to persist better in less-disturbed systems such as the NT system (Cardina et al. 2002; Steckel et al. 2007). Moreover in the NT system, the majority of common waterhemp seeds were likely placed closer to the soil surface, favoring greater germination and seedling establishment in comparison with the CT system (Yenish et al. 1992; Leon and owen 2006). Further, the greater overall weed densities with the NT system could also be explained in part by the lack of soil incorporation of the PRE-applied pendimethalin in this system. Grey et al. (2008) reported that pendimethalin works best for weed control when it is incorporated into the soil. Greater densities of small-seeded weeds in the NT system warrants proper selection of herbicide tools for effective weed management in this system.

V.4.3: Weed diversity indices

In both GSB and ESB analyses, the Shannon-Weiner index (*H*), species richness (*S*), Simpson index (*D)* and Pielou evenness index (*E*) were not influenced by tillage in soybean monoculture (Table 22). However, the similarity index [Jaccard measurement (C_J)] indicated that 38% of the weed species were common to both the tillage systems in the GSB analysis, whereas 69% of the species were common in the ESB assay (data not shown). Reports by Plaza et al. (2011) also indicated that there were no differences in weed diversity between the NT and CT systems after 23 years. These results show that weed diversity in a system is time dependent and can change over the years. Further, lower similarity index values obtained in this long-term tillage study likely results from a limited number of weed species observed in the experimental site.

V.4.4: Cumulative seedling emergence

The four-parameter logistic function (equation 5) provided a good fit to the seedling emergence data, based on the *RMSE* and E_f values (Table 23). Tillage systems did not affect ($P \geq 0.05$) the GDD required to obtain 50% of the total emergence (X_0) of prostrate spurge and tall waterhemp (Table 23). The X_0 (GDD) values ranged between 112 and 116 for prostrate spurge, and between 160 and 164 for tall waterhemp in both tillage systems (Figure 10). However, a considerable delay in X_0 was observed with red sprangletop, wherein the values were 162 and 168, respectively for NT and CT. Residue cover and a low soil temperature in the NT system compared to CT could have caused the delayed emergence of red sprangletop. In a study conducted in Philippines, Chauhan and Johnson (2008) reported that the 50% germination of Chinese sprangletop (*Lebtochloa chinesnsis*), a closely related species to red sprangletop, was delayed by 5 days at 25/15ºC compared to 30/20 and 35/25ºC day/night temperature regimes. The late-emerged red sprangletop in the NT system can escape the application of post-emergence herbicides and add considerable amount of seeds to the soil seedbank.

V.4.5: Seedbank distribution

Vertical distribution of viable weed seeds across the different depth profiles is illustrated in Figure 11. The top 5-cm soil of the NT system contained 77, 57, 80 and 66 % of henbit, prostrate spurge, red sprangletop and tall waterhemp seeds, respectively, whereas in CT, these values were lower (54, 50, 56, and 38%, for henbit, prostrate spurge, red sprangletop and tall waterhemp, respectively) at the same depth (Figure 11). However, 50 to 62 % of henbit, prostrate spurge, red sprangletop, and tall waterhemp seeds in the CT system were extracted deeper than 5 cm soil depth. Furthermore, the CT system had more even distribution of weed species compared to NT. The CT system showed a greater percentage of seed distribution across the soil depths, whereas the NT system retained most of the weed seeds closer to the soil surface (0 to 5 cm). Pareja and Staniforth (1985) found that 85% of the weed seeds were extracted from 0 to 5 cm soil depth in reduced tillage, but it was only 25% in the CT system. Similarly, Clements et al. (1996) reported that more than 70% of weed seeds were located in the top 0 to 5 cm soil depth in the NT system compared to only 37% seeds in the CT system. Farmer et al. (2017) also reported that 91% of seeds of *Amaranthus* species were located in the 0 to 5 cm depth in the NT system compared to CT (71%).

V.5: Conclusions

Results of this long-term tillage study showed that the NT system had greater weed densities, especially small-seeded broadleaved species, and that the emergence of red sprangletop was delayed. Weed diversity indices did not differ between the CT and NT systems. The majority of the weed seeds (57 to 80%) were placed near the soil surface (0 to 5 cm depth) in the NT system, whereas it was low (38 to 56%) in CT at the same soil depth. The increased density of weed seeds near the soil surface in the NT system indicates greater opportunities for the germination and establishment of these weeds. Changes to weed species diversity and population dynamics in long-term NT suggest that growers must select and implement robust weed management programs such as the inclusion of effective crop rotation and a postemergence weed control option in addition to the preemergence application at the time of crop planting.

Table 19: Monthly temperature and rainfall data (average) in 2016 and 2017 (May to September) at College Station, TX[a].

Month	Mean temperature			Total precipitation		
	2016	2017	36 yr average °C	2016	2017	36 yr average mm
May	26	27	24	347	129	123
June	31	31	28	68	125	99
July	33	34	29	9	9	53
August	32	32	30	159	582	79
September	30	30	27	51	39	86
Annual	21	22	20	1188	1325	1024

[a] Air temperature and precipitation data were obtained from HPRCC, the High Plains Regional Climate Center (2018).

Table 20: Impact of long-term conventional-tillage and no-tillage on the weed species composition in soybean in College Station, TX.[a]

Summer germinable seedbank (GSB) species	Growth habit	Conventional-tillage[b]	No-tillage[b]
Common purslane (*Portulaca oleracea* L.)	Annual	×	✓
Hophornbeam copperleaf (*Acalypha ostryifolia* Riddell)	Annual	✓	✓
Horseweed (*Conyza canadensis* L.)	Annual	✓	✓
Ivyleaf morningglorry (*Ipomoea hederacea* Jacq.)	Annual	✓	✓
Jungle rice [*Echinochloa colona* (L.) Link]	Annual	✓	✓
Palmer amaranth (*Palmer amaranth* S. Watson)	Annual	✓	✓
Prostrate spurge [*Chamaesyce humistrata* (Engelm.) ex A. Gray]	Annual	✓	✓
Red sprangletop [*Dinebra panicea* (Retz.) P.M. Peterson & N.Snow]	Annual	✓	✓
Smellmelon [*Cucumis melo (L.) var. dudaim (L.) Naud]*	Annual	✓	✓
Tall waterhemp [*Amaranthus tuberculatus* (Moq.) J.D.]	Annual	✓	✓
Texas millet [*Urochloa texana* (Buckley) R.Webster]	Annual	✓	✓
Witchgrass (*Panicum capillare* L.)	Annual	✓	✓
Yellow nutsedge (*Cyperus esculendus* L.)	Perennial	✓	✓

Table 20 continued

Winter germinable seedbank species	Growth habit	Conventional-tillage[b]	No-tillage[b]
Cutleaf evening-primrose (*Oenothera laciniata* Hill)	Biennial	✓	✓
Henbit (*Lamium amplexicaule* L.)	Annual	✓	✓
Italian ryegrass [*Lolium perenne* ssp. *Multiflorum* (Lam.) Husnot]	Annual	✓	×
Parsley-piert (Aphanes arvensis L.)	Annual	×	✓
Shepherd’s-purse [Capsella bursa-pastoris (L.) Medik.]	Annual	✓	✓
Estimated seedbank (ESB) species			
Common purslane (*Portulaca oleracea* L.)	Annual	✓	✓
Cutleaf evening-primrose (*Oenothera laciniata* Hill)	Biennial	✓	✓
Cutleaf groundcherry (*Physalis angulata* L.)	Annual	×	✓
Henbit (*Lamium amplexicaule* L.)	Annual	✓	✓
Prostrate spurge [*Chamaesyce humistrata* (Engelm.) ex A. Gray]	Annual	✓	✓
Red sprangletop [*Dinebra panicea* (Retz.) P.M. Peterson & N.Snow]	Annual	✓	✓
Tall waterhemp [*Amaranthus tuberculatus* (Moq.) J.D.]	Annual	✓	✓
Wild radish (*Raphanus raphanistrum* L.)	Annual	✓	×

[a] weed species data were presented from 2016 and 2017

[b] ✓= present; × = not present

Table 21: Effect of long-term conventional-tillage (CT) and no-tillage (NT) on weed density in soybean in College Station, TX.

Tillage	Summer					Winter		
	Cutleaf evening-primrose	Prostrate spurge	Red sprangletop	Tall waterhemp	Total weed	Henbit	Shepherd's purse	Total weed
	#plants m^{-2}							
CT	0	1	1	1	3	44	1	45
NT	3	6	2	4	14	64	22	86
P value[a]	0.17	0.05	0.46	**0.02**	**0.007**	0.15	**0.001**	**0.02**

[a] Bold values are significant at α =0.05

Table 22: Effect of long-term conventional-tillage (CT) and no-tillage (NT) on the Shannon-Weiner's diversity index (*H*), richness (*S*), Simpson dominance index (*D*), and Pielou's measure of evenness (*E*), in soybean in College Station, TX.

	Tillage	*H*	*S*	*D*	*E*
Germinable seedbank (GSB)	CT	0.9	4.0	0.4	0.6
	NT	1.1	4.0	0.3	0.6
	P value	0.48	0.73	0.34	0.64
Extractable seedbank (ESB)	CT	0.9	5.0	0.7	0.5
	NT	0.6	5.0	0.5	0.3
	P value	0.08	0.15	0.06	0.14

Table 23: Parameter estimates and the goodness of fit (RMSE and E_f) [a] of the three-parameter function[b] fitted to cumulative weed seedling emergence data in long-term conventional-tillage (CT) and no-tillage (NT) systems in College Station, TX.

Weed species	Tillage system	X_0	B	RMSE	E_f	50% Emergence
		GDD[a]				*P* value[c]
Prostrate spurge	CT	116	-6	9	0.9	0.05
	NT	112	-4	7	0.9	
Red sprangletop	CT	162	-5	7	0.9	**0.001**
	NT	168	-4	11	0.9	
Tall waterhemp	CT	164	-4	8	0.9	0.33
	NT	160	-4	9	0.9	

[a] Abbreviations: E_f, modelling efficiency coefficient; RMSE, root mean square error; SSRT, sum of square reduction test; GDD = growing degree days

[b] $Y = Y_0 + [A/ 1+(X/X_0)^{-B}]$, where, Y is the cumulative seedling emergence (%) at GDD; GDD is the growing degree days; Y_0 is the lower asymptote; A is the upper asymptote; X_0 is the GDD required to reach 50% of the final seedling emergence; and B is the slope of the logistic function at X_0.

[c] Bold values are significant at α =0.05

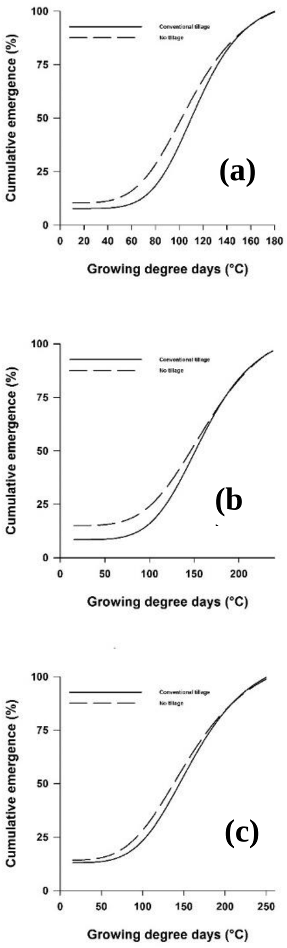

Figure 10: The impact of long-term conventional-tillage and no-tillage on cumulative emergence of (a) prostrate spurge, (b) red sprangletop, and (c) tall waterhemp in soybean production in College Station, TX.

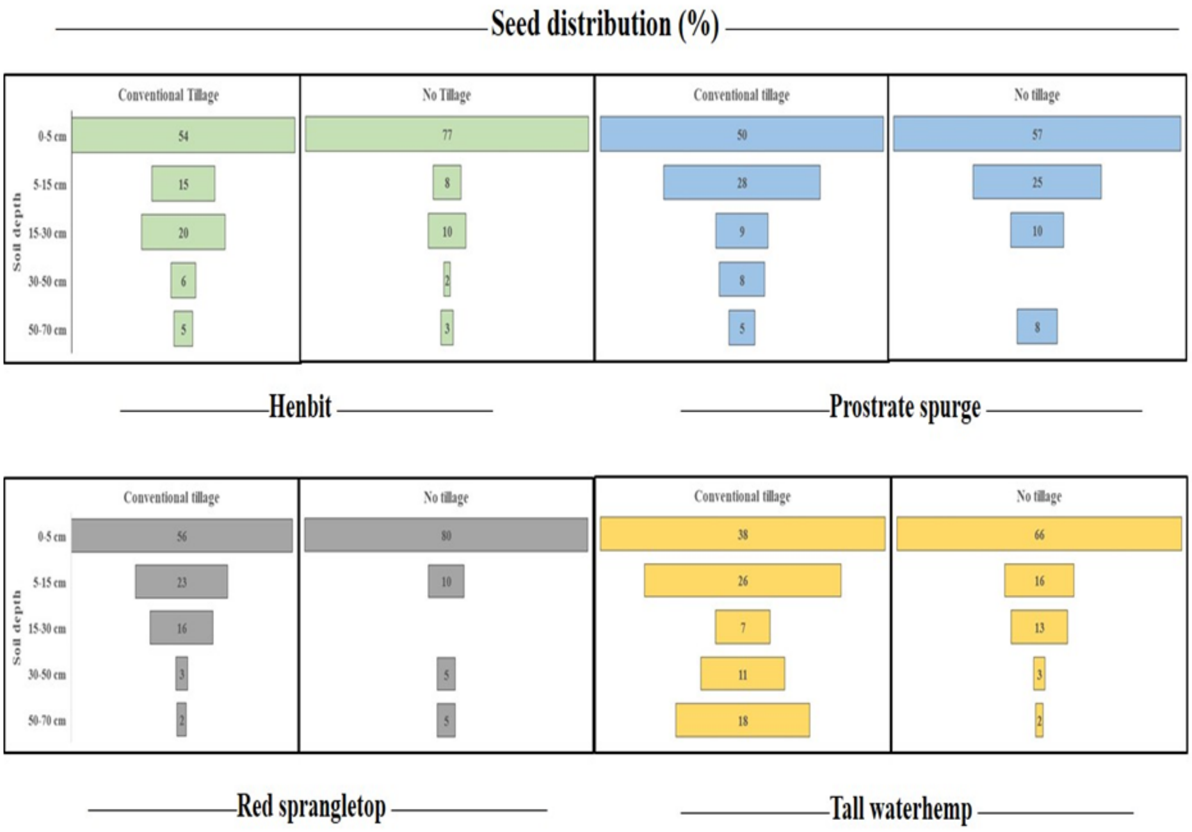

Figure 11: Vertical distribution of henbit, prostrate spurge, red sprangletop and tall waterhemp viable seeds in the soil profile as influenced by conventional tillage, and no tillage in a 36-year long tillage experiment in College Station, TX.

CHAPTER VI

A MINI-RHIZOTRON REVEALS THE EFFECT OF LONG-TERM TILLAGE PRACTICES ON ROOT GROWTH OF GRAIN SORGHUM

VI.1: Introduction

Roots are very important to plants because they support aboveground plant parts; help with water absorption and uptake of nutrients from the soil; and prevent soil erosion by providing anchorage (Reid and Goss, 1982). Knowledge of root growth and development is vital to improve crop productivity because, the ability of crops to extract and retain soil water and nutrients from deeper soil layers is influenced by factors such as root length, depth and hairiness (Kristensen and Thorup-Kristensen 2004). Kashiwagi et al. (2006) reported a positive relationship between root length density and yield at 45 to 60cm soil depth ($p<0.05$); the authors have associated the deeper root systems in those chickpea genotypes with drought tolerance. Similarly, Lampurlanes et al. (2001) reported a positive correlation between barley root length density and water use ($p<0.05$). Therefore, production systems that favor root length and depth distribution may facilitate efficient use of soil water and nutrients.

Crop root growth and yield can be influenced by changes to soil BD, MI, porosity and soil water content (Bengough et al. 2006; Lipiec and Stepniewski 1995). Alteration of these soil physical properties by tillage practices can directly affect root systems of crop plants. Lampurlanes and Cantero-Martinez (2003) reported that BD was greater (0.14 Mg m^{-3} greater) in NT (at 0 to 7 cm soil profile) compared to CT in a fine loamy soil. Similarly, Hill (1990) observed 19% greater BD at 5 to 19 cm soil profile in NT than CT. The changes to soil BD can also influence MI because they are interrelated.

Improved soil water contents (13 to 24% greater) have been widely reported with long-term adoption of NT compared to CT (Abdullah 2014; Alvarez and Steinbach 2009; Fabrizzi et al. 2005). In a study conducted in North Dakota, Merrill et al. (1996) found greater wheat root length (50 cm cm^{-2} greater) in NT system compared to CT, and associated the increase in root length to the improved soil moisture characteristics and cooler soil surface in NT. Enhanced soil water content (13 to 24% greater) has been widely reported with long-term adoption of NT compared to CT (Abdullah 2014; Alvarez and Steinbach 2009; Fabrizzi et al. 2005). High residue retention (and absence of tillage) with NT can also increase soil water content, SOC and nutrient use efficiency. Martinez et al. (2008) reported greater wheat root length density under NT than CT, and authors believed that increased SOC due to continuous addition of crop residues in NT might have created a new soil layer with stable aggregates and high water content that may in turn have favored root growth. Improvements in SOC with NT have been widely reported (e.g. Kahlon et al. 2013; Huang et al. 2015).

Root measurements are generally made using soil core methods, mini-rhizotrons and, more recently, ground penetrating radar (GPR) systems (Majdi 1996; Borden et al. 2014). The mini-rhizotrons and GPRs are non-destructive methods and allow for a more convenient measurement of root growth in comparison to soil core methods. In particular, the mini-rhizotrons have been used in the past 30 years to study root architecture and morphology (Box et al., 1989; Majdi et al., 1992; Upchurch and Ritchie, 1983). Box et al. (1989) reported that the mini-rhizotron root data can be used to predict corn yield. Further, comparison studies between mini-rhizotron, monolith sampling and soil core have also been conducted by researchers (Brag et al., 1983; Majdi et al., 1992; Samson and Sinclair, 1994).

Despite the utility of mini-rhizotrons, investigations on plant root characteristics using this tool is limited due to high cost (Smit et al., 2000). There is a need for low-cost technologies to advance root research. The objective of this study was to develop and evaluate a low-cost and user friendly mini-rhizotron with maximum precision for studying rooting depth, root length and area. This device was also used to compare rooting characteristics between NT and CT.

VI.2: Materials and Methods

VI.2.1: Low cost mini-rhizotron

Low cost mini-rhizotrons were made using acrylic tubes (15 cm diameter and 60 cm length) (Figure 1 a). The bottom and top opening were sealed with a plastic cap to avoid any entry of water. Reference lines (4 cm × 4 cm square) were made on the outer side of the acrylic tubes to serve as reference points for measurement (Figure 1 b). A 360°camera (360fly, Inc. 1000 Town Center Way, Suite 200 Canonsburg, PA 15317 United States) was used to capture the root images and an artificial light source (12v) was attached for better visibility and image clarity.

VI.2.2: Experimental site

The mini-rhizotron evaluations were conducted in a long-term field experiment initiated in 1982 at the Texas A&M University research farm near College Station (30.46ºN, 96.43ºW), Texas. The soil type was Weswood clay loam (290 g kg^{-1} sand, 420 g kg^{-1} silt, and 290 g kg^{-1} clay at 0 to 15 cm depth), with a pH of 8.0. The region’s average annual rainfall is 102 cm. This experiment had two tillage treatments (NT and CT) in a continuous grain sorghum production. The plots (4 m × 12 m) were arranged in a randomized complete block design with three replications. The CT operations consisted of disking the soil at 10 to 15 cm depth after sorghum harvest, followed by chisel plowing at 20 to 25 cm depth and bed forming prior to winter. Immediately after harvest (and prior to disking in the CT), sorghum stalks were shredded and spread on the ground in both the tillage systems. The grain sorghum crop was planted at 1-m wide rows during mid-to late-March and harvested during late July to early August. Prior to planting, nitrogen fertilizer was applied in a band to provide 135 kg N ha^{-1}. Atrazine (Atrazine 4L, Helena chemical company, 225 Schilling Boulevard, Suite 300 Collierville, Tennessee 38017) was applied preemergence at 680.4 g ai ha^{-1} at the time of sorghum planting in all plots

VI.2.3: Installation of mini-rhizotron and measurements

The mini-rhizotrons were installed in the continuous sorghum experiment during summer 2017. The experimental design was a factorial randomized complete block with three replications. The factors include two tillage treatments (NT and CT) and three soil depths (15 to 20, 30 to 35 and 40 to 45 cm). The acrylic tubes were buried at 60 cm soil depth with a 45° angle at the side of the grain sorghum row. After installation, the part of the tube that remained above ground was covered with aluminum foil sheet to avoid light. The root images were captured at 7-day intervals by inserting the 360°camera into the tubes at 3 different depths prior to the harvest of sorghum.

VI.2.4: Image analysis

The captured images were processed using the ImageJ software (V 1.51r, U. S. National Institutes of Health, Bethesda, Maryland, USA). ImageJ is an open source software for image analysis. The acquired images had background noises due to the use of artificial lighting to capture the images. These were overcome by using the manual operation in ImageJ to process the visible roots. The sorghum root length and root area in each treatment were quantified based on the reference lines previously marked on the outer surface of the tube. Root length and area was measured cm and cm^{-2}. Root area in this study means the amount of area is occupied by a root.

VI.3: Statistical analyses

All the statistical analysis were performed using SAS 9.4 [SAS Institute Inc, Cary, NC). The normality of residuals was verified (Shapiro-Wilk test) prior to conducting ANOVA; data transformation was not required. ANOVA was carried out using the GLIMMIX procedure in SAS. Tillage system and depth of measurement were considered fixed effects in the model, whereas the blocks were considered random effects. Multiple comparison of treatment means was conducted using the LSMEANS procedure ($P < 0.05$). Further, the relationship between root length and area obtained using mini-rhizotron were regressed with soil depth using a linear model (Equation 1), that took the following form:

$$Y = B^{*}X + Y_0 \qquad \text{(VI.1)}$$

where Y represents root length (cm) and area (cm^2) at soil depth X; Y_0 is the overall intercept; B is the slope; and X is soil depth (cm).

VI.4: Results and discussion

The interaction effect of tillage-by-depth was significant ($P \leq 0.05$) for root length; therefore, data from the three depths were presented separately. However, the interaction effect of tillage-by-depth was not significant ($P \leq 0.05$) for root area. Monthly average temperature (ºC) and total rainfall (mm) in 2017 is presented in Figure 13.

VI.4.1: Root length and area

Tillage had no effect on the root length of grain sorghum at 15 to 20 and 25 to 30 cm soil depth (Table 24 and Figure 14). However, the NT plots had 87% greater root lengths at 40 to 45 cm soil depth compared to CT plots. Our findings support several previous studies that reported considerable increase in root length under NT management (Holanda et al. 1998; Lampurlanes and Cantero-Martinez 2001). In a study conducted on a clay loam soil, Holanda et al. (1998) observed 21% greater corn root length in NT at 20 to 25 cm compared to CT. Similarly, Ehlers et al. (1983) reported that oat root density was 20% greater at 20 to 25 cm in NT than CT. The greater root length values in the NT plots at lower depths could be attributed to the larger space between soil aggregates, previous root channels, earthworm pores and increased soil water availability. Results suggests that the greater root density in the NT system could enhance water use efficiency and overall crop productivity, by considering all other crop production factors normal. However, root area (size) of grain sorghum was not effected by tillage practices ($P > 0.05$). It indicates that root size is a trait of grain sorghum, it may not influenced by the crop management practices such as tillage systems.

VI.4.2: Relationship between root parameters and soil depth

The relationship between root length and root area is presented in Figure 15 and 16. The linear model shows the root length were decreased with depth in the CT plots ($r^2 = 0.95$), with the lowest values (4 cm) recorded at the 40 to 45 cm soil depth (Table 24 and Figure 15). This trend had an inverse relationship with the penetrometer readings in the CT plots (data not shown). It has been revealed that there may be a negative relationship between root density and penetration resistance which is explaining the trends in root length observed in this study.

However, the trend was opposite in the NT system ($r^2 = 0.72$), with the highest values (31 cm) recorded at same depth (Table 24 and Figure 15). This trend is indicating that though the penetration resistance was increased with depth in the NT plots but the range is very smaller compared to the CT plots. Furthermore, root length data did not indicates poor soil conditions for root growth because root length was greater in NT, the tillage system also observed the greatest penetration resistance. This demonstrate that the stress required to penetrate the cone penetrometer is four to eight time that required for the roots to penetrate the soil as reported by Bengough and Mullins (1991) and Cantero-Martinez and Lampurlanes (2003). The differences in the rooting pattern of grain sorghum between NT and CT are consistent with improved soil structure, soil water and nutrient content in NT. Better root systems increase water and nutrient uptake of plants and thereby improve crop productivity. A similar trend also was observed with root area (Figure 16).

VI.5: Conclusions

The low-cost mini-rhizotron developed in this research was effective in capturing root architecture, particularly root length and area even from deeper soil profiles. Further, the cost of making the mini-rhizotron was 98% lower than purchasing the commercially available mini-rhizotron (data not shown). Two notable limitations are that only visible roots can be quantified and the image resolution is somewhat nominal. Majdi et al. (1992) indicated that mini-rhizotron underestimated corn roots compared to the soil core method. Nevertheless, the low cost mini-rhizotrons developed in this study can still provide a cost-effective and convenient means to study crop root characteristics. Research is required to compare the mini-rhizotron with soil core method to determine its accuracy. Results obtained using the mini-rhizotron have clearly demonstrated that adoption of NT systems with crop residue retention increases crop root length. This was particularly evident at the deeper soil layer (40 to 45 cm depth) due to increased soil water content and a void created by the dead roots. The greater root length under NT illustrates the high levels of soil suitability to crop root growth in this system, particularly in the 20 to 25 and 40 to 45 cm soil profiles. These findings further highlight the benefits of implementing long-term NT practices.

Table 24. Root length and area of grain sorghum as influenced by tillage and soil depth in a long-term (36 years) continuous sorghum experiment in Southeast Texas.

Tillage	Soil depth (cm)	Root length (cm)	Root area (cm^2)
CT	15-20	21 (±5.46) ab	2.50 (±0.40) abc
	25-30	14 (±3.31) b	2.06 (±0.84) bc
	40-45	4 (±2.36) c	0.50 (±0.25) c
NT	15-20	20 (6.18) b	3.53 (0.60) ba
	25-30	21 (5.39) ab	3.96 (1.04) ba
	40-45	31 (6.71) a	4.70 (1.13) a
p-value		0.003	0.15

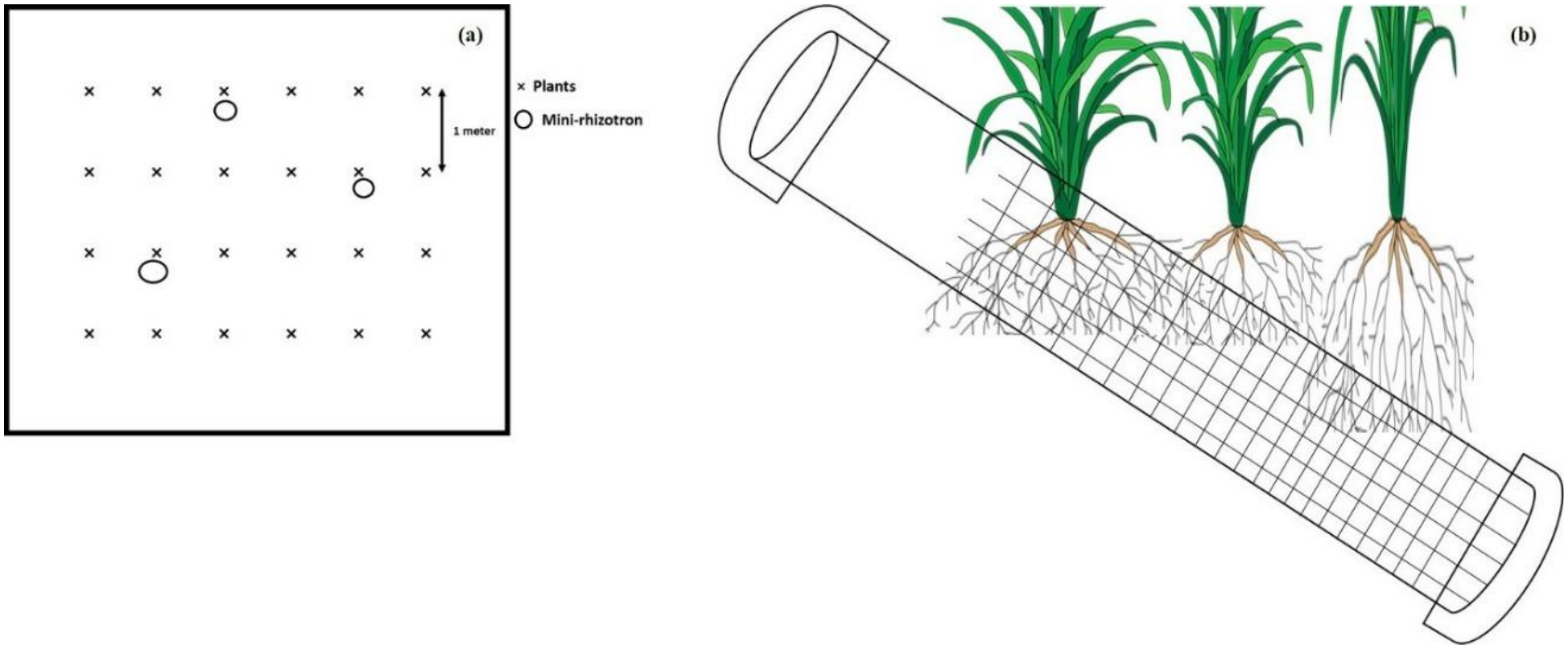

Figure 12. Field layout of (a) buried tubes and (b) the orientation of mini-rhizotron in a long-term sorghum experiment in Southeast Texas.

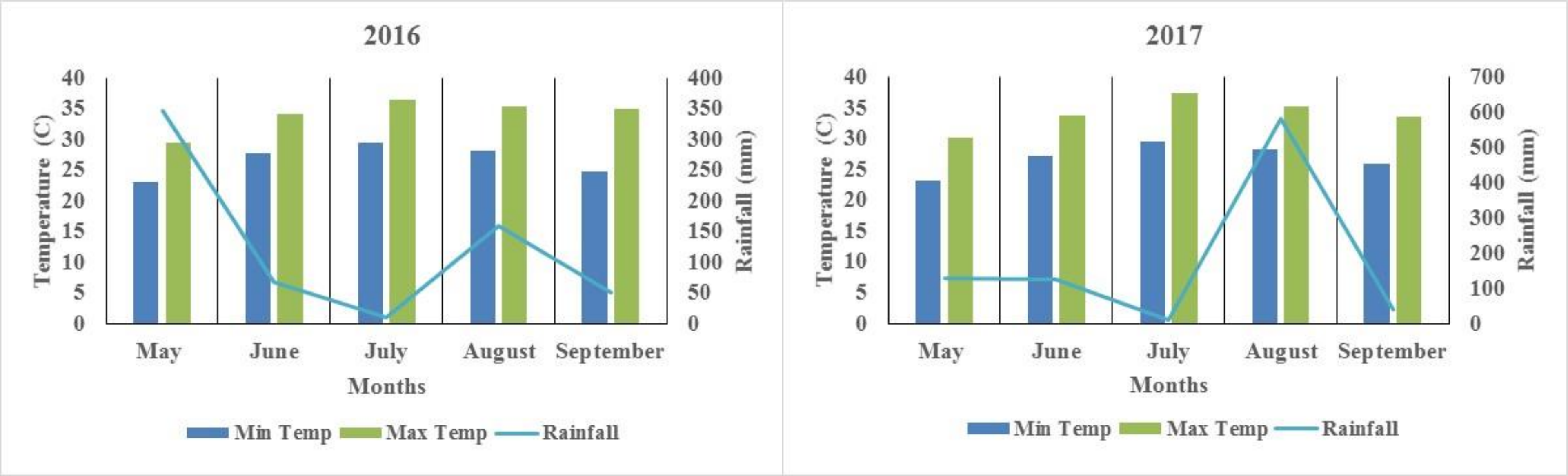

Figure 13. Mean monthly maximum and minimum temperatures (C) and rainfall (mm) recorded in (a) 2016 and (b) 2017 in a 36-year long grain sorghum experiment.

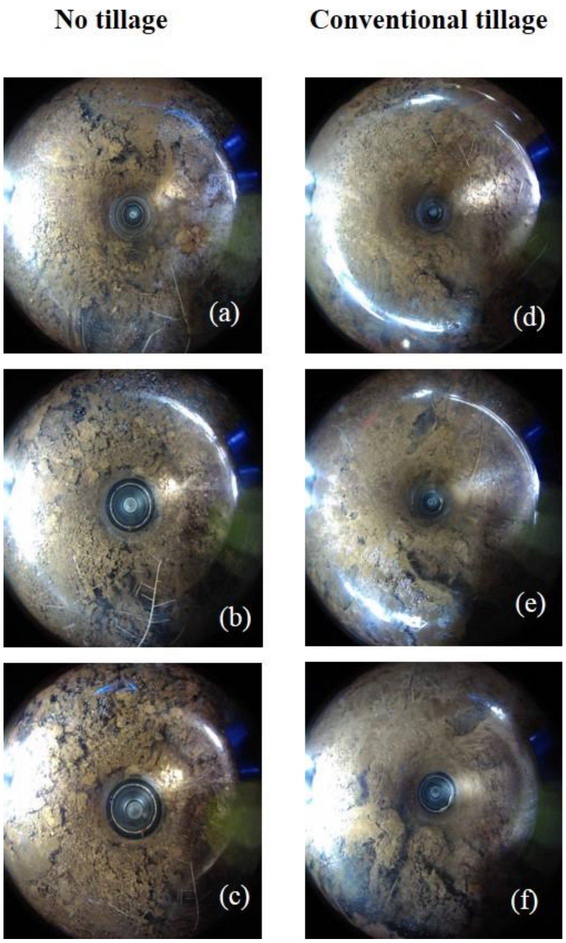

Figure 14. Root density observed using a mini-rhizotron at different soil depths in no-tillage: (a) 15 to 20 cm, (b) 25-30 cm (c) 40-45 cm; and conventional tillage (d) 15 to 20 cm, (e), 25-30 cm and (f) 40-45 cm in a long-term sorghum experiment in Southeast Texas.

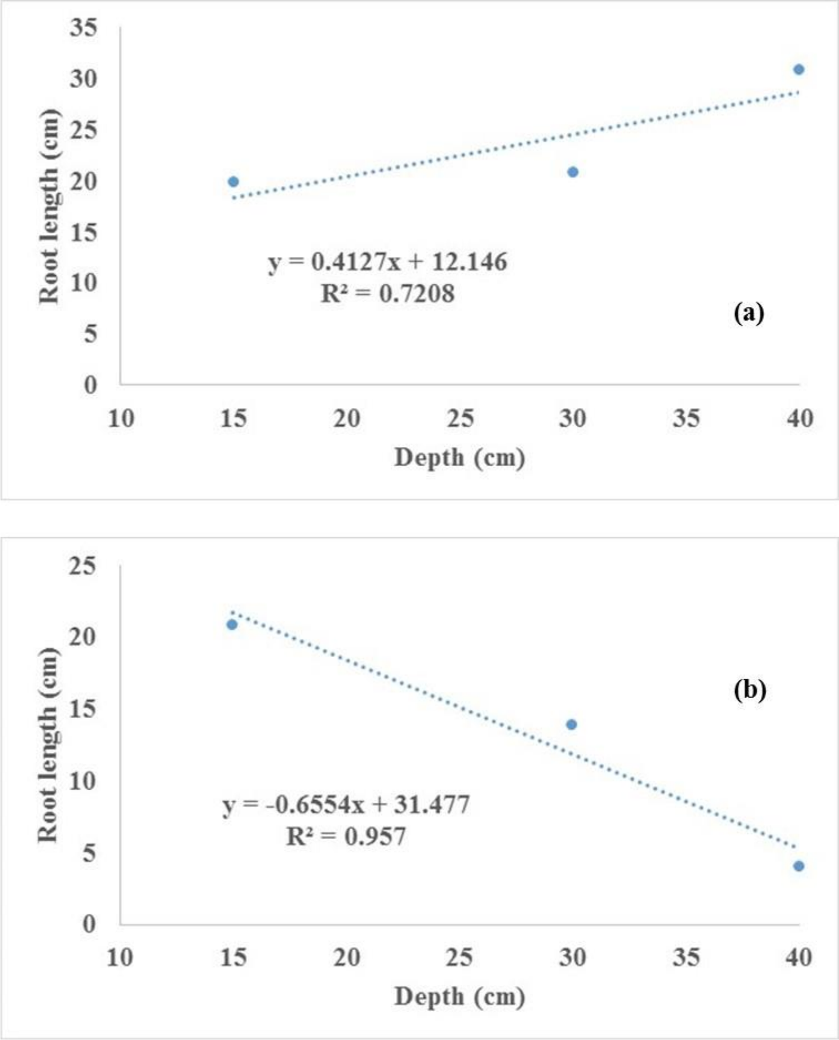

Figure 15. A relationship between root length and soil depth (15 to 20, 25-30 and 40-45 cm soil depth) in no-tillage (a) and conventional tillage (b) as influence by tillage in a long-term sorghum experiment in Southeast Texas.

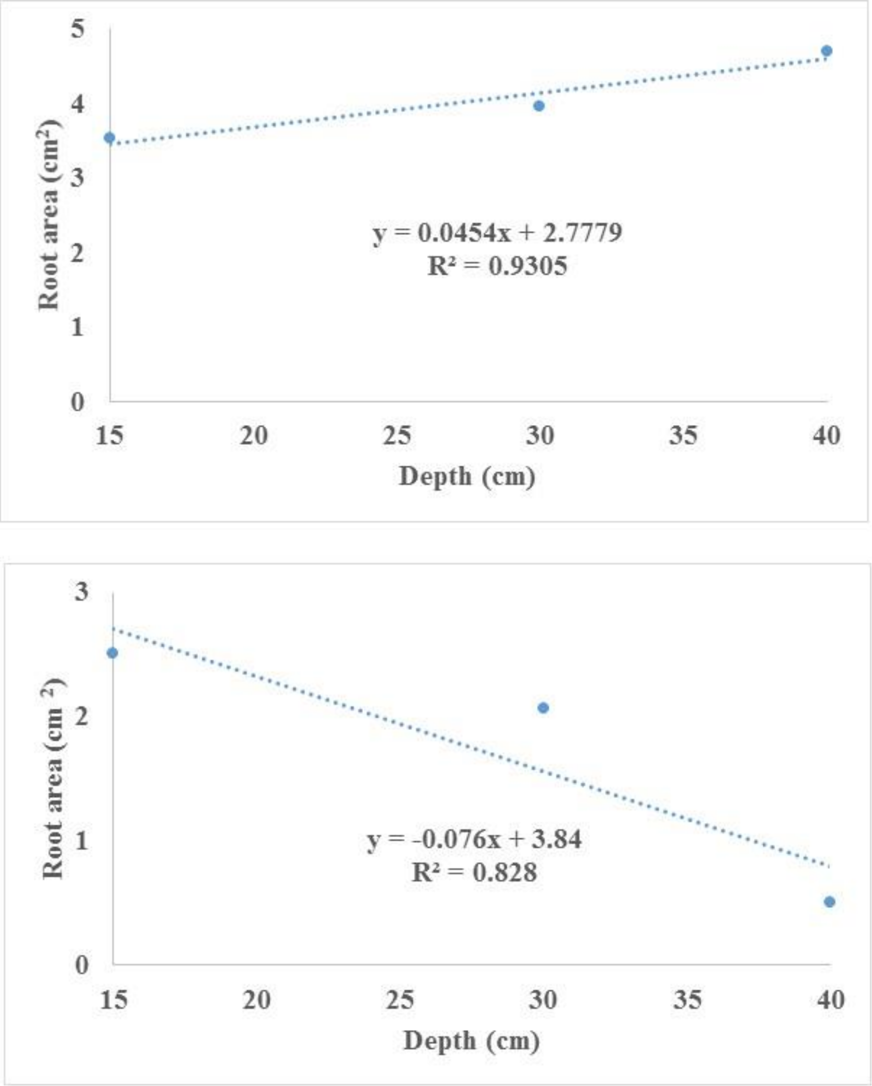

Figure 16. Relationship between root area and soil depth (15 to 20, 25-30 and 40-45 cm) in (a) no-tillage and (b) conventional tillage as influence by tillage in a long-term sorghum experiment in Southeast Texas.

CHAPTER VII

SUMMARY AND CONCLUSIONS

This study is among the few studies published so far that report long-term impacts of tillage practices on soil physico-chemical properties and weed population dynamics. Results from this study demonstrated that tillage regimes affect WHC, MI, infiltration, SOC, C-min, CO_2 emission, weed species composition, weed density, weed seedling emergence, weed diversity, and weed seedbank distribution. This study had four specific objectives and each objective was developed based on a well-defined hypothesis.

The first hypothesis was that long-term NT practices improve soil physical properties more so than conventional tillage (CT) practices, but results from this study revealed that it was only true with WHC. Unlike several other studies, which have reported increased BD and reduced soil aeration with long-term NT, our study did not find any increase in BD in NT compared to CT. Nevertheless, soil BD, TP, AFP, WFPS, and Θv values differed with depth. The BD values were greater in the 10 to 20 cm depth, compared to the 0 to 5, and 5 to 10 cm depths, which could be attributed to increased pore space caused by root penetration and earthworm activities. Likewise, Θv values were also greater in the 10 to 20 cm depth compared to the 0 to 5, and 5 to 10 cm depths; the lower Θv values observed in the top layer (0 to 10 cm depth) could be attributed to the depletion of soil moisture by plants during the growing season. Nevertheless, the long-term NT system improved WHC by 25 .8% compared to the CT system. The WHC declined with soil depth, and this trend was consistent with a decline in SOC content at deeper soil profiles. The lack of plowing along with soil settlement due to wheel traffic over the period could have resulted in the higher MI values at the surface in the NT system compared to CT. However, the long-term CT system had greater cumulative infiltration than the NT system and it is believed that initial soil dryness, roughness, and lesser consolidated soil surface in the CT system could have resulted in the greater cumulative infiltration level.

The second hypothesis was that the long-term NT system improves SOC content and minimizes C-min and CO_2 emission compared to CT. Based on the results obtained, we fail to reject this hypothesis because the long-term NT system had a greater SOC (43% greater), cumulative C-min in the laboratory incubation study (183 μg of CO_2 g^{-1}) at the soil surface, and lower CO_2 emission (28.70%) than the CT system. Long-term retention of crop residues was believed to have resulted in greater SOC content in NT. Higher levels of C-min in the laboratory incubation study confirms high levels of C storage in the NT system, compared to the CT system. Greater C-min in the incubation study was likely facilitated by constant temperature and moisture conditions as well as breaking of the soil clods. Further, the lower CO_2 emission in the NT system confirm the climate change mitigation potential of long-term NT systems.

The third and fourth hypotheses were that the long-term NT system influences a change in weed species dynamics (diversity, emergence pattern, and seedbank distribution). These experiments were conducted in continuous grain sorghum as well as continuous soybean production systems. We fail to reject these hypotheses because the long-term NT grain sorghum as well as soybean systems had greater weed species composition, weed diversity, and seedbank distribution compared to the CT system. However, the magnitude of these differences observed in the grain sorghum experiment was considerably different from the soybean experiment.

In grain sorghum, the NT system showed greater weed diversity (Shannon-Weiner’s index, $H = 0.8$) and species richness ($S = 6.2$), compared to the CT system ($H = 0.6$; $S = 4.2$). Seedling emergence patterns of some dominant weeds were also altered by tillage. In particular, the NT system showed a slower rate of emergence of johnsongrass and common waterhemp, with substantially greater GDD requirements to achieve 50% emergence. Further, a greater proportion of the total seedbank was present at the top 5 cm of the soil in the NT system than in the CT system; moreover, the NT system was dominated by small-seeded weeds and perennials, demonstrating the need for adjusting weed management programs when shifting to the NT practice.

In the soybean monocropping system, however, the weed diversity indices including Shannon-Weiner's diversity index (*H*), richness (*S*), Simpson dominance index (*D*), and Pielou's measure of evenness (*E*) did not differ between the tillage systems in both the germinable seedbank (GSB) and extractable seedbank (ESB) analysis. The lack of differences in weed diversity is attributed to delayed planting of soybean (typically in May), which requires a burndown application of glyphosate to the emerged weed seedlings, eventually reducing the number of weed escapes that can produce seeds in the soybean monocropping system. Nevertheless, weed species composition varied between the CT and NT systems. The Jaccard index also revealed that only 36 and 68% of the weed species were common in both CT and NT systems in GSB and ESB analysis, respectively. Overall, weed densities were greater in the NT system (14 plants m^{-2}) compared to the CT system (3 plants m^{-2}), in particular tall waterhemp (*Amaranthus tuberculatus*) and shepherd's purse (*Capsella bursa-pastoris*) were present in high densities in NT. The vertical distribution of weed seeds in the soil profile was also influenced by the tillage systems, and a larger amount of weed seeds were retained on the soil surface in the NT system, compared to the CT system.

In closing, this study demonstrated the environmental and production benefits associated with long-term NT systems. However, the NT practice also increases weed densities and present greater challenges for weed management, and thus warrants a robust weed management planning.

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