SOIL BIOGEOCHEMISTRY AND WATER DYNAMICS OF CONTINUOUS WINTER WHEAT AS IMPACTED BY COVER CROPS AND MIXED INTERCROPPING

A Dissertation

by

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ABSTRACT

Texas is ranked among the top winter wheat (*Triticum aestivum* L.) producers in USA. Monoculture wheat production systems are a customary practice in the Southern Great Plains, but have negative effects on ecosystem services and soil functions. The resurgence of cover crops technology in the twenty-first century has been viewed as restoring and sustaining soil ecosystem services and functions. The introduction of cover crops and intercropping during the fallow period may increase diversity, productivity and sustainability. This study was conducted for 3 years at the Smith/Walker Ranch near Vernon, TX, a rainfed leased landholding of Texas A&M AgriLife Research at Vernon. The objectives were to determine the impact of cover crops on nutrient cycling, soil microbial community structure and diversity, soil physical properties and soil moisture dynamics in continuous wheat systems. The study was a randomized complete block design with seven treatments replicated four times. Treatments were: (1) conventional till (CT) wheat without a cover crop; (2) no-till (NT) wheat without a cover crop; (3) NT wheat intercropped with turnip (*Brassica rapa* subsp. Rapa)/radish (*Raphanus sativus*) without a summer cover crop; (4) NT wheat with a terminated summer cover crop; (5) NT wheat with a grazed summer cover crop; (6) NT wheat intercropped with turnip/radish with a terminated summer cover crop; and (7) no-till wheat intercropped with turnip/radish with a grazed summer cover crop. Legumes and grasses multi-species mix was used as a warm-season cover crop mix.

Introduction of cover crops in continuous wheat systems during the fallow period significantly depleted soil moisture and was reflected in the following wheat period and exacerbated by recurrent drought when study was initiated in 2013. Treatment effects were more pronounced in the top 0-60 cm of the soil profile. Conventional till and NT treatments without cover crops and NT intercropped with radishes and turnips without summer cover crops recorded

highest stored soil moisture compared to all NT cover crops treatments during periods of peak cover crops growth. The first two years of investigation showed no differences in soil moisture storage among all no cover crops treatments; however, CT trended lowest during the third year, indicating negative tilling effects. The second and third years of cover crops, which had more normal precipitation, showed improved soil water recharge by all cover crop treatments, with cover crop treatments storing highest soil water compared to no cover crops treatments.

Soil nitrate-N was lowest under cover crop treatments compared to no cover crop treatments in the fall and was related to N immobilization and cover crops using N during growth. Generally, no significant soil organic carbon (SOC) sequestration was observed during this investigation. However, water extractable organic C (WEOC) showed a gradual increase under no-till with cover crops.

Total living soil microbial biomass, microbial activity and organic C were numerically higher for all NT treatments compared to CT. Conventional till had the least organic N, C, NH_4^+–N and CO_2–C emission compared to other treatments, although not always significant. No significant effects due to intercropping or grazing were recorded.

Conventional till wheat resulted in the highest soil bulk density compared to all other treatments. Aggregate-size distribution was significantly different in the top 5 cm compared to 5-10 cm depth ($p<0.05$). Large macroaggregates (>2 mm) were highest under the grazed NT with cover crops plus intercropping treatment. Conventional till resulted in the quickest time to surface runoff initiation compared to all other treatments. Runoff volumes collected were highest under CT compared to NT with cover crops and recorded the highest total P, NH_4^+–N and total solids in runoff ($p<0.05$). No-till with cover crops improved soil water infiltration, transmission and holding capacity. No significant effects due to turnips and radishes were observed.

DEDICATION

To my beautiful wife, Kudzai and wonderful children, Farai, Tinaye, Rufaro & Tanaka for bearing and covering up for me when I was constantly away from home. You are the best!

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NOMENCLATURE

°C	degrees Celsius
µm	micrometer
AB	actinomycetes biomass
AMB	arbuscular mycorrhizal biomass
ANOVA	analysis of variance
BD	bulk density
C	carbon
C:N	carbon:nitrogen ratio
cm	centimeter
CO_2–C	carbon dioxide carbon
Conv.Till	conventional till wheat without a cover crop
CT	conventional till
dASD	dry aggregate size distribution
DI	diversity index
dMWD	dry mean weight diameter
FAME	fatty acid methyl esters
FBR	fungi:bacteria ratio
g cm^{-3}	grams per cubic centimeter
GIS	geographical information systems
GNB	gram (-) biomass
GPB	gram (+) biomass
ha	hectare

K	potassium
Kg	kilogram
kg ha^{-1}	kilogram per hectare
LSD	least significance difference
m	meter
m^2	square meter
Mg	megagram
mg kg^{-1}	milligrams per kilogram
mm	millimeter
MWD	mean weight diameter
N	nitrogen
Na	sodium
NASS	National Agricultural Statistics Service
ng g^{-1}	nanograms per gram
NH_4^+–N	ammonium nitrogen
NLFA	neutral lipid fraction
NMM	neutron moisture meter
NO_3^-–N	nitrate nitrogen
NRCS	National Resources Conservation Service
NT	no till
NT.Cover.Graze	no-till wheat with a grazed summer cover crop
NT.Cover.Graze.Int	no-till wheat intercropped with turnip (*Brassica rapa subsp*. Rapa)/radish (*Raphanus sativus*) with grazed summer cover crop

NT.Cover.No.Graze	no-till wheat with a terminated summer cover crop
NT.Cover.No.Graze.Int	no-till wheat intercropped with turnip/radish with terminated summer cover crop
NT.No.Cover	no-till wheat without a cover crop
NT.No.Cover.Int	no-till wheat intercropped with turnip /radish without summer cover crop
OCONR	organic C:organic N ratio
P	phosphorus
PB	protozoa biomass
Pg	petagram
pH	potential hydrogen
RB	Rhizobia biomass
PLFA	phospholipid fatty acid
POC	particulate organic carbon
POXC	permanganate oxidizable carbon
RB	rhizobia biomass
RMSE	root mean square error
S	sulfur
SAS	statistical analysis system
SB	saprophytes biomass
SOC	soil organic carbon
SON	soil organic nitrogen
SOP	soil organic phosphorus

SRP	soluble reactive phosphorus
SUR	saturated: unsaturated ratio
TB	total biomass
TBB	total bacteria biomass
TFB	total fungi biomass
TP	total phosphorus
TS	total sediment
TX	Texas
t ha^{-1}	tonnes per hectare
U.S.	United States
U.S.A.	United States of America
UB	undifferentiated biomass
USDA	United States Department of Agriculture
WEOC	water extractable organic carbon
WEON	water extractable organic nitrogen

CONTRIBUTORS AND FUNDING SOURCES

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Problem statement

Cover crop use is a technology that may reduce soil erosion, increase nutrient use efficiency, improve soil physical properties, increase soil water infiltration and soil organic C (SOC), protect water quality, and aid in weed control. Research has further shown that cover crops may increase yields of subsequent cash crops (Clark, 2007; Dabney et al., 2010; Delgado et al., 2007). The introduction of cover crops to continuous wheat systems prevalent in the Southern Great Plains may potentially increase diversity in the system without eliminating traditional practices like grazing. The use of cover crops in the agricultural industry is not a new phenomenon. Cover crop use dates back at least two hundred years prior to World War I (Groff, 2015). Ancient civilizations utilized cover crops to augment production of main crops. The advent of the Haber-Bosch process resulted in the post-World War II N fertilizer revolution, which decimated cover crops usage in the U.S. Only a small number of U.S. farmers, mostly organic, were still using cover crops post World War II (Groff, 2015), and excessive use of fertilizer has brought about more focus and concerns on environmental issues. Conventional tillage and monoculture cropping systems' impact on the soil ecosystem was also a cause for concern, and consequently resulted in a reintroduction and upsurge in use of cover crops in the twenty-first century. Cover crop resurgence was intensified with the introduction of the USDA-NRCS Soil Health Initiative in fall 2012, which proposed five basic principles as key to improving the health of soil, including:

1. Keep the soil covered with a crop as much as possible
2. Disturb the soil as little as possible

3. Keep plants growing throughout the year to provide C and nutrients for soil organisms
4. Diversify crops as much as possible using crop rotation and cover crops
5. Use proper grazing management.

The Soil Health checklist provided by NRCS stated that management for soil health is one of the easiest and most effective ways for farmers to increase crop productivity and profitability while improving the environment (USDA-NRCS, 2012). Furthermore, it also stated that results are often realized immediately, and last well into the future. The release of the initiative coupled with an intensification of local and regional soil health workshops promoting the key principles generated much interest on the use of cover crops and soil health. The Soil Health Initiative also promoted the Haney Soil Health Assessment as a new national soil test (Haney et al., 2006). However, hesitation exists for cover crop adoption in semi-arid environments as most farmers remain skeptical of the technology, with the primary concern being the loss of soil moisture due to cover crop implementation, since water is often the limiting factor in crop production within these environments. Furthermore, dryland farming in semi-arid environments often comprises low input, elevated risk systems; hence, additional input costs and risk are often difficult to justify.

Literature Review

Southern Great Plains Wheat Systems

Winter wheat (*Triticum aestivum* L.) is one of the most important and valuable cash crops grown in Texas. On average, 6 million acres are planted to winter wheat annually, with about 2 million acres harvested in 2014 and 2015 (USDA-NASS, 2014). Continuous, or monoculture, wheat production is a customary practice in the Southern Great Plains. Winter wheat is also utilized as forage by some farmers prior to harvest as grain. About a third of U.S. wheat farmers also raise livestock and wheat makes an excellent winter forage. The continuous wheat systems in this region are characterized by CT, grazing, and grain harvest. Grazing, however, can increase soil compaction, decrease infiltration, and increase the potential of soil erosion (Van Haveren, 1983; Daniel and Phillips, 2000; Daniel et al., 2002; Wheeler et al., 2002). The majority of wheat producers in the Southern Great Plains, about 80%, practice CT, with only 5% using no-till (NT) (Ali, 2002). Under continuous wheat production, tillage is often used to help control weeds and diseases (Heer, 2006).

Conventional tillage, however, hastens soil organic matter decomposition through increased aeration and disruption of soil aggregates (Six et al., 2000). Cultivation also reduces soil physical protection of organic C, thereby stimulating microbial activity and soil C loss. On the other hand, NT reduces or eliminates soil disturbance, resulting in increased micro aggregation, SOC and N storage and improved soil physical, chemical and biological properties (Paustian et al., 2000; Six et al., 2000). In a study on tillage impacts on soil aggregation and C and N sequestration under wheat cropping sequences, Wright and Hons (2004) demonstrated how NT crop rotations improved soil aggregation and SOC and N sequestration over continuous wheat monoculture.

Crop rotations and practices that leave plant residues on the soil surface mimic natural ecosystems that bring about microbial diversity, which is conducive to biogeochemical processes that enhance nutrient cycling. No tillage crop rotations have shown higher particulate organic matter (POM) content and potentially higher mineralizable N and microbial biomass C compared to tilled monoculture practices (Liebig et al., 2004). Wet aggregate stability and infiltration rates were three times higher in NT systems compared to CT, thereby improving water transmission (Havlin et al., 1990; Wienhold and Halvorson, 1998).

Cover Crops

Cover crops can bring about numerous benefits depending on type selected and management. Generally, cover crops conserve N, add N or C to an agricultural system, and optimize C:N ratio of residues. Cover crops have been reported to suppress emergence of some grassy weeds (Putnam and DeFrank, 1983), and supply residues for erosion control or for improving N availability to subsequent crops (Clark et al., 1997). Increases in soil N and C under conservation practices utilizing cover crops and rotations has been reported in several studies (Halvorson et al., 2002; Al-Kaisi et al., 2005; Wright and Hons, 2004). Some of the crucial factors to consider for optimum benefits from cover crops are species selection, adopting multi-species mixtures and planting/termination dates. Treadwell et al. (2010) noted that planting multi-species cover crop mixtures can optimize C:N balance, obtain multiple benefits, or more fully achieve a particular objective such as organic matter production or weed suppression, while reducing the risk of crop failure.

Species selection, as well as planting and termination dates are critical in optimally managing C and N concentrations and subsequent C:N ratios of plant residues. The C:N ratio is a

useful tool in determining potential N release during decomposition processes (Muller et al., 1988; Quemada and Cabrera, 1995). Legume cover crops usually have C:N ratios less than 20, whereas cereal and some grass cover crops higher in lignin content have significantly higher C:N ratios. Net N immobilization is highly likely at a C:N ratio greater than 35, followed by slow N release (Pink et al., 1948). A C:N ratio less than 20 normally results in net N mineralization and a faster N release rate. The threshold delineating the two processes is a C:N ratio of about 25 (Paul and Clark, 1996). A cover crop mix not only increases crop diversity but may be important in maintaining a nutrient cycling balance that ensures N availability during mineralization and immobilization processes.

Mbuthia et al. (2015) evaluated 31 years of tillage, cover crop, and fertilization effects on microbial community structure, activity and implications for soil quality. These authors showed NT with cover crops resulted in a greater overall soil quality index, which was manifested by greater crop yield, abundance of gram positive bacteria (GPB), mycorrhizal fungi and actinomycetes compared to tillage. Bacteria and fungi are organic matter decomposers that are essential in nutrient cycling. Arbuscular mycorrhizal fungi are associated with efficient nutrient acquisition, particularly phosphorus (P) and are important in promoting soil aggregation. A positive correlation of glomalin concentrations and soil aggregate stability with mycorrhizal root volume has been reported (Bedini et al., 2009). Glomalin is a protein produced by arbuscular mycorrhizal fungi.

Intercropping

Intercropping is the growing of two or more crops in proximity to each other in the same field at the same time. Intercropping or companion cropping may keep land producing at its full

potential, especially under continuous cropping systems, and increases the biodiversity of agroecosystems. Turnips (*Brassica rapa subsp*. Rapa) and radishes (*Raphanus sativus*) have been reported to have deep tap roots that help open subsoils, thereby improving water and air infiltration and earthworm activity (Kennedy, 2012). Higher resource efficiency is realized by intercropping component crops when they have a major difference in growth duration and their critical need for nutrients occurs at separate times (Fukai and Trenbath, 1993). Neely (2013), however, reported a reduction in yields for grain and biomass sorghum [*Sorghum bicolor (L.) Moench*.] intercropped with iron-and-clay cowpea [*Vigna unguiculata (L.) Walp*.] in eastern Texas. Mixed intercropping is the total mixing of component crops at planting in the field. Other types of intercropping are row, strip and relay intercropping.

Soil Water

Water is normally the most limiting factor in crop production in semi-arid regions. Continuous wheat production practices in the Texas Rolling Plains historically leaves the land fallow during the summer, reserving the moisture captured during this period for the following winter wheat crop. Cover crop adoption, therefore, may reduce available soil moisture (Dabney et al., 2001; Balkcom et al., 2007), and can be catastrophic to subsequent crops, especially in drought periods. However, significant stored soil surface water recharge has been reported following cover crops in Alabama (Balkcom et al., 2007). In another Alabama cover crop study, Balkcom and Reeves (2005) reported an average corn (Zea mays L.) yield of 6.9 Mg ha^{-1} following the legume, sunn-hemp (*Crotalaria juncea cv*), compared to 5.7 Mg ha^{-1} following winter fallow. Other studies in the Texas Rolling Plains, however, have shown no impact of cover crops on cotton [*Gossypium hirsutum (L.)*] lint yields (DeLaune et al., 2012; Sij et al.,

2004). In contrast, Baughman et al. (2007) reported a reduction in cotton lint yield in NT cotton with cover crops in the Texas Rolling Plains. Nielsen et al. (2015) demonstrated how cover crops negatively affected yields of subsequent crops through soil moisture depletion in the Central Great Plains. However, there is still limited information on the impact of cover crops in wheat systems in semi-arid regions and little or no multiple year information.

New Soil Extraction Methods

The cover crops resurgence saw the evolution of more recent soil chemical test methodologies theoretically tailored to prevailing natural soil conditions (Haney et al., 2006). Initially, the development of the H^3A extractant was proposed to be used as a limited multi-nutrient extractant which would eliminate the need for two extractants to test for plant-available NH_4^+, NO_3, and P (Haney et al., 2006). The H^3A extractant was named after the first letter of the 4 authors' last names', thus H.H.H.A abbreviated as H^3A. The authors' names are R.L. Haney, E.B. Haney, L.R. Hossner and J.G. Arnold. The H^3A soil extractant is used for extracting NH_4^+–N, NO_3^-–N, P, K, Ca, Al and Fe. The H^3A extractant is made up of organic acids whose selection was centered on the composition of root exudates in the rhizosphere, which theoretically should more naturally mimic plant nutrient availability (Rengel, 2002; Baudoin et al., 2003). The organic acids used are citric acid, oxalic acid and malic acid. The H^3A soil extractant composition includes 0.02 M lithium citrate (5.0 grams), 0.0024 M citric acid (0.5 grams), 0.004 M malic acid (0.5 grams), 0.004 M oxalic acid (0.5 grams), 0.002 M EDTA (0.25 grams) and 0.001 M DTPA (0.25 grams), all dissolved in one liter of water.

Haney et al. (2006) also postulated the use of water, a natural solvent as an extractant for organic C, N and P. Water extractable C is approximately 800% lower than soil organic C and is

usually a readily available C source that drives soil microbial activity. Correlation analyses of these methods were very high for soil extractable nitrate and ammonium, with H^3A and water showing R^2 of 0.97, and 1 M KCl and H^3A having R^2 of 0.95. The H^3A soil extraction process, however, still requires standardization, cross-lab validation and more extensive field research calibration (Sullivan and Granatstein, 2015).

Over time, the Soil Health Tool evolved and became the NRCS' recommended soil testing procedure, as biological and chemical soil testing procedures were combined to determine an overall soil health assessment. The Soil Health Tool combined procedures outlined in Haney et al. (2006) with measures of biological activity using the amount of CO_2-C evolved by a dry soil in a 24-hour period following rewetting, termed Solvita 1-day CO_2–C. This test purportedly mimics the natural environmental conditions of soil drying and rewetting in the field and is an indirect measurement of soil microbial activity that is positively correlated to soil fertility. The Soil Health Tool ultimately provides a Soil Health Calculation and recommends a custom legume/grass cover crop mix for sampled fields. The Soil Health Tool is promoted to potentially increase profitability by lowering input costs and associated production risks (Harmel and Haney, 2013).

As soil biology has moved to the forefront because of the recent Soil Health Initiative, soil tests based upon soil microbial activity have received increased interest. One such test is the phospholipid-linked fatty acid (PLFA) soil analysis. The PLFA method quantifies the total living soil microbial community structure and diversity (Frostegard, 1996; Frostegard and Baath, 1996), which play a pivotal role in nutrient cycling. Phospholipids, common to every living cell and used as biomarkers, degrade rapidly upon death of a cell. This method, therefore, captures only the living microbial community. Microbial populations that are different have characteristic

lipid profiles that are unique to each population, with different phospholipids having different fatty acid chain structures. The functional groups that are identified include total bacteria (actinomycetes and rhizobia), total fungi (arbuscular mycorrhizal and saprophytes), protozoa and undifferentiated microbiota. Community composition ratios like fungi:bacteria, predator:prey, gram (+):gram (-), and stress and community activity ratios are also evaluated as part of the analysis which include saturated:unsaturated and monounsaturated:polyunsaturated ratios. The PLFA method utilizes the application of fatty acid methyl esters (FAME) analysis. Fatty acid methyl esters from the phospholipid fraction (PLFAs) of extracted soil lipids reflect soil microbial biomass (Frostegard, 1996; Frostegard and Baath, 1996) and FAMEs from the neutral lipid fraction (NLFAs) indicate the physiological condition of soil fungi (Baath, 2003). Clapperton et al. (2005) gives a detailed account of FAMEs analysis.

Soil Moisture

Soil profile moisture may be monitored using a Neutron Moisture Meter (NMM). The NMM is made up of an electronic meter and a cylindrical probe. The measuring of soil volumetric water content and data logging is operated from the meter, while the probe takes measurements in the soil profile. The cylindrical probe, which is lowered into the soil through aluminum or PVC access tubes, has a source and detector of radioactive material that is used for measuring soil moisture. The source is composed of americium-241(Am) and beryllium (Be). The Am-Be nuclear reaction results in Am emitting alpha particles which are absorbed by Be, subsequently producing ^{12}C and a fast-moving neutron (Evett, 2008). The fast-moving neutron is thermalized, or slowed, by hydrogen atoms, and this is pronounced because hydrogen and the neutron have equal masses. The count of thermalized neutrons detected by the probe is then

converted to volumetric water content. Aluminum, calcium carbonate and silicon found in the soil also scatter neutrons. However, change in hydrogen in soil is primarily due to soil water content variations. Over and above on-site calibration of the NMM is performed against the direct gravimetric water content measurement method of soil samples taken in the field. Calibration equations that are soil horizon specific are derived which are employed in converting readings or counts to more accurate soil volumetric water contents.

The volume of soil moisture measured by the neutron probe is spherical with a radius, R, that is dependent on soil wetness and bulk density, ranging from about 15 cm in wet soil to about 30 cm in dry soil (Van Bavel et al., 1956). According to Olgaard (1965) and Kristensen (1973), 95% of the flux of neutrons in the sphere of influence, radius R, is defined by the equation:

$$R=100/(1.4+0.1\theta)$$

where R is the radius (cm), and θ is the volumetric water content in percent (%). Generally, the drier the soil is, the larger the radius, R, of the sphere of influence.

The NMM technique is an effective means for long-term in-situ soil moisture monitoring. It is non-destructive, can take readings to depths that are not easily attainable with other methods, and is one of the best for repeated measurements.

Objectives

Soil biogeochemical processes are highly influenced by soil, substrate type and quality, temperature and moisture conditions. These factors are subsequently the drivers in nutrient cycling and plant availability, defining ultimate soil quality and overall fertility status. This study investigated the biogeochemistry and soil moisture dynamics of continuous wheat systems as impacted by cover crops, grazing and mixed intercropping in the Texas Rolling Plains.

Specifically this study sought to: i) characterize soil physical properties in monoculture wheat as impacted by conservation practices, ii) delineate the impact of cover crops, grazing, intercropping and no till practices on soil water dynamics and crop growth in continuous wheat systems, iii) determine soil nutrient cycling of N, P, C, S and K in continuous wheat production systems as impacted by cover crops, intercropping and NT practices, and iv) conduct a comparative analysis of soil microbial community structure and diversity and relationships with nutrient cycling under continuous wheat systems employing conservation practices. The four aforementioned objectives i, ii, iii and iv are dealt with in detail in the next chapters II, III, IV and V, respectively.

CHAPTER II

SOIL PHYSICAL PROPERTIES IN CONTINUOUS WHEAT AS IMPACTED BY COVER CROPS, GRAZING, INTERCROPPING AND NO TILL

Summary

Monoculture wheat systems prevalent in the Southern Great Plains are often practiced under conventional tillage (CT) with grazing. The wheat is grazed and often harvested for grain as well. No-till (NT) is susceptible to compaction given the large equipment that is an integral part of farming operations. Grazing, that comes with animal trampling, can also increase soil compaction, decrease infiltration, and increase the potential for soil erosion. The introduction of cover crops and intercropping with radishes and turnips is predicted to benefit monoculture wheat systems by improving soil physical properties for more sustainable production. The objective of this study was to characterize soil physical properties under continuous wheat as impacted by cover crops, intercropping, grazing and no-till practices. The study utilized a randomized complete block design with seven treatments replicated four times. Treatments were CT and combinations of NT, cover crops, grazing and intercropping with radishes and turnips.

Conventional till wheat without a cover crop had the highest bulk density ($p<0.05$) in the 0-15 cm depth compared to all other treatments. Aggregate-size distribution was significantly different in the top 5 cm of soil compared to the 5-10 cm depth ($p<0.05$). Large macroaggregates (>2 mm) were lowest under CT wheat.

Conventional till resulted in the least time to surface runoff initiation, with the NT no cover crops treatment having the greatest time to runoff. Runoff volumes collected during the first rainfall event showed no cover crops treatments having about 5 to 6 times higher runoff

volumes compared to cover crops treatments ($p<0.05$). Cover crops treatments also had lower runoff nutrient loads for P, N and sediment.

Cover crops and NT interactions improved soil quality against continuous cultivation monoculture system which physically disrupted the soil increasing phosphorus and nitrogen churned to the environment with possible hypoxia and eutrophication in lakes and oceans. No till and cover crops enhanced soil water infiltration and water quality discharged to the environment from farmlands through runoff.

Introduction and Literature Review

Soil quality is the ability of a soil to perform and sustainably fulfill its ecosystem services and functions (Cleland, 2011; Tilman et al., 2006), and is also a reflection of soil health. The capacity of a soil to resist and recover from degradation is critical for sustainability. Soil is the backbone of agricultural activities and yet it is often taken for granted. The basic indicators of soil quality revolve around soil physical, chemical and biological characteristics. These parameters are interconnected with soil physical properties being the fulcrum and foundation upon which biological and chemical functions are laid to define and drive overall soil fertility. This objective of this chapter was to measure and quantify the impact of tillage, cover crops, grazing and intercropping on soil physical properties.

Parameters, such as soil aggregate stability, bulk density, compaction and water infiltration, have direct impact on soil productivity and susceptibility to wind and water erosion. The importance of cover crops and associated benefits for wind and water erosion control are well documented (Kasper et al., 2001; Blanco-Canqui et al., 2013). Cover crops have been shown to improve soil aggregate water stability, bulk density and penetration resistance (Villamil et al., 2006). Aggregate stability is a measure of soil aggregates' capability to withstand disruptive forces due to tillage, wind and/or water (Kemper and Rosenau, 1986). The higher the aggregate stability, the more physical protection also provided for SOC against decomposition (Wander and Bidart, 2000). Aggregate stability is influenced by soil texture, organic matter content and cropping history. Strong coherence of soil particles results in more stable aggregates (Soil Science Society of America, 1997). Root entanglement, fungal hyphae and precipitated solute cementation often provide the forces responsible for soil particle cohesion. Cover crops

have been shown to increase aggregate stability and positively correlate with SOC (Blanco-Canqui et al., 2013). Research also showed cover crop root biomass positively correlated with soil microbial biomass (Fae et al., 2009; Lehman et al., 2014), and was related with increased arbuscular mycorrhizal fungi interacting with cover crops roots, root exudates and glomalin. Arbuscular mycorrhizal fungi produce glomalin, important for cementing soil particles into aggregates (Wright et al., 1996).

Disruptive forces from CT negatively affect soil aggregate stability (Tisdall and Oades, 1982; Wang et al., 2010). While traffic on soils causes soil compaction, the use of heavy equipment is inevitable for agricultural production. In the 1940s, tractors weighed 4000 kg, but went up to 45,000 kg in the 2000s (Sidhu and Duiker, 2006). Working in wet fields also increases chances of soil compaction, but sometimes is unavoidable. Soil compaction reduces yields by negatively impacting root growth, water and nutrient uptake, and gas exchange (Schafer-Landefeld et al., 2004). Cover crops may potentially help in offsetting undesirable compaction problems. Brassicas, like radishes, with penetrating taproots are more effective in reducing the impacts of compaction. Cresswell and Kirkegaard (1995) reported tap rooted radishes as having greater ability to penetrate subsoils compared to fibrous rooted cover crops. Compaction tests showed a 65% reduction in penetration resistance where cover crops were grown (Folorunso et al., 1992). Other long-term cover crops studies also showed reduction in bulk density (Blanco-Canqui et al., 2011; Steele et al., 2012). Blanco-Canqui et al. (2011) summarized cover crop benefits to soil physical properties: provide physical cover to soil, reduce raindrop impact to soil, reduce soil aggregate disruption, slow runoff initiation and velocity, and increase infiltration and stable soil aggregate formation.

In semi-arid and arid environments, dry aggregate size distribution (dASD) is an important indicator of a soil's vulnerability to wind erosion and is directly related to size of aggregates (Pachepsky and Rawls, 2003). Dry ASD is related to soil structure, stability and fertility. Dry mean weight diameter (dMWD) is a common index for dASD. High soil water permeability and gas capacity is reflected by high dMWD values and is also an indication of lower soil erodibility.

Grazing can increase soil compaction, decrease infiltration, and increase the potential of soil erosion (Van Haveren, 1983; Daniel and Phillips, 2000; Daniel et al., 2002; Wheeler et al., 2002). We hypothesized that use of cover crops, intercropping and NT would improve soil physical properties and overall soil quality. The objective of this study was to quantify soil physical properties under continuous wheat production as impacted by cover crops, grazing, intercropping and NT.

Materials and Methods

Field plots were located at a rainfed research site at the Texas A&M AgriLife Research Smith Walker Research Unit (34°03'28.7"N 99°14'35.8"W) near Vernon, Texas (Fig. 2.1). Continuous wheat has been in NT production since 2001 at this site and has been utilized as a dual-purpose grain/grazing system whenever conditions allowed for adequate forage. The soil type is Rotan clay loam (Fine, mixed, superactive, thermic Pachic Paleustolls). The average annual precipitation in this semi-arid region is 711 mm and mean annual temperature is 17.1^{o} C (U.S. climate data, 2017).

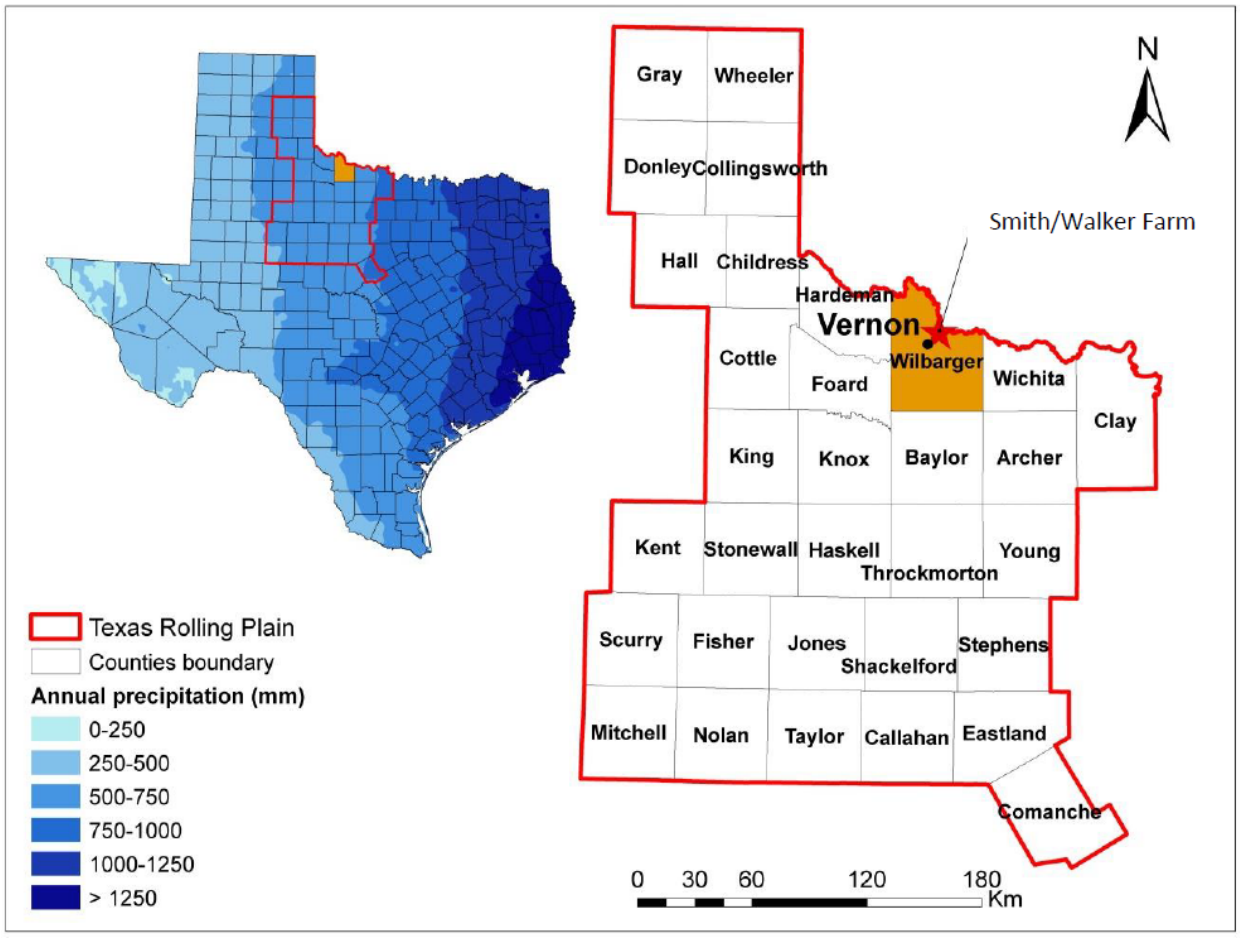

Figure 2.1: Study location at Smith/Walker Research Farm, Texas Rolling Plains near Vernon, TX

The experimental design was a randomized complete block design with 7 treatments replicated 4 times. Each research plot, or replicate, was 0.2 hectares (2025 m^2) in size (Figure 2.2). Cover crops were all grown during summer months, while intercropped species were seeded with wheat. The following treatments were evaluated:

1. CT wheat without a cover crop (Conv.Till);
2. NT wheat without a cover crop (NT.No.Cover);

3. NT wheat intercropped with turnip/radish without a summer cover crop (NT.No.Cover.Int);
4. NT wheat with a grazed summer cover crop (NT.Cover.Graze);
5. NT wheat with a terminated summer cover crop (NT.Cover.No.Graze);
6. NT wheat intercropped with turnip/radish with a grazed summer cover crop (NT.Cover.Graze.Int); and
7. NT wheat intercropped with turnip/radish with a terminated summer cover crop (NT.Cover.No.Graze.Int).

As the entire field had been in no-till wheat production since 2001, CT plots were converted to tillage for the first time in twelve years in summer of 2013. A plough disc and chisel sweep were used to a depth of 15 cm every season. A multi-species mix of legumes and grasses was used as a warm season cover crop, as recommended by the USDA-ARS Soil Health Assessment Program in Temple, TX (NRCS, 2011). The mix was similar to then current NRCS recommendations to producers and was meant to add diversity to the prevalent continuous wheat system. The cover crop mix that was used during the study period is shown in Table 2.1. A no till drill was used for seeding.

Table 2.1: Cover crop mix used during the study.

Cover Crop Species	**Seeding Rate (kg ha^{-1})**	
	2013	**2014 - 2015**
Iron & Clay Cowpea (*Vigna unguiculata*)	6.7	5.6
Guar (*Cyamopsis tetragonoloba*)	-	6.7
Mungbeans (*Vigna radiate*) [1]	-	6.7
Pearl Millet (*Pennisetum glaucum*)	-	2.2
Giant Foxtail Millet (*Setaria italic*)	1.7	1.1
Sorghum Sudangrass *(Sorghum bicolor*× *S. bicolor* var. *sudanense)*	2.8	-
Forage Sorghum [*Sorghum bicolor* (L.) Moench.]	-	3.4
Buckwheat (*Fagopyrum esculentum*)	3.4	2.2
Sesame *(Sesamum indicum)*	0.6	-
Browntop Millet (*Urochloa ramosa* (L.) Nguyen)	1.7	-
Catjang Pea (Vigna unguiculata subsp. Cylindrica)	6.7	-
Lablab Bean *(Lablab purpureus)*	1.1	-
Forage Soybean *(*Glycine max *(L.) Merr.)*	9.0	-
Total Rate	33.6	28.0

The multi-species cover crop mix was custom mixed by regional seed companies and was modified in the second year based upon availability and performance in the first year. Inoculant (Micronoc) for legumes produced by Sono Ag Company in Denton, TX, was added during mixing. The cover crop mixes were planted in June every year after wheat harvest using a NT drill at a row spacing of 19 cm (Table 2.2). Cover crops were chemically terminated after grazing in August/September each year. Glyphosate was primarily used each year with an additional application of paraquat in 2015. Termination was not completely effective with a single spray application in 2013 and 2015 due to stressed plant conditions at time of spraying.

Grazing

Two adjacent grazed cover crop treatment plots were combined and fenced into a single 4050 m^2 paddock, resulting in a total of 4 grazing paddocks (Fig. 2.2). The first year, 15 cow/calf pairs with an estimated live weight of about 9,525 kg were rotated through the paddocks from August 26 to 30, 2013.

Each paddock was grazed for 24 consecutive hours before moving into the next paddock. Fifteen stocker calves grazed wheat on the entire 14 ha field including all treatment plots from January 6 to February 25, 2014. Additionally, in 2014, grazed cover crop treatments were again grazed during August 11 and 12th. Seven cow/calf pairs, 9 heifers and 9 cows were rotated through 4050 m^2 paddocks, with grazing occurring for 6-hours in each paddock. Estimated live cattle weight was 13,270 kg. Two paddocks were grazed per day, totaling 4 paddocks over the two-day period. In 2015, 31 cattle (18 cows and 13 calves) were rotated through the four paddocks, six hours per paddock, from September 9 and 10. Estimated live cattle weight was 11,340 kg.

Figure 2.2. Google Map of experimental design of study site at Smith Walker Research Unit near Vernon, TX. Numbers indicate treatment. Highlighted plot edges of same color represent plots grouped together as a single grazing paddock.

Wheat Planting

Information on wheat and cover crop planting, intercropping, fertilizer application and harvesting are summarized in Table 2.2. Winter wheat was seeded at a rate of 67.2 kg ha^{-1} each year. Winter wheat at 65 kg ha^{-1} was mixed with turnips at 0.56 kg ha^{-1}, radishes at 1.68 kg ha^{-1} and all planted at a row spacing of 19 cm in 2013 and 25 cm in 2014 and 2015.

Table 2.2: Information for wheat planting and harvesting, intercropping and fertilization.

Crop	**2013/2014**		**2014/2015**		**2015/2016**	
	Planted	Harvested /Terminated	Planted	Harvested /Terminated	Planted	Harvested /Terminated
Wheat (variety)	10.03.13 (TAM112)	06.11.14	10.20.14 (Gallagher)	06.05.15	11.29.15 (TAM112)	06.11.16
Cover crops	06.08.13	08.30.13	06.23.14	08.18.14	06.25.15	09.15.15
Fertilizer	**Fall 2013**	**Spring 14**	**Fall 2014**	Spring 15	**Fall 2013**	**Spring 14**
Rate	33.6 kg N ha^{-1}	31.4 kg N ha^{-1}	22.4 kg N ha^{-1}	31.4 kg N ha^{-1}	22.4 kg N ha^{-1}	33.6 kg N ha^{-1}
	33.6 kg P_2O_5 ha^{-1}		11.2 kg P_2O_5 ha^{-1}			
Source	blend of 46-0-0 18-46-0	28-0-0	blend of 46-0-0 18-46-0 in-row	28-0-0	46-0-0 in-row	46-0-0

Soil physical properties

Soil physical properties were measured at the end of the 3-year project cycle. Soil physical properties measured included bulk density (BD) as described by Miller and Donahue (1990) and infiltration rates as outlined by De Laune and Sij (2012). Two BD soil cores were taken in each plot to a depth of 60 cm in depth increments of 0-15, 15-30 and 30-60 cm using a hydraulic Giddings machine with a 5-cm diameter soil probe. Soil aggregate stability characterization samples, two per plot were taken in four depth increments of 0-5, 5-15, 15-30

and 30-60 cm using hydraulic Giddings machine and 5-cm diameter soil probe. Aggregate stability was determined as documented by Nimmo and Perkins (2002), and mean weight diameter (MWD) was used as the soil aggregation index. Soil sample portions from 0-5 and 5-15 depths weighing 100 g each were crushed gently using a wooden roller, and rotary sieved into four aggregate classes (Chepil and Bisal, 1943; Kemper and Chepil, 1965). After dry sieving, four aggregate classes were categorized as large macroaggregates (4 mm - 2 mm), small macroaggregates (2 mm - 250 µm), microaggregates (250 µm - 53 µm) and silt + clay (<53µm). Mean weight diameter was computed as a weighted average of the soil size fraction percentages. The greater the proportion of large aggregates retained in the sieve, the higher the soil MWD. Active organic C was determined in the four aggregate classes using permanganate oxidizable C (POXC) as described by Weil et al. (2003). Subsamples of each aggregate category were finely ground, a 2.5 g sample was allowed to react with potassium permanganate ($KMnO_4$), and an aliquot was then diluted with deionized water for reading on a spectrophotometer for POXC calculation.

Portable rainfall simulators (three) were used for assessing runoff water quantity and quality from the treatment plots as described by DeLaune and Sij (2012). Four treatments were evaluated: CT wheat without a cover crop (Conv.Till); NT wheat with a grazed summer cover crop (NT.Cover.Graze); NT wheat with a terminated summer cover crop (NT.Cover.No.Graze) and NT wheat without a cover crop (NT.No.Cover).

Two rainfall simulation events on each plot were conducted, October 7th and October 27th, 2015. Three 1.5 m X 2.0 m runoff plots were constructed within one large plot for each treatment for logistical ease of moving rainfall simulators and equipment from one plot to another. Rainfall simulators provided a 7 cm hr^{-1} storm event during the experiment (Humphry et

al., 2002). Upon the initiation of runoff, the rainfall simulation process continued for an additional 30 minutes. Runoff water was collected during this time in a single collection barrel. Runoff weight was also recorded over time. Time to runoff and runoff volume were recorded and infiltration rates calculated. Infiltration was calculated as total amount of water applied per plot minus runoff volume collected. Random runoff water aliquots were collected from the barrel after thoroughly mixing. Aliquots were acidified with sulfuric acid (H_2SO_4) after filtering through a 0.45 µm membrane filter for future analysis of nitrate-N (NO_3^-–N), ammonium-N (NH_4^+–N) and soluble reactive P using a segmented flow analyzer. These analyses were as outlined by APHA (2005) for NO_3^-–N and soluble reactive P and USEPA (1983) for NH_4^+–N. Total P was determined by segmented flow analyzer according to the ascorbic acid reduction method (APHA, 2005), following digestion with nitric acid. Total sediment (TS) was determined by oven drying a 20 ml aliquot at 105 °C for 24 hours (APHA, 2005).

Statistical Analysis

The collected data were analyzed by ANOVA using the general linear models procedure (SAS Institute, 2008). Mean separations were accomplished using Fisher's protected least significant difference (LSD) at $P<0.05$ when the ANOVA was significant at $P<0.05$.

Results and Discussion

Bulk Density

Treatment significantly affected BD in the top 15 cm of soil, with values ranging from 1.36 to 1.62 Mg m^{-3}. No treatment differences in BD were noted for the 15-30 cm and 30-60 cm depths, implying that radish/turnip intercrops did not lower BD. The average BD for all treatments for the 0-15 cm, 15-30 cm and 30-60 cm depths were 1.44, 1.65 and 1.86 Mg m^{-3}, respectively. Conventional till wheat without a cover crop (Conv.Till) had the highest BD of

1.62 Mg m^{-3} in the 0-15 cm depth, while no-till wheat intercropped with turnip/radish with grazed summer cover crop (NT.Cover.Graze.Int) had the lowest BD of 1.36 Mg m^{-3} (Table 2.3). Surface soil bulk density of the NT.No.Cover treatment was also significantly lower than Conv. Till. The study site had been under NT since 2001 and tillage practices over the 3-year study period in the Conv. Till treatment appeared to be increasing compaction. Grazing did not increase BD, contrary to assertions that it hinders NT adoption in North Texas due to soil compaction concerns under dual forage/grain systems (Sij et al., 2011). Tillage appeared to have a more deleterious effect compared to grazing.

Table 2.3: Treatment effects on soil bulk density by depth.

Treatments	**Bulk Density (Mg m^{-3})**		
	0-15 cm depth	**15-30 cm depth**	**30-60 cm depth**
Conv. Till	1.62a†	1.63a	1.89a
NT.No.Cover	1.50ab	1.65a	1.83a
NT.No.Cover.Int	1.44bc	1.62a	1.80a
NT.Cover.Graze	1.43bc	1.69a	1.94a
NT.Cover.No.Graze	1.36c	1.67a	1.86a
NT.Cover.Graze.Int	1.37bc	1.64a	1.82a
NT.Cover.Graze	1.43bc	1.69a	1.94a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Dry Aggregate Stability

Aggregate-size distribution was significantly different in the top 5 cm as affected by treatment (Table 2.4; $p<0.05$). Large macroaggregates (>2mm) with Conv. Till were significantly lower compared to two cover crop treatments, NT wheat intercropped with turnip/radish with a grazed summer cover crop (NT.Cover.Graze.Int) and NT wheat with a terminated summer cover crop (NT.Cover.No.Graze) (Table 2.4). NT.Cover.Graze.Int was about

34% higher than the Conv. Till treatment. All no cover treatments were numerically lower in large macroaggregates compared to cover crops treatments, though not significantly. Large macroaggregates are important in that they have a strong bearing on soil aggregate stability (Tisdall and Oades, 1980; Elliott, 1986). Conversely, small macroaggregates (2 mm–250 µm) were highest under conventional till wheat without a cover crop (Conv.Till) and lowest under no-till wheat intercropped with turnip/radish with grazed summer cover crop (NT.Cover.Graze.Int) ($p<0.05$). Conventional till was about 33% higher in small macroaggregates compared to the NT.Cover. Graze.Int. treatment. NT.Cover.Graze, NT.Cover.No.Graze, and NT.Cover.No.Graze.Int also had fewer small macroaggregates compared to Conv.T (Table 2.4).

No significant treatment effects for found for microaggregates (250 µm–53 µm) or silt plus clay (Table 2.4). Conventional tillage exhibited the least mean weight diameter (MWD) of 1.75 mm, and no-till wheat intercropped with turnip/radish with grazed summer cover crop (NT.Cover.Graze.Int) had the highest MWD of 2.16 mm ($p<0.05$). Treatments without cover crops tended to have numerically lower MWD compared to treatments with cover crops.

Mean weight diameter is a tool for evaluating soil physical conditions. A higher MWD is an indication of higher aggregate stability and an improvement in soil physical condition. Research has shown that no-till and cover crops can increase soil aggregation (Kabir and Koide, 2000; Sainju et al., 2003) and stability of soil aggregates (Roberson et al., 1991). A positive correlation of soil organic matter content and total SOC with soil aggregate stability has been reported (Tisdall and Oades, 1980). Polysaccharides exuded by cover crops roots can help bind soil particles together into aggregates. Dapaah and Vyn (1998) showed how aggregate stability was greater following cover crops than where no cover crops were used. Stavi et al. (2012) in a study in the Midwestern USA showed how mixed cover increased MWD, and had a strong

positive correlation with SOC. They also showed that soil BD strongly and negatively correlated with SOC.

Table 2.4: Aggregate size distribution and mean weight diameter for the 0-5 cm soil depth.

Treatments	Aggregate sizes & mean weight diameter (MWD) for 0-5 cm depth				
	Large-macro	Small-macro	Micro-aggreg.	Silt + clay	MWD
	>2 mm	2 mm-250µm	250µm-53 µm	<53 µm	mm
Conv. Till	42.38b†	40.34a	12.40a	4.88a	1.75b
NT.No.Cover	49.17ab	33.74ab	11.92a	5.18a	1.87ab
NT.No.Cover.Int	54.42ab	30.27ab	10.52a	4.79a	1.99ab
NT.Cover.Graze	57.60ab	29.10b	8.97a	4.33a	2.07ab
NT.Cover.No.Graze	59.52a	27.61b	8.92a	3.96a	2.11a
NT.Cover.Graze.Int	61.34a	27.00b	8.14a	3.53a	2.16a
NT.Cover.No.Graze.Int	55.78ab	30.08b	9.90a	4.24a	2.03ab

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Aggregate size distribution and MWD for the 5–15 cm soil depth showed no significant differences due to treatment for large and small macroaggregates, microaggregates and silt plus clay, though trends were similar as for 0-5 cm (Table 2.5). Greater uniformity observed in the 5-15 cm depth might be because tillage only occurred to a depth of about10 cm.

Table 2.5: Aggregate size distribution and mean weight diameter for 5-15 cm soil depth.

Treatments	Aggregate sizes & mean weight diameter (MWD) for 5-15 cm depth				
	Large-macro	Small-macro	Micro-aggreg.	Silt + clay	MWD
	>2 mm	2 mm-250µm	250µm-53 µm	<53 µm	mm
Conv. Till	48.20a†	34.08a	12.7a	5.03a	1.85a
NT.No.Cover	62.64a	25.98a	8.20a	3.18a	2.18a
NT.No.Cover.Int	48.20a	34.08a	12.7a	5.03a	1.85a
NT.Cover.Graze	59.21a	28.31a	8.68a	3.80a	2.11a
NT.Cover.No.Graze	63.12a	25.03a	8.54a	3.31a	2.19a
NT.Cover.Graze.Int	62.58a	22.00a	12.4a	3.03a	2.14a
NT.Cover.No.Graze.Int	65.11a	23.64a	8.18a	3.07a	2.23a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Active Carbon

Active carbon concentrations in the 0-5 and 5-15 cm separates (Tables 2.6 and 2.7) were generally analogous to aggregate sizes and mean weight diameters shown in Tables 2.4 and 2.5. Active C in large macroaggregates from 0-5 cm was lowest for Conv. Till and highest for NT.Cover.Graze, and treatments with cover crops tended to have greater POXC compared to those without (Table 2.6). No treatment differences for POXC were observed in aggregate fractions from 5-15 cm (Table 2.7). Cultivation tends to disrupt soil macroaggregates, resulting in loss of particulate organic matter (POM) C and N protected by soil aggregates (Cambardella and Elliot, 1992; Tiessen and Stewart, 1983). No-till may shield organic C and N from decomposition through formation of more stable aggregates.

Table 2.6: Active carbon in aggregate fractions from the 0-5 cm depth. Values are in mg C kg^{-1}.

Treatment	Active carbon (POX-C) in aggregate fractions for 0-5 cm depth			
	Large-macro	Small-macro	Micro-aggregate	Silt + clay
	>2mm	2mm-250µm	250µm-53 µm	<53 µm
Conv. Till	236b†	295a	300a	319a
NT.No.Cover	266ab	266a	343a	298a
NT.No.Cover.Int	242ab	293a	321a	290a
NT.Cover.Graze	323a	311a	381a	330a
NT.Cover.No.Graze	292ab	296a	324a	310a
NT.Cover.Graze.Int	305ab	317a	399a	313a
NT.Cover.No.Graze.Int	288ab	313a	383a	316a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

The soil active C pool, though a small proportion of total SOC (5-20%) plays a significant role in defining soil quality (Wander and Drinkwater, 2000; Haynes, 2005). Active C functions in C accrual and associated cycling and availability of nutrients (Grandy and Robertson, 2007; Weil and Magdoff, 2004).

Table 2.7: Active C in aggregate fractions from the 5-15 cm depth. Values are in mg kg^{-1}.

Treatment	Active carbon (POX-C) in aggregate fractions for 5-15 cm depth			
	Large-macro	Small-macro	Micro-aggregate	Silt + clay
	>2mm	2mm-250µm	250µm-53 µm	<53 µm
Conv. Till	424a†	466a	509a	425a
NT.No.Cover	397a	505a	667a	562a
NT.No.Cover.Int	432a	474a	611a	607a
NT.Cover.Graze	509a	447a	594a	421a
NT.Cover.No.Graze	431a	524a	542a	415a
NT.Cover.Graze.Int	484a	467a	582a	441a
NT.Cover.No.Graze.Int	497a	482a	598a	429a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Cover crops have been reported to improve soil aggregation and stability (Liu et al., 2005; McVay et al., 1989) that can result in enhanced soil macroporosity, pore connectivity, saturated hydraulic conductivity and water infiltration (Blanco-Canui et al.,2013; Keisling et al., 1994).

Rainfall Simulation

Rainfall simulators were used to measure time to runoff (min), runoff volume (L) and Infiltration (cm). The first rainfall simulation trial on the 6th of October, 2015 showed Conv.Till taking the least time to surface runoff initiation compared to the rest of the treatments, with the NT.No.Cover treatment taking greatest amount of time (Table 2.8; $p<0.05$). All no till treatments had significantly longer times to runoff initiation compared with Conv. Till. A similar pattern was repeated on the second date of rainfall simulation on October 27th, 2015, though shorter times were recorded as the soil was no longer as dry as it was first time.

Runoff volumes collected during the first simulated rainfall event showed significant differences between cover crop treatments and those with no cover crops. Runoff volumes of 10% of applied for CT and 7.8% of applied for NT were significantly higher compared to

treatments with cover crops ($p<0.05$; Table 2.8). The difference in runoff volume between CT and NT can be explained by the amount of water applied due the length of the rainfall simulation on respective treatments. The greatest TRO observed for NT.No.Cover (38 min) resulted in soil saturation and greater water application for this treatment. Since the procedure continued water application for 30 min after initial runoff and the soil was saturated at this point, this treatment also resulted in the highest runoff volume compared to other NT treatments (Table 2.8). The total rainfall that was applied by the simulators was highest in no-till treatments compared to CT treatments ($p<0.05$). There was no significant difference among NT treatments in infiltration percentage of total applied water although cover crops treatments trended higher. Similarly there were no significant differences between no-cover crops treatments CT and NT (Table 2.8).

In the second trial on the 27th of October, CT again resulted in the least time to runoff initiation (2.9 min) and the highest runoff volume of 47% of applied compared to the rest of the treatments which averaged 25% of applied ($p<0.05$; Table 2.8). Cover crops reduced surface runoff by between 12 to 22% compared to no cover crops treatments under NT and CT, respectively. Other studies have shown up to an 80% decrease in runoff loss using cover crops (Krutz et al., 2009; Kasper et al., 2001). DeLaune and Sij (2012) reported a 38% increase in runoff due to conversion of NT to CT.

Table 2.8: Time to runoff initiation (TRO), infiltration and runoff volumes (RO) as affected by treatments.

Treatment	**October 6, 2015**				**October 27, 2015**			
	Applied	TRO	Infiltration	RO	Applied	TRO	Infiltration	RO
	(liters)	(minutes)	(%)	(%)	(liters)	(minutes)	(%)	(%)
Conv. Till	135b†	8.6b	79b	21a	115c	2.9c	51b	47a
NT.No.Cover	238a	38a	85ab	16a	144a	11a	75a	25b
NT.Cover.Graze	189a	24a	97a	3.5b	122c	4.9b	74a	26b
NT.Cover.No.Graze	203a	28a	96a	3.8b	127b	6.3b	76a	24b

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Infiltration rates were significantly higher for NT treatments, with or without cover crops, than Conv. Till, especially on the first date. Smith et al. (1987) also reported that NT and cover crops reduced surface runoff and increased infiltration and stored soil water. Rainfall simulations did not show any differences in water infiltration rates due to cover crops or grazing in no-till systems. DeLaune and Sij (2013), however, reported an increase in runoff volumes under grazed systems.

Water Quality

Conventional till had the highest concentrations of total solids (TS) and total P (TP) in runoff for both the first and second days of rain simulations (Table 2.9; $p<0.05$). The sediment load for Conv. Till was on average 8 and 5 times greater than that for NT treatments for the first and second rainfall dates. Conventional tillage leaves the soil susceptible to erosion, thus more sediment loss, and P adheres to soil particles and is carried along with solids, therefore explaining the relationship between TS and TP runoff loads. Soluble reactive phosphorus (SRP) was highest under NT.Cover.No.Graze compared to all other treatments on the first date of rain simulation (Table 2.9; $p<0.05$). Research has shown variable impacts of cover crops on soil P ranging from no discernible effect (Eckert, 1991) to lowering soil P concentration (Hargrove, 1986). DeLaune and Sij (2012) showed that converting no-till to conventional tillage increased runoff volumes by 38% and also had 2.8 times higher TS compared to no-till. Results from the first date of rain simulation showed higher NH_4^+–N runoff loads in treatments without cover crops compared to cover crop treatments. The higher NH_4^+–N concentrations might be explained by NH_4^+ chemistry which like P is fixed by clay and is susceptible to erosion. Findings of DeLaune and Sij (2012) concur with this result. We did not find any effect due to grazing in this portion of the study. DeLaune at al. (2013) reported higher TP and SRP under graze out

compared to graze and grain systems. Cover crops have been reported to reduce nutrient loads downstream, averting pollution (Kovar et al., 2011).

Table 2.9: Runoff concentrations of total solids (TS), total phosphorus (TP), soluble reactive phosphorus (SRP), organic carbon (OC) and NH_4^+–N.

Treatment	October 6, 2015					October 27, 2015				
	TS (kg ha^{-1})	TP (g ha^{-1})	SRP (g ha^{-1})	OC (g ha^{-1})	NH_4^+–N (g ha^{-1})	TS (kg ha^{-1})	TP (g ha^{-1})	SRP (g ha^{-1})	OC (g ha^{-1})	NH_4^+–N (g ha^{-1})
Conv. Till	484a†	95a	6b	456c	34a	238a	59a	8ab	553a	33a
NT.No.Cover	34b	22b	15b	645c	39a	37b	5b	7b	890a	17a
NT.Cover.Graze	91b	44b	17b	1485a	12b	67b	9b	9ab	890a	25a
NT.Cover.No.Graze	55b	41b	40a	1157b	20b	53b	13b	13a	891a	32a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

The first date of simulated rainfall showed cover crops treatments NT.Cover.Graze and NT.Cover.No.Graze exhibiting higher concentrations of OC compared to no cover crops treatments (Table 2.9; $p<0.05$), with the NT.Cover.Graze treatment having the highest OC compared to all treatments. Cover crops have been shown to increase SOC concentrations (Blanco-Canqui et al., 2014; Acuna and Villamil, 2014), with some research showing mixed species increasing SOC compared to single species (Stavi et al., 2012; Fae et al., 2009).

Conclusion

The differences observed in aggregate size distribution and MWD between NT with and without cover crops compared to Conv. Till was a clear indication of how disruptive conventional tillage can be compared to conservation practices. No till and cover crops increased soil aggregation. The relatively low dry mean weight diameter (dMWD) observed under Conv. Till leaves top soil vulnerable to wind and water erosion. Conventional tillage also led to more rapid runoff initiation, reduced infiltration rates, and increased sediment and N and P loading in

runoff. Conventional till showed more detrimental effects to the soil compared to grazing in this investigation, while NT and cover reduced losses. The high runoff exacerbated by higher soil BD recorded under Conv. Till indicated that fewer large aggregates and compaction reduced infiltration rates and increased runoff risks during storms. The numerically higher number of large macroaggregates observed in the top 5 cm of soil under cover crops treatments may likely be attributed to the cover crops surface residues and root biomass. The higher number of large macroaggregates recorded under NT cover crops treatments positively related with active C concentrations that were analyzed in these separates and the higher OC concentrations that were recorded in runoff water. Conservation practices and cover crops in this study improved soil physical properties and overall runoff water quality.

Conventional tillage practice physically destroyed soil structure leaving soil prone and vulnerable to both wind and water erosion. This increased potential discharge of phosphorus and nitrogen from farmlands into the environment, with a potential of causing eutrophication and hypoxia in water bodies. No till and cover crops can reduce nutrient loads into waterways and lakes enhancing nutrient cycling in agricultural production fields. Cover crops and NT synergies improved soil quality increasing soil water availability which is critical in semi-arid areas farmlands.

CHAPTER III

SOIL WATER DYNAMICS AND COVER CROP PRODUCTION IN CONTINUOUS WHEAT SYSTEMS

Summary

Although cover crop technology is perceived as a tentative benefit to monoculture wheat systems in the semi-arid Southern Great Plains, the biggest hurdle is water. Semi-arid regions are characterized by evapotranspiration that considerably exceeds precipitation. Monoculture wheat practices in the Texas Rolling Plains leave the land fallow during the summer in an attempt to conserve captured moisture for the following winter wheat season. Adopting cover crops just for the protection and enrichment of soil makes this practice complicated and inevitably hinders acceptance. The impact of cover crops on soil moisture availability is therefore a major cause for concern in the Texas Rolling Plains. This research determined the impact of cover crops on soil water storage of monoculture wheat systems and utilized a randomized complete block design with seven treatments replicated four times. Treatments were conventional tillage and combinations of no-till, cover crops, grazing and intercropping with radishes and turnips. A neutron moisture meter (NMM) was used to measure soil water storage once every two weeks at 20 cm depth increments to 140 cm for 3 years from 2013 to 2016.

While cover crops added biomass, they also depleted soil moisture throughout their use during this experiment, with this deficit reflected into the following wheat crop. However, the level of deficit was only catastrophic in the first year of cover crops which was exacerbated by drought. The subsequent growing season 2014/15 showed cover crops treatments capturing more precipitation compared to no cover crops, with this difference even reflected in wheat yields. The

same trends were observed in the 2015/16 season; however, increased water storage at this time was not reflected in yields as an accumulation of residue in cover crops treatments likely immobilized N and hindered plant growth. Cover crops in this study did improve soil water transmission and holding capacity. No significant effects due to turnips and radishes were observed compared to NT only. While cover crops unavoidably use soil moisture during peak growth periods, they did add biomass and improved soil moisture storage and recharge capacity under dryland conditions of this study.

Introduction and literature review

Continuous winter wheat production systems are common in the semi-arid Southern Great Plains. Wheat is sown in fall and harvested in late spring, with fields generally left fallow during the summer. Despite erratic precipitation prevalent in semi-arid regions, such as the Texas Rolling Plains, introducing cover crops during fallow periods is envisaged as a way to sustain productivity.

Water is usually the most limiting factor in crop production in semi-arid regions. Monoculture wheat production in the Texas Rolling Plains leaves the land fallow during the summer, theoretically reserving the moisture captured during this period for the following winter wheat crop. Although CT winter wheat/fallow practice is a common phenomenon in the southern and northern Great Plains, low water use efficiencies have been reported (McGee et. al., 1997) with this practice. Switching fallowing with summer cover crops will potentially exhaust soil moisture which could be utilized by the dryland winter wheat. Often dryland winter wheat production in semi-arid regions is hampered by characteristic low precipitation exacerbated by high evaporation and low stored soil moisture (Prihar et al., 1975; Soon et al., 2008). Norton (2007) reported more than 75% of the rainfall being lost where conservation management was not practiced. Cover crop adoption may further reduce available soil moisture and may be catastrophic to subsequent crops in drought periods (Dabney et al., 2001; Balkcom et al., 2007).

Smith et al. (1987) reported significant stored soil water reductions by winter cover crops, but reduced soil evaporation by the mulching provided by cover crops after termination. Cover crops were also found to decrease surface runoff, add organic matter and consequently improve soil structure. Increased surface roughness due to cover crops facilitates soil water infiltration by reducing runoff velocity. The mulch also reduces rain drop impact on the soil

surface, decreasing soil aggregate disruption and crusting that makes the soil surface less permeable and decreasing evaporation. A mulch covering 90% of the soil surface resulted in maximum infiltration into a dry soil (Felton et al., 1987).

Cover crops can reduce soil compaction through both surface and below ground effects on soil (Chen and Weil, 2010). Brassicas like radishes, with deep tap roots, naturally till the subsoil, while more fibrous roots are more effective on the top soil (Cresswell and Kirkegaard, 1995). Cover crop root systems create channels and macropores upon termination that improve soil hydraulic properties and increase water infiltration into the soil (Chen and Weil, 2010). Keisling et al. (1994) reported increased soil hydraulic conductivity, porosity and water holding capacity after 17 years of hairy vetch, winter rye and crimson clover cover crops. Cover crops, therefore, often increase soil macro porosity and connectivity and water movement into and in the soil system, improving precipitation capture and storage.

No till and cover crops synergies are frequently more beneficial compared to the combination of CT and cover crops. Cover crops create surface mulch that shades, insulates, and retards water vapor movement, allowing condensation inside the mulch and reducing evaporative losses (Phillips, 1984; Bond and Willis, 1969). Cover crop insulation of the soil surface also helps regulate soil temperature. Cover crops generally lower maximum soil temperatures in summer and raise minimum temperatures in winter. Research has shown a reduction of up to 5 °C and increase by 1°C in hot and cold climates, respectively (Teasdale and Mohler, 1993; Blanco-Canqui et al., 2011). Cover crops' reduction in soil temperature in summer reduces soil water evaporation and conserves soil moisture. In semi-arid regions, summer air temperatures can be as high as 45°C.

Significant stored soil surface water recharge was reported following cover crops in Alabama (Balkcom et al., 2007), often resulting in similar or higher yields of following crops. Other studies in the Texas Rolling Plains, however, have shown no impact of cover crops on cotton [*Gossypium hirsutum* (L.)] lint yields (DeLaune et al., 2012; Sij et al., 2004). Baughman et al. (2007) actually reported a reduction in cotton lint yield in NT cotton with cover crops in the Rolling Plains. Nielsen et al. (2015) demonstrated how cover crops, either single or mixed species, negatively affected subsequent crop yields through soil moisture depletion in the Central Great Plains and reported an average 10% reduction in wheat yields following cover crops compared to fallow. In semi-arid regions, cover crops deplete stored soil moisture but can potentially enhance soil chemical, physical and biological processes, contributing to sustainable soil ecosystem service functions and productivity. Cover crop adoption in semi-arid regions, given the soil moisture availability pros and cons discussed, poses a huge challenge to the farmer. Research geared on mitigation of challenges and enhanced benefits for sustainable practices is critical for producers to fully embrace new technology under dryland agriculture in semi-arid areas. However, there is still limited information on the impact of cover crops in wheat systems in semi-arid regions. We hypothesized that cover crops would deplete reserved soil moisture during fallowing and negatively affect following winter wheat main crop in the semi-arid regions where evapotranspiration exceeds precipitation.

The objectives of this study were to determine the impact of NT, cover crops, and grazing on soil water dynamics in continuous wheat systems and the subsequent viability of cover crop production in the Texas Rolling Plains.

Materials and Methods

A neutron moisture meter (NMM) was used to measure soil water storage (Evett, 2008). Aluminum access tubes, about 5-cm diameter and 180 cm long were placed by the plant row in each plot to a depth of 150 cm. The installation was done using a Giddings hydraulic coring machine. Soil water stored in the profile was measured once every two weeks at 20 cm depth increments from 0 to 140 cm. The NMM readings were converted to volumetric soil water content with three calibration equations determined for the soil type under investigation at one of the experimental sites for the NMM that was used (Model 503DR, CPN International Inc, Martinez, CA, Serial No. H350607921). The calibration process and derivation of soil moisture computation equations shown in Table 2.3 are well documented by Evett, (2003). The three equations were based on the soil profile characteristics of the soil under investigation. The same calibration equations for Abilene clay loam were used for Rotan clay loam.

Table 3.1: Calibration equations for Abilene clay loam type.

Depth (cm)	**Equations**	**RMSE**	**r^2**
10	$\theta v = -0.0696 + 0.2698 C_R$	0.010	0.990
30-50	$\theta v = 0.1046 + 0.0730 C_R$	0.070	0.930
70-130	$\theta v = -0.0395 + 0.1766 C_R$	0.016	0.984

Where,

θv is volumetric water content in ($m^3\ m^{-3}$), C_R is the count ratio, that is the count of the measured material to the standard count, RMSE is root mean squared error and r^2 is the coefficient of determination.

A HydraProbe field portable soil moisture sensor was used to measure surface volumetric water content top 5 cm (http://www.stevenswater.com/products/sensors/soil/hp-field/). The HydraProbe has a sensor with 5 pins about 5 cm long that are pushed into soil surface. The sensor was connected to an aluminum housing having wireless connectivity (WI-FI). Data logging was wirelessly achieved through a cell phone connected to the sensor using the HydraMon application. The sensor measured soil volumetric water content (VWC%), electrical conductivity (EC) and soil temperature.

Historical and observed average temperature and precipitation was accessed through U.S Climate data online (U.S. climate data, 2017). Observed precipitation was recorded on site using two rain gauges on the farm.

Biomass

Summer cover crop biomass production was determined by clippings taken 2 cm above ground level from two randomly placed 1–m^2 grids per plot immediately prior to cover crop termination (Chapter 2 for more details). For grazed cover crop treatments, above ground biomass clippings were taken before and after grazing to estimate the amount of biomass removed by grazing and/or trampling. Removal was estimated by the difference between pre-grazed and post-grazed biomass measurements. Biomass samples were oven dried at 65 °C for 48 hours or longer as necessary. Dry weights were recorded, samples were ground with a Wiley Mill forage grinder to pass a 2-mm screen, and 250 mg samples were weighed for C and N analysis using a Macro Elementar analyzer, Vario Max CN, Elementar Analysensysteme GmbH, Langenselbold, Germany (McGeehan and Naylor, 1988). C:N ratios were subsequently calculated.

Results and Discussion

Climate

Climatic data, including historical and observed average monthly temperature and precipitation, are presented in Table 3.2. The US Drought Monitor classified the study area as enduring exceptional drought conditions from November 6, 2012 through May 5, 2015 (http://droughtmonitor.unl.edu/). The US Drought Monitor is jointly produced by the National Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Exceptional drought is the most intense drought rating. Average annual rainfall for the study site is 711 mm (U.S. climate data, 2017). Historical average rainfall during critical phases of the wheat growing season (October-March) is 266 mm. While wheat is maturing in April and into May, rainfall received during this period is often not fully utilized for crop yield. Precipitation during October-March period was 107, 236, and 440 mm for years 1-3, respectively. Historical average rainfall for the summer cover crop growing season (June-August) is 223 mm (Table 3.2). The final summer of the study received below normal precipitation. However, the summers of 2013 and 2014 were above normal due to significant rainfall events in July, which were at least 292% above normal for the month.

Table 3.2: Historical and observed average temperature and precipitation for the study period (2013- 2016).

Month	Historical		Observed 2013		Observed 2014		Observed 2015		Observed 2016	
	Avg. Temp ºC	Precip (mm)	Avg. Temp ºC	Precip (mm)	Avg. Temp ºC	Precip (mm)	Avg. Temp ºC	Precip (mm)	Avg. Temp ºC	Precip (mm)
January	5	30	3	30	4	4	4	46	5	18
February	7	36	8	74	4	22	5	7	10	37
March	12	56	12	6	10	36	12	47	14	28
April	17	57	15	68	18	70	18	109	17	116
May	22	85	23	20	23	72	20	528	22	138
June	27	108	29	50	15	110	27	58	27	76
July	29	53	29	226	28	208	30	64	31	53
August	29	62	29	47	29	57	29	38	29	66
September	24	80	26	68	25	51	27	12	25	183
October	18	71	18	28	20	56	19	100	21	138
November	11	42	10	9	9	70	12	96	14	59
December	5	31	3	8	7	10	8	161	7	36
Total		**711**		**635**		**766**		**1265**		**948**

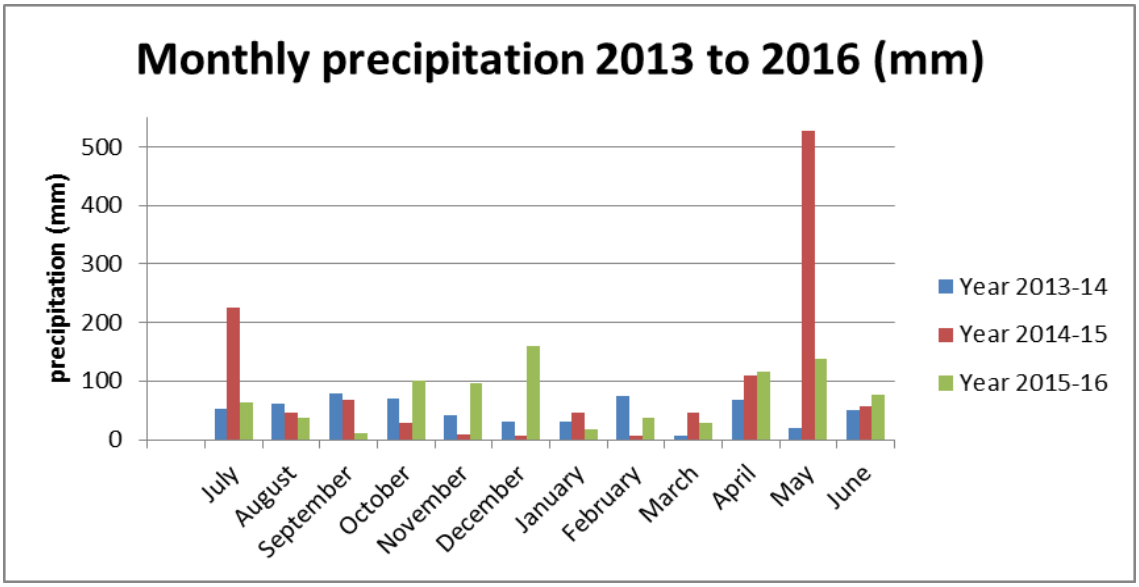

Figure 3.1: Monthly Precipitation for 2013 to 2016

Cover Crop Biomass

Annual dry biomass yields from cover crops ranged from 1796 kg ha^{-1} to 3644 kg ha^{-1} (Table 3.3). Averaged across treatments, mean biomass production was 2141 kg ha^{-1} in 2013, 3503 kg ha^{-1} in 2014, and 2861 kg ha^{-1} in 2015. During 2013, lower biomass levels were observed than other years (Table 3.3), although seeding rates were 5.6 kg ha^{-1} higher than 2014 and 2015.

Approximately 16 mm rainfall was received on June 9, 2013, the day after the cover crop was planted. This provided sufficient moisture for germination. However, after emergence, temperatures exceeding 38 ^{o}C occurred over the next 2-3 weeks, which negatively affected legume species. Two large rainfall events occurred in July 2013. Following the first rainfall event in mid-July, annual grassy weeds emerged throughout the entire study area. While glyphosate easily controlled grassy weeds in non-cover crop treatments, grassy weeds dominated treatments with cover crops. Millets and sorghum Sudan grass became the dominant planted species in late summer, with little to no evidence of legume species. Similar to legumes, no sesame or buckwheat were noted in any cover crops stands at termination.

Of the three-cover crop growing seasons, 2014 produced the greatest amount of biomass (Table 3.3). As in 2013, grassy volunteer weeds dominated cover crops treatments. In contrast to 2013, however, a good representation of each species within the mix was observed, except for buckwheat. Due to stress conditions related to drought, glyphosate was not fully effective in termination and some regrowth of grasses was noted following rainfall in September. Mungbeans and cowpeas were fully mature by mid-August. Grasshoppers heavily damaged some of the legumes, particularly guar in late summer. While cover crops have been reported to suppress emergence of some grassy weeds (Putnam and DeFrank, 1983), this was not evident in

this study as sprangletop [Leptochloa chinensis (L.) Nees.] grew uncontrollably during this investigation. Similar trends were also noted in 2015.

Post-grazing biomass measurements were made in 2014 and 2015. In 2014, post-graze clippings resulted in 58-67% lower biomass (Table 3.3). For 2015, grazing resulted in 47-55% lower biomass readings. Thus, we can conclude that 47-67% of standing biomass was removed due to grazing over relatively short grazing periods. The USDA-NRCS has promoted a goal of leaving 50% of cover crop biomass after grazing (local soil health workshops).

Table 3.3: Annual cover crop dry biomass produced.

Treatments	Cover crop biomass production (kg ha^{-1})					
	2013		2014		2015	
	Pre-Graze	Post-Graze	Pre-Graze	Post-Graze	Pre-Graze	Post-Graze
NT.Cover.Graze	2169b†	-	3133b	1305a	3120a	1391b
NT.Cover.No.Graze	2129b	-	3629a	-	2381c	-
NT.Cover.Graze. Int	1796c	-	3590a	1190b	2961b	1557a
NT.Cover.No.Graze.Int	2474a	-	3644a	-	2987b	-

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Biomass C:N ratios averaged 33 to 35 for the first two growing seasons before increasing to 48 in 2015 (Table 3.4). The cover crop seed mix averaged about 70% grasses and 30% legumes throughout the study period. The relatively high C:N ratios that were observed were attributed to poor performance by legumes in the cover crops mix that was seeded. Grasses in the mix dominated the cover crop composition, and potential N mineralization forecasting may need to be adjusted to account for this in semi-arid environments where moisture is a limiting factor.

Table 3.4: Total carbon (TC) and total nitrogen (TN) concentrations and C:N ratio of cover crop biomass.

Treatment	2013			2014			2015		
	TC (%)	TN (%)	C/N	TC (%)	TN (%)	C/N	TC (%)	TN (%)	C/N
NT.Cover.Graze	46.3a†	1.51a	31c	41.0a	1.29a	32b	41.2a	0.86a	48a
NT.Cover.No.Graze	39.4b	1.08c	36a	40.5a	1.10b	37a	41.9a	0.90a	47a
NT.Cover.Graze. Int	42.7b	1.26b	34ab	40.5a	1.26a	32b	41.8a	0.99a	42b
NT.Cover.No.Graze.Int	40.3b	1.10c	37a	40.6a	1.26a	32b	41.9a	0.86a	48a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Grazed cover crops added an average of about 500 kg C ha^{-1} and 16 kg N ha^{-1} in 2014 and about 600 kg C ha^{-1} and 14 kg N ha^{-1} in 2015. Post grazing biomass was not quantified in 2013. Ungrazed cover crops added more than double the C into the soil system, averaging 1475 kg C ha^{-1} and 43 kg N ha^{-1} in 2014. In 2015, non-grazed cover crops added a mean of 1125 kg C ha^{-1} and 24 kg N ha^{-1} (Table 3.5). The amount of N added to the soil system in 2015 by non-grazed cover crops dropped by almost half from the preceding year, partly because of less legumes in the cover crop stand.

Table 3.5: Biomass carbon (C) and nitrogen (N) soil input (kg ha^{-1}).

Treatment	2013		2014		2015	
	kg ha^{-1}					
	C	N	C	N	C	N
NT.Cover.Graze	1004a†	33a	535b	17b	573b	12b
NT.Cover.Graze. Int	767b	23b	482b	15b	651b	15b
NT.Cover.No.Graze	839b	23b	1470a	40a	998a	21a
NT.Cover.No.Graze.Int	997a	27a	1479a	46a	1252a	26a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Intercropping

Performance of intercropped radishes and turnips was fair to poor the first two years. Emergence was observed each year, but extreme winter-kill occurred. The third year, although

not markedly greater, had evidence of more brassicas in the spring. Successful intercropping of brassicas is probably best suited for earlier fall planting, ideally 6 weeks before the first frost, with the potential optimum planting date for brassicas being September 20th for the Rolling Plains region. Based upon the noted performance, we cannot conclude with confidence that intercropping of radishes and turnips contributed to any observed treatment effects.

Soil Water

Soil moisture characterization by depth showed more significant effects in stored soil moisture in the top 60 cm of soil compared to 60-140 cm ($p<0.05$). A synopsis of the stored soil water in the 0-60 cm depth from 2013 to 2016 showed consistent soil moisture depletion by cover crops treatments every year during this study. The no cover crops treatments: CT, NT and NT no cover crops intercropped with radishes and turnips had greater stored soil moisture compared to all cover crops treatments (Fig. 3.1; $p<0.05$). The site under investigation has been under NT since 2001. The 2013/14 and 2014/15 growing seasons had no observed differences in stored soil moisture among all no cover crop treatments. However, in the third-year, CT showed significantly less stored soil moisture among treatments with no cover crops and was likely a manifestation of negative cultivation impacts on soil physical properties and subsequent decreased capacity to store soil moisture (Fig. 3.1). In addition, precipitation for June-August was much lower in year 3 than the first two years, indicating how tillage can reduce surface moisture. Conventional tillage had only 3% and 2% less stored soil moisture compared to NT treatments without cover crops during the 2013 and 2014 cover crops periods, respectively. However, during the 2015 cover crops period, CT contained 13% less stored soil moisture compared to NT with no cover crops (Fig. 3.2; $p<0.05$).

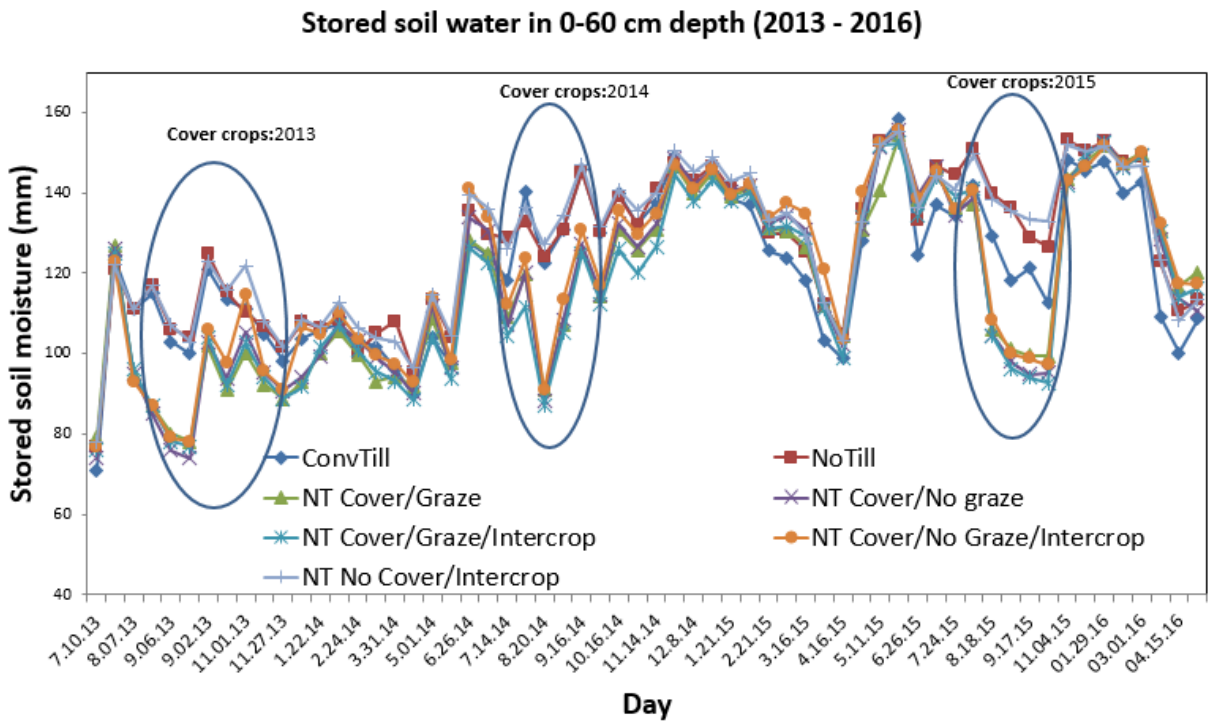

Figure 3.2: Stored soil water in 0-60 cm depth (2013-2016).

The 2013/14 growing season showed an enormous impact of cover crops moisture depletion well into the wheat growing season (Fig. 3.3). This was the first year of cover crops and was exacerbated by the recurrent exceptional drought that was experienced during that period. Treatment differences for the 2014/15 wheat period following cover crops were not as highly significant and severe compared to 2013/14 season. The 2015/16 growing season was even better compared to both preceding seasons. The average stored soil moisture for all treatments averaged 100 mm, 138 mm and 148 mm for the 2013/14, 2014/15 and 2015/16 growing seasons, respectively, 5 months after planting winter wheat. Annual precipitation amounts for 2013, 2014 and 2015 were 635 mm, 766 mm and 1265 mm, respectively (Table

3.2). A focused analysis of each growing season revealed even more detail on the impact of cover crops on soil moisture dynamics during this investigation.

2013/2014 Growing Season

Tables 3.6 and 3.7 show stored soil water for the 0-60 cm depth for the period spanning July 2013 to June 2014, and tables 2.10 and 2.11 show soil water for the 60-140 cm depth. Cover crops were planted on June 8, 2013 and terminated on August 30, 2013. Winter wheat was subsequently planted on October 3, 2013 along with radishes and turnips in intercropped treatments.

a. Stored soil water 0-60 cm depth (2013-2014)

Stored soil moisture was statistically the same for all treatments at the inception of the investigation prior to cover crops seeding, averaging 125 mm in the top 60 cm (Table 3.6). The cover crop mix was seeded June 8, and August readings showed cover crops treatments having 15% less stored soil moisture compared to no cover crops treatments in the upper 60 cm (Table 3.6; $p<0.05$). At the peak period of cover crop growth, cover crop treatments averaged 26 % less stored soil water compared to no cover crops treatments ($p<0.05$). At the time of seeding winter wheat on October 3, 2013, cover crop treatments showed about 18% less stored water than treatments without covers ($p<0.05$). About 8 weeks into the wheat growing period, soil moisture was still 14% higher under no cover crops treatments before becoming more similar. Cover crop treatments trended lower during the wheat growing period till harvest time. Moisture deficit due to cover crops negatively affected critical wheat growing periods, subsequently negatively impacting yields. Although drought overall literally wiped out the entire wheat crop regardless of

treatment, average grain yields of no cover crops treatments were about 4 times higher than those with cover crops. Cover crops were planted June 8 and terminated August 30, 2013, while wheat was planted October 3, 2013 and harvested June 11, 2014. A total of 588 mm precipitation was received during the period, June 8, 2013 to June 11, 2014.

Table 3.6: Stored soil water (mm) for 0-60 cm depth for 2013-14 season- July to Nov. 2013. Cover crops planted 06.08.13 and terminated 08.30.13; wheat planted 10.03.13 and harvested 06.11.14.

Treatment	Date & Stored soil water (mm) for 2013-14 season-July to Nov. 2013									
	7.10.13	7.30.13	8.07.13	8.22.13	9.06.13	9.19.13	10.02.13	10.17.13	11.14.13	11.27.13
Conv. Till	72b†	124a	111a	115a	103a	100a	121a	114a	105a	98ab
NT.No.Cover	77ab	121a	111a	117a	105a	104a	126a	115a	107a	102a
NT.No.Cover.Int	78a	122a	111a	117a	108a	103a	123a	116a	108a	102a
NT.Cover.Graze	79a	127a	95b	87b	80b	78b	102b	91b	92b	89c
NT.Cover.No.Graze	74ab	126a	95b	85b	76b	74b	104b	94b	95b	91bc
NT.Cover.Graze. Int	77ab	125a	97b	87b	78b	77b	104b	92b	94b	89c
NT.Cover.No.Graze.Int	77a	123a	94b	87b	79b	78b	106b	98b	96b	91bc

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Table 3.7: Stored soil water (mm) for 0-60 cm depth for 2013-2014 season- Dec. 2013 to May 2014.

Treatment	Date & Stored soil water (mm) for 2013-2014 season-Dec to May, 2014								
	12.17.13	1.22.14	2.12.14	2.24.14	3.10.14	3.31.14	4.15.14	5.01.14	5.20.14
Conv. Till	104a†	106a	107a	103a	102abc	96ab	90ab	104a	98ab
NT.No.Cover	108a	107a	109a	100a	105a	108a	95ab	114a	104a
NT.No.Cover.Int	108a	107a	113a	107a	104ab	103ab	97a	115a	105a
NT.Cover.Graze	93b	100a	106a	100a	93c	94b	92ab	109a	98ab
NT.Cover.No.Graze	94b	99a	108a	103a	99abc	95b	90ab	112a	97ab
NT.Cover.Graze. Int	92b	102a	107a	101a	96bc	93b	89b	104a	94b
NT.Cover.No.Graze.Int	107a	105a	111a	104a	99abc	98ab	93ab	114a	98ab

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

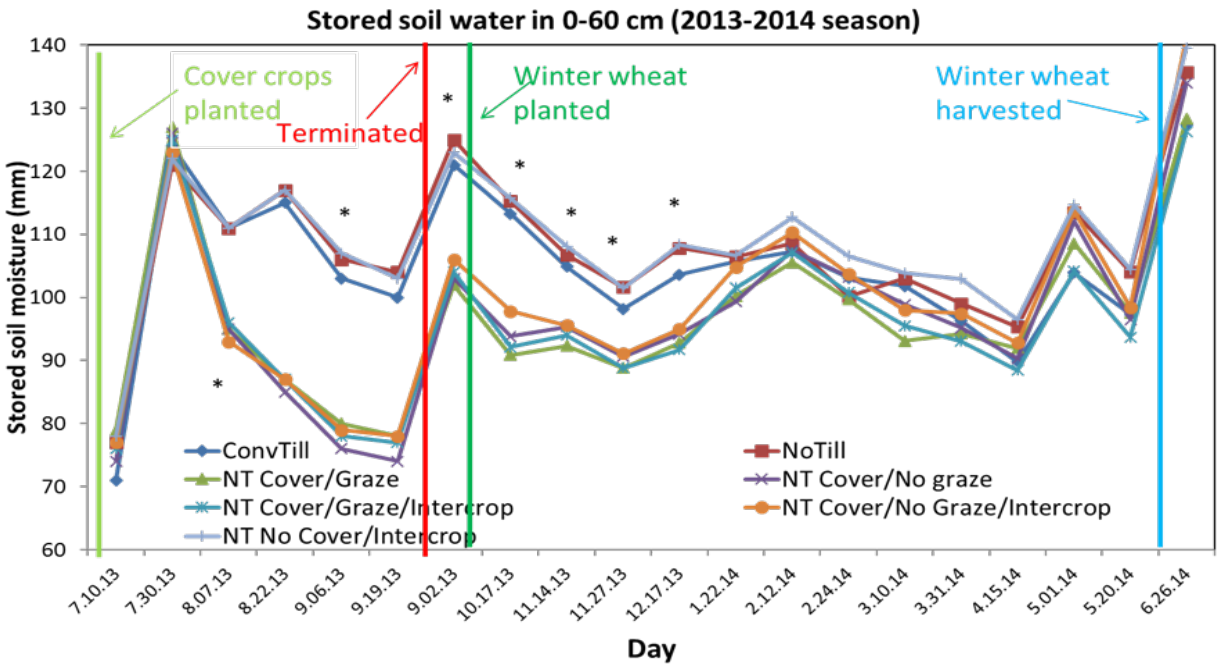

Figure 3.3: Stored soil water in 0-60 cm depth (2013-2014 season). *Significant at P<0.05.

b. Stored soil water 60-140 cm depth (2013-2014)

Generally, the stored soil water content for 60-140 cm depth did not interact significantly with treatments during the first growing season (Tables 3.8 and 3.9).

Table 3.8: Stored soil water (mm) at 60-140 cm depth for 2013-14 season- July to Nov. 2013.

Treatment	Date & Stored soil water (mm) for 2013-14 season-July to Nov, 2013									
	7.10.13	7.30.13	8.07.13	8.22.13	9.06.13	9.19.13	10.02.13	10.17.13	11.14.13	11.27.13
Conv. Till	141a†	152a	153a	153a	152ab	152ab	152ab	153ab	149ab	151ab
NT.No.Cover	146a	147a	149a	148a	149ab	148ab	148ab	148ab	146ab	146ab
NT.No.Cover.Int	149a	149a	150a	147a	146ab	144ab	144ab	144ab	143ab	143ab
NT.Cover.Graze	152a	153a	155a	153a	149ab	148ab	148ab	148ab	148ab	148ab
NT.Cover.No.Graze	139a	142a	144a	141a	138b	138b	137b	136b	137b	137b
NT.Cover.Graze. Int	140a	149a	149a	142a	135b	135b	135b	135b	134b	136b
NT.Cover.No.Graze.Int	156a	159a	160a	159a	159a	159a	159a	160a	158a	159a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Table 3.9: Stored soil water (mm) at 60-140 cm depth for 2013-2014 season- Dec. 2013 to May 2014.

Treatment	Date & Stored soil water (mm) for 2013-2014 season-Dec. 2013 to May 2014								
	12.17.13	1.22.14	2.12.14	2.24.14	3.10.14	3.31.14	4.15.14	5.01.14	5.20.14
Conv. Till	151ab†	151ab	143a	144ab	151ab	148ab	144a	147ab	141a
NT.No.Cover	146ab	147ab	135a	134b	148ab	148ab	148a	151ab	148a
NT.No.Cover.Int	143ab	143ab	146a	146ab	145ab	145ab	146a	148ab	146a
NT.Cover.Graze	148ab	149ab	138a	137ab	150ab	152ab	152a	155ab	154a
NT.Cover.No.Graze	138b	138b	149a	149ab	139b	140ab	141a	143ab	141a
NT.Cover.Graze. Int	136b	135b	152a	153ab	138b	138b	138a	140b	139a
NT.Cover.No.Graze.Int	159a	159a	154a	154a	159a	160a	157a	164a	159a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

2014/2015 Growing Season

Tables 3.10 and 3.11 show stored soil moisture in the 0-60 cm depth, while tables 3.12 and 3.13 show that in the 60-140 cm depth for the second season of investigation spanning the June 2014 to June 2015 time period. Cover crops were planted on June 23, 2014 and terminated August 18, 2014. Winter wheat intercropped with turnips and radishes were seeded October 20, 2014 and harvested on June 5 of 2015.

a. Stored soil water 0-60 cm depth (2014-2015)

Stored soil moisture was not significantly different among treatments three days after planting cover crops in 2014 (Table 3.10). About two weeks after seeding cover crops, however, cover crops treatments were showing a moisture deficit of about 13% compared to treatments without cover crops. Moisture measurements taken on this date (July 14) showed significantly lower stored soil moisture for all cover crop treatments compared to NT without cover crops, but not different than CT (Table 3.10). The moisture deficit for cover crops treatments peaked at an average of 28% compared to non-cover crop treatments on August 20, 2014 ($p<0.05$).

Significantly lower soil water for cover crops treatments persisted through September 29, 2014. At the time of seeding winter wheat, the difference had dropped to 6% following about 65 mm of precipitation received after cover crop termination. Two weeks into the wheat growing period, there were no significant differences among treatments in stored soil water ($p<0.05$), which was attributed to about 70 mm of precipitation that was received in the month of November. About 16 weeks into the wheat growing season, Conv. Till had the least stored soil water (about 15% less) compared to the NT cover crops non-grazed and intercropped treatments (Fig. 3.4; $p<0.05$). During the months of February and March 2015, a reversal of the 'normal' trend was observed. Cover crops treatments showed about 5% more stored soil moisture in March compared to no cover crops treatments (Fig. 3.3). A total of 1189 mm precipitation was received during the period under review, June 2014 to June 2015. Higher rainfall amounts that were received during this period drastically reduced the impact of cover crops on wheat production. Cover crops treatments captured more of the rainfall compared to no cover treatments because of increased hydraulic conductivity and soil macro porosity (Chen and Weil, 2010). The NT cover crops grazed intercropped treatment captured even more water compared to the other NT treatments, although radishes and turnips did not do well in the first two years of study. This difference in stored water was also reflected in wheat yields with conventional tillage recording 21% lower yields on average compared to NT and cover crops treatments (data shown later).

Table 3.10: Stored soil water (mm) at 0-60 cm depth for 2014-15 season- June to Nov., 2014. Cover crops planted 06.23.14and terminated 08.18.14; wheat planted 10.03.14 and harvested 06.11.15.

Treatment	Date & Stored soil water (mm) for 2014-15 season-June to Nov. 2014									
	6.26.14	7.14.14	8.1.14	8.20.14	9.2.14	9.16.14	9.29.14	10.16.14	10.27.14	11.14.14
Conv. Till	127a†	118ab	140a	123a	131a	146a	130a	140ab	132ab	138a
NT.No.Cover	136a	129a	133ab	124a	131a	145a	131a	139ab	132ab	141a
NT.No.Cover.Int	140a	126a	137a	127a	135a	147a	132a	141a	136a	140a
NT.Cover.Graze	128a	109bc	120c	91b	107b	125b	114b	131ab	126ab	131ab
NT.Cover.No.Graze	134a	107bc	120c	88b	108b	127b	115b	132ab	127ab	132ab
NT.Cover.Graze. Int	126a	105c	111c	87b	105b	125b	112b	126b	120b	127b
NT.Cover.No.Graze.Int	141a	112bc	124bc	91b	113b	131b	117b	136ab	130ab	135ab

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Table 3.11: Stored soil water (mm) at 0-60 cm depth for 2014-15 season- Nov. 2014 to June, 2015.

Treatment	Date & Stored soil water (mm) for 2014-15 season-Nov. 2014 to June 2015									
	11.25.14	2.09.15	2.21.15	3.03.15	3.16.15	3.31.15	4.16.15	4.30.15	5.11.15	6.03.15
Conv. Till	149a†	137a	125a	124b	118b	104b	99a	128a	152a	158a
NT.No.Cover	147a	141a	130a	130ab	125ab	112ab	105a	136a	153a	155a
NT.No.Cover.Int	151a	145a	133a	135a	130a	113ab	103a	133a	152a	156a
NT.Cover.Graze	147a	141a	131a	131ab	127ab	112ab	104a	131a	141a	154a
NT.Cover.No.Graze	149a	142a	132a	135a	131a	112ab	102a	131a	151a	156a
NT.Cover.Graze. Int	144a	140a	131a	132ab	129a	111b	99a	134a	152a	152a
NT.Cover.No.Graze.Int	147a	142a	134a	138a	135a	121a	104a	140a	152a	156a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

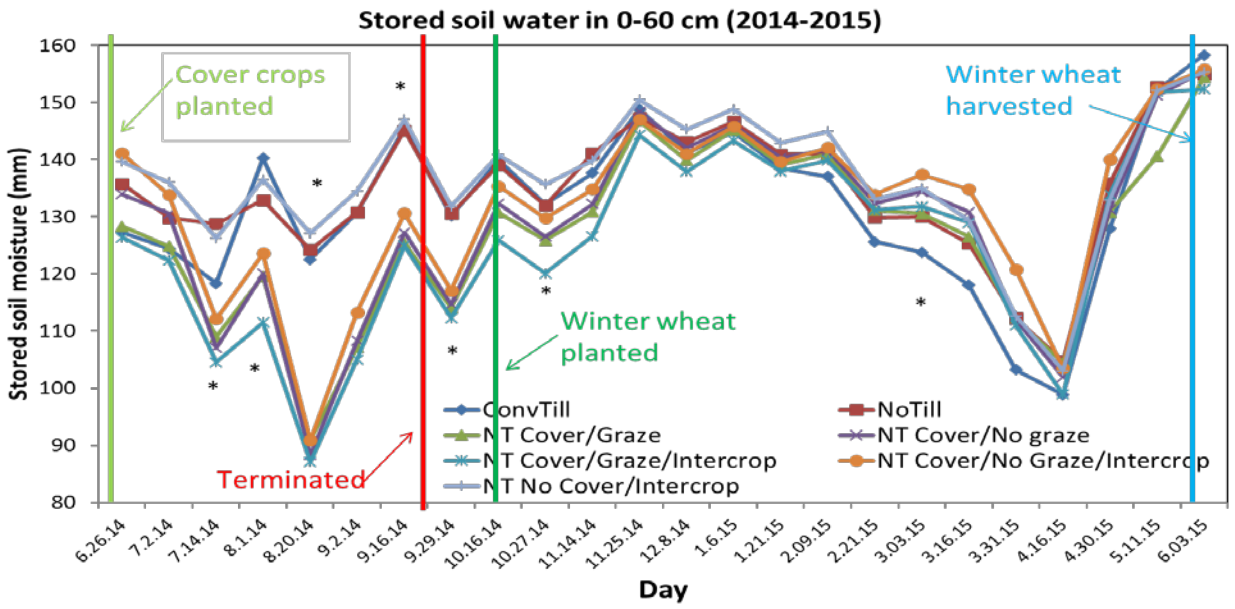

Figure 3.4: Stored soil water in the 0-60 cm depth (2014-2015). *Significant at P<0.05.

b. Stored soil moisture 60-140 cm depth (2014-2015)

Although, a substantial amount of precipitation was received during the growing season, there was no significant treatment interaction in the 60-140 cm depth compared to top 60 cm (Table 3.12 and 3.13) during the 2014/2015 growing season. It was interesting, however, that the NT cover non-grazed intercropped treatment generally had the statistically greatest soil water content during the 2014/2015 season. This possibly can partially be attributed to radishes and turnips which were planted together with the wheat. Radishes have been reported to grow into subsurface soil horizons, improving water infiltration to greater depths (Kennedy, 2012).

Table 3.12: Stored soil water (mm) at 60-140 cm depth for 2014-15 season- June to Nov., 2014.

Treatment	Date & Stored soil water (mm) for 2014-15 season-June to Nov. 2014									
	6.26.14	7.14.14	8.1.14	8.20.14	9.2.14	9.16.14	9.29.14	10.16.14	10.27.14	11.14.14
Conv. Till	141a†	141ab	143b	144ab	146ab	147ab	146ab	147ab	147b	148ab
NT.No.Cover	148a	147ab	147ab	147ab	148ab	150ab	149ab	150ab	151b	152ab
NT.No.Cover.Int	148a	148ab	146ab	146ab	146ab	148ab	145b	146ab	145b	146b
NT.Cover.Graze	154a	154ab	154ab	152ab	153ab	152ab	152ab	151ab	151b	152ab
NT.Cover.No.Graze	144a	142ab	141b	141b	142b	143b	141b	141b	140b	141b
NT.Cover.Graze. Int	140a	140b	139b	139b	139b	138b	139b	139b	139b	139b
NT.Cover.No.Graze.Int	159a	161a	162a	163a	163a	166a	165a	164a	166a	164a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Table 3.13: Stored soil water (mm) at 60-140 cm depth for 2014-15 season- Nov. 2014 to June 2015.

Treatment	Date & Stored soil water (mm) for 2014-15 season-Nov. 2014 to June 2015									
	11.25.14	2.09.15	2.21.15	3.03.15	3.16.15	3.31.15	4.16.15	4.30.15	5.11.15	6.03.15
Conv. Till	153ab†	154ab	155ab	153ab	155ab	150b	143b	142b	152ab	178a
NT.No.Cover	158ab	160ab	159ab	160ab	159ab	158b	152ab	155ab	156ab	180a
NT.No.Cover.Int	146b	147b	146b	147b	147b	148b	147ab	147b	149ab	173a
NT.Cover.Graze	153ab	157ab	156ab	157ab	157ab	156b	154ab	152ab	152ab	182a
NT.Cover.No.Graze	141b	143b	142b	143b	143b	144b	142b	145b	141b	173a
NT.Cover.Graze. Int	141b	144b	142b	144b	144b	144b	141b	144b	150ab	171a
NT.Cover.No.Graze.Int	167a	170a	169a	171a	169a	170a	165a	166a	169a	184a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

2015/2016 Growing Season

During the final season of study, cover crops were planted on June 25, 2015 and terminated on August 6, 2015, while winter wheat intercropped with turnips and radishes were seeded on November 29, 2015 and wheat harvested on June 14, 2016. Tables 3.14 and 3.15

characterize stored soil moisture in the 0-60 cm depth and tables 3.16 and 3.17 show that for the 60-140 cm depth from the July 2015 to July 2016 duration. Precipitation of about 51 mm was received in the third season just prior to seeding cover crops treatments in June 2015 and was reflected in stored soil moisture, with cover crops treatments having 5% higher stored soil moisture compared to no cover crops treatments (Table 3.14; $p<0.05$). Except for the NT grazed cover with intercrop, all other cover crop treatments resulted in significantly higher soil moisture than CT at cover crop planting. Tilling the soil seemed to impede water infiltration and water holding capacity. As anticipated, cover crops used more water with increasing growth. Similar to year 2, stored soil moisture was significantly lower for all cover crop treatments compared to non-cover crop treatments on August 18. Soil moisture deficit was highest for cover crops treatments in September 2015 at 24% less compared to no cover crops treatments (Fig. 3.5; $P<0.05$). Furthermore, NT without cover crops had significantly higher soil moisture than CT. After seeding wheat in November 2015, the research site experienced a series of rain storms that reversed moisture status, with cover crops treatments recording up to 10% higher soil water content compared to no cover crops treatments in early March 2016 (Table 3.15; $P<0.05$). The months of November and December 2015 and January, February and March 2016 received 96, 161, 18, 37 and 28 mm precipitation, respectively (Table 3.2).

a. Stored soil water 0-60 cm depth (2015-2016)

Table 3.14: Stored soil water (mm) at 0-60 cm depth for 2015-16 season- July to Nov. 2015. Cover crops planted 06.25.15 and terminated 08.06.15; wheat planted 11.29.15 and harvested 06.14.16.

Treatment	Date & Stored soil water (mm) for 2015-16 season-July to Nov. 2015								
	6.26.15	7.13.15	7.24.15	8.05.15	8.18.15	09.03.15	9.17.15	10.15.15	11.04.15
Conv. Till	125b†	137b	134b	142ab	129b	118b	121a	113b	148ab
NT.No.Cover	133ab	147a	145a	151a	140a	136a	129a	127a	153a
NT.No.Cover.Int	137ab	144ab	141ab	150a	138ab	135a	134a	133a	152a
NT.Cover.Graze	139a	146a	136ab	137b	106c	101c	100b	100c	144bc
NT.Cover.No.Graze	140a	147a	135b	139b	105c	98c	95b	95c	142bc
NT.Cover.Graze. Int	135ab	144ab	139ab	141ab	104c	97c	94b	93c	142c
NT.Cover.No.Graze.Int	139a	146a	136b	141ab	108c	100c	99b	97c	143bc

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Table 3.15: Stored soil water (mm) at 0-60 cm depth for 2015-16 season- Dec. 2015 to July 2016.

Treatment	Date & Stored soil water (mm) for 2015-16 season-Dec. 2015 to July 2016							
	12.18.15	01.29.16	02.16.16	03.01.16	03.29.16	04.15.16	05.12.16	07.13.16
Conv. Till	146a†	148b	140c	143b	121a	110a	112a	132a
NT.No.Cover	151a	153ab	148a	149ab	123a	109a	115a	121a
NT.No.Cover.Int	151a	152ab	147ab	147ab	126a	113a	113a	128a
NT.Cover.Graze	148a	151ab	148a	150a	131a	117a	117a	130a
NT.Cover.No.Graze	149a	153a	146b	149a	124a	108a	114a	129a
NT.Cover.Graze. Int	150a	153ab	146b	149a	125a	111a	114a	125a
NT.Cover.No.Graze.Int	147a	152ab	147ab	150a	129a	113a	115a	129a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

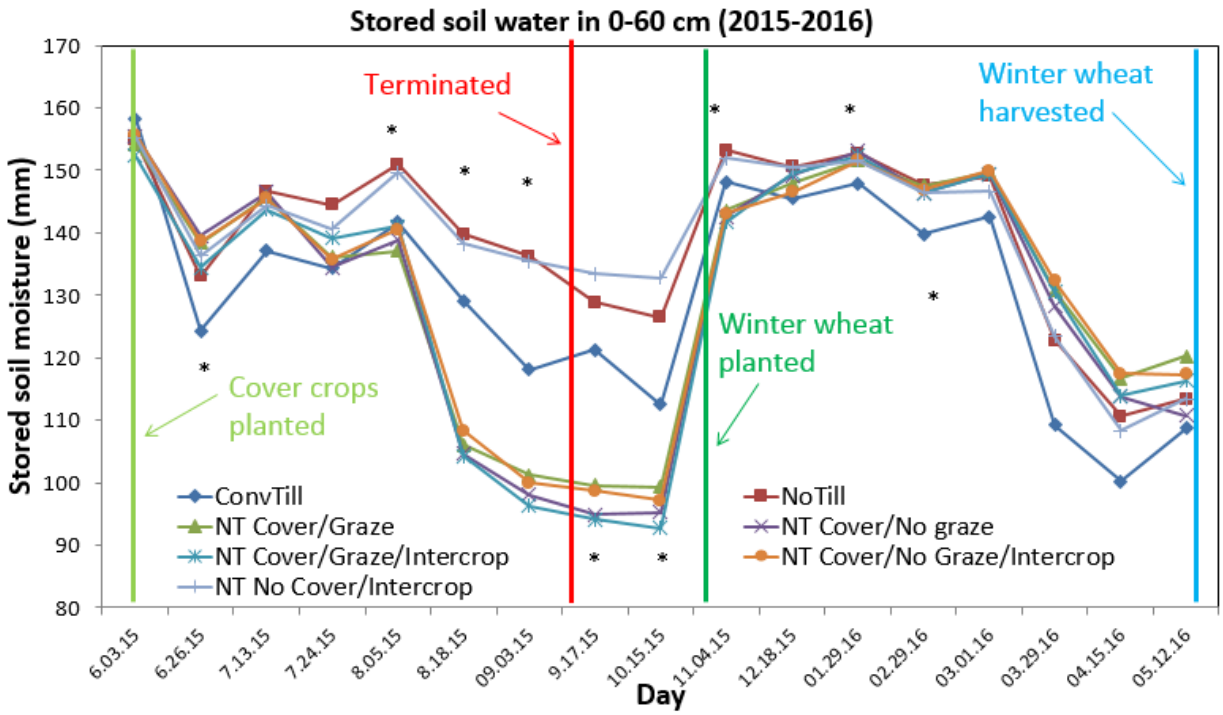

Figure 3.5: Stored soil water in 0-60 cm depth (2015-2016). *Significant at P<0.05.

The effects of tillage following the initial 12 years of no-till were beginning to be manifested after 3 years of traditional cultivation in the CT treatment. In 2016, we did not observe as much increase in stored soil moisture for the CT treatment following the substantial precipitation received compared with other treatments. Stored soil water with CT was statistically lowest compared to all other treatments with and without cover crops in February 2016 (P<0.05), likely indicating greater runoff with this treatment.

b. Stored soil water 60-140 cm depth (2015-2016)

Stored soil water at the lower depth of 60-140 cm again generally did not show treatment effects during the third growing season (Tables 3.16 and 3.17). Soil water removal during this time appeared to be mostly associated with the 0-60 cm depth, although lower values were

observed for NT cover crops non-grazed and NT cover crops grazed and intercropped treatments during September to December 2015.

Table 3.16: Stored soil water (mm) at 60-140 cm depth for 2015-16 season- June to Nov. 2015.

Treatment	Date & Stored soil water (mm) for 2015-16 season-June to Nov. 2015								
	6.26.15	7.13.15	7.24.15	8.05.15	8.18.15	09.03.15	9.17.15	10.15.15	11.04.15
Conv. Till	174a†	173a	172a	175a	174a	172ab	170ab	170ab	172ab
NT.No.Cover	172a	173a	170a	176a	173a	173ab	172ab	170ab	177a
NT.No.Cover.Int	170a	171a	169a	174a	168a	159bc	154bc	153bc	153bc
NT.Cover.Graze	177a	176a	179a	179a	173a	165abc	162abc	159abc	160abc
NT.Cover.No.Graze	171a	172a	171a	173a	167a	150c	144c	143c	144c
NT.Cover.Graze. Int	168a	169a	168a	170a	165a	154c	150c	149c	148c
NT.Cover.No.Graze.Int	180a	180a	185a	182a	180a	180a	179a	176a	177a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Table 3.17: Stored soil water (mm) at 60-140 cm depth for 2015-16 season- Dec. 2015 to July 2016.

Treatment	Date & Stored soil water (mm) for 2015-16 season-Dec. 2015 to July 2016							
	12.18.15	01.29.16	02.16.16	03.01.16	03.29.16	04.15.16	05.12.16	07.13.16
Conv. Till	175ab†	176ab	173a	173a	156b	150b	149a	163a
NT.No.Cover	179ab	178ab	178a	177a	172ab	166ab	154a	160a
NT.No.Cover.Int	162b	174ab	173a	174a	170ab	165ab	160a	162a
NT.Cover.Graze	171ab	178ab	178a	179a	179a	174a	155a	165a
NT.Cover.No.Graze	159b	170ab	170a	170a	174ab	166ab	155a	154a
NT.Cover.Graze. Int	158b	169b	168a	169a	170ab	164ab	155a	157a
NT.Cover.No.Graze.Int	189a	184a	182a	181a	174ab	168ab	164a	168a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Surface soil moisture characterization

Soil water in the surface (5 cm) at wheat seeding time showed interesting results for the 2014/15 and 2015/16 growing seasons (Table 3.18). Wheat was planted on 10.20.14 and 11.29.15 for the 2014/15 and 2015/16 growing seasons, respectively.

Table 3.18: Stored soil water (mm) at 0-5 cm depth at wheat seeding in 2014 and 2015.

Treatment	Date & Stored soil water (mm) in top 5 cm for 2014-15 and 2015/16 seasons						
	2014/2015 season				2015/2016 season		
	09.08.14	09.18.14	10.16.14		07.14.15	07.24.15	11.03.15
Conv. Till	11.0a†	9.6b	10.8b		9.0b	3.9c	11.1b
NT.No.Cover	13.1a	16.4a	12.4ab		16.7a	14.6b	20.3a
NT.No.Cover.Int	12.6a	17.7a	14.3ab		16.9a	17.2a	21.2a
NT.Cover.Graze	12.5a	20.6a	14.1ab		15.1a	14.2b	22.0a
NT.Cover.No.Graze	12.8a	17.7a	16.4a		16.0a	13.2b	20.1a
NT.Cover.Graze. Int	11.0a	15.3ab	14.0ab		15.2a	14.2b	20.4a
NT.Cover.No.Graze.Int	10.1a	18.8a	17.3a		15.2a	13.5b	20.6a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

During the 2014/15 growing season after cover crops termination, there was no significant treatment difference in stored soil water in the top 5 cm on 09.08.14. However, the least stored soil water at later dates was observed for CT compared to NT treatments (Table 3.18; $p<0.05$), even though cover crops treatments had significantly less stored soil moisture compared to no cover crops treatments in the 0-60 cm depth at the same time (Fig. 3.4; $p<0.05$). A total of about 56 mm and 100 mm of precipitation was recorded on site during the months of October 2014 and 2015, respectively. At the time of wheat seeding on 10.16.14 (2014/15 season) and 11.03.15 (2015/16 season), the CT treatment had the least stored soil moisture, especially in 2015 (Table 3.18; $p<0.05$). No-till and cover crops increased infiltration into dry soil (Felton et al. 1987), with cover crops residue likely reducing surface runoff and soil evaporation (Smith et

al. 1987). The relatively higher soil moisture under conservation practices at seeding is critical in facilitating wheat seed germination.

Soil profile moisture changes due to evapotranspiration

No till, with and without cover crops, displayed less upper soil horizon (top 20 cm) evapotranspiration rates compared to CT that was illustrated in three stages during the 2014/2015 season (Figure 3.6). In stage 1, all treatments had stored soil water of about 64 mm in the top 20 cm depth, which dropped to 54 mm and 59 mm for CT and NT cover crops treatments, respectively, in stage 2, and finally to 39 mm and 49 mm for these treatments in stage 3. This change signified a 39% decrease in stored water for CT compared to an average of 23% for the rest of the treatments ($p<0.05$). No till cover no graze with intercrops only lost 17%. Cover crops residue can insulate the soil surface, thereby lowering soil temperature and slowing soil evaporation (Phillips, 1984; Bond and Willis, 1969). Slowed evaporative loss potentially enhances transpiration, which is important for plant growth and development.

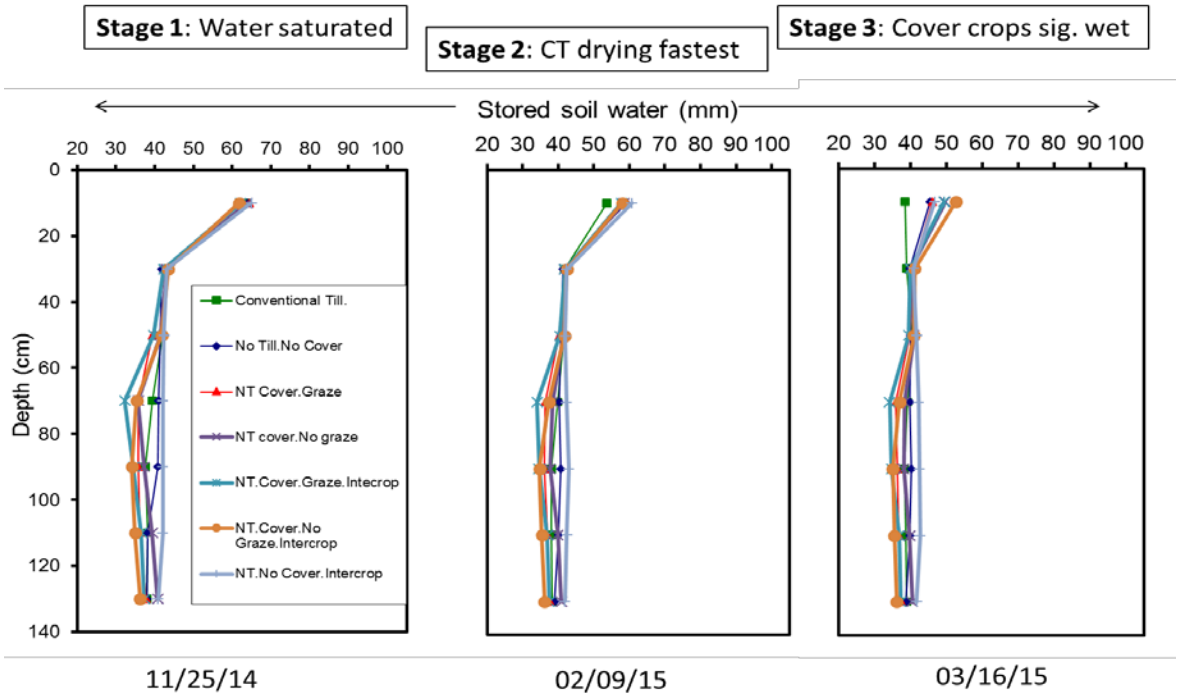

Figure 3.6: Soil profile moisture change due to evapotranspiration at 0-20 cm.

Soil profile moisture recharge during precipitation

The following is a point-in-time analysis of soil water change, especially in the top 20 cm of soil, with rainfall events that occurred during 2015 (Figure 3.7). At stage 1 in mid-April, all treatments exhibited similar soil water contents at the 0-20 cm depth. In stage 2 after a rainfall event in late June, soil water content for CT at 0-20 cm increased 11 mm, or 41% more than at stage 1 (Figure 3.7). The NT no cover treatments at stage 2 gained 20 mm, or 65 % more than at stage 1, and NT cover crops treatments increased 24 mm, or 82 % more than at stage 1. At stage 3, somewhat similar trends were observed, with stored soil moisture for CT increasing to 51 mm, while NT treatments with or without cover crops exhibited an average soil water content of 60 mm. These differences likely can be explained by decreased soil surface runoff and enhanced soil hydraulic conductivity in NT treatments (Keisling et al., 1994). The enhanced ability of

conservation practices to store more precipitation is critical in semi-arid regions where rainfall is limited.

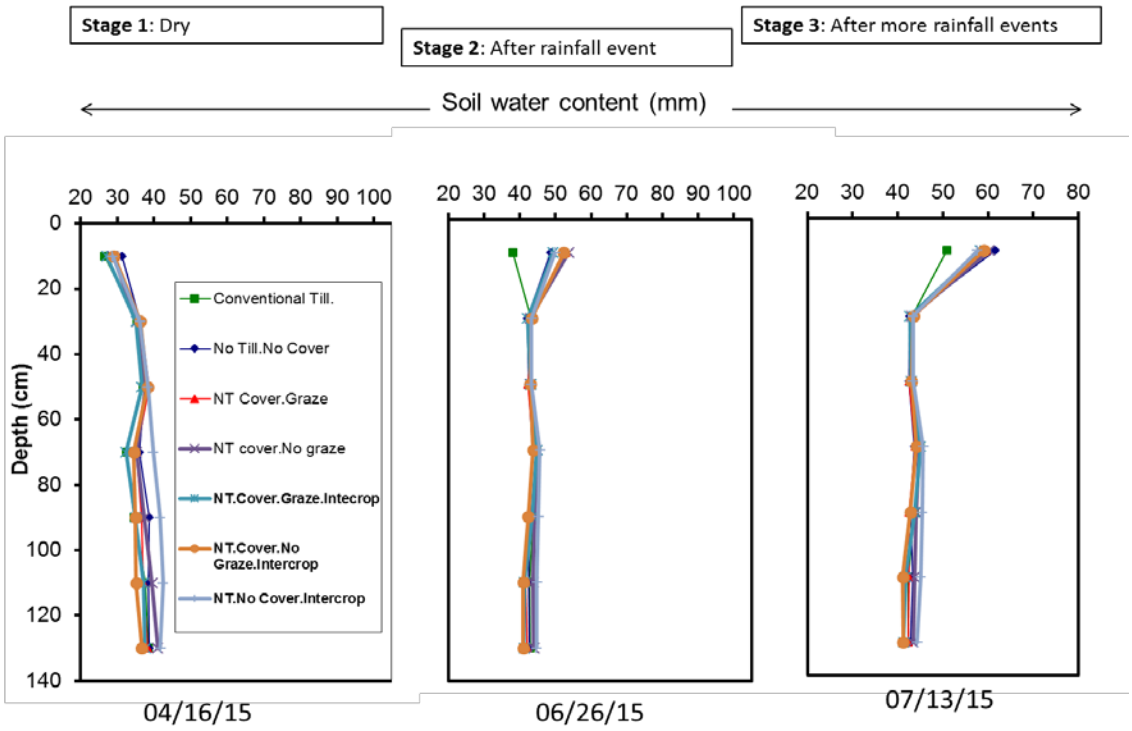

Figure 3.7: Soil profile moisture recharge with depth during precipitation events in 2015.

Wheat Yields

Wheat yields were lowest during the first study year of 2013/2014 across treatments. Although there were no significant differences in yields among treatments, no cover crops treatments, CT, NT.No.Cover and NT.No.Cover.Int, showed relatively higher yield compared to cover crops treatments though all yields were extremely low (Table 3.19) due to exceptional drought. In the following year, 2015, CT had the numerically least yield, being 21% less on average than that of all NT treatments, although the difference was not significant. However, CT

produced the highest yield in 2016, about 20% higher compared to no cover crops treatments and 40% higher compared to the average for all cover crops treatments (Table 3.19; $p<0.05$). No significant effects due to grazing or intercropping were noted.

Table 3.19: Wheat yields during the three study years of 2014 to 2016.

Treatments	Wheat Yields (kg ha^{-1})		
	2014	2015	2016
Conv. Till	151a†	1202a	2067a
NT.No.Cover	75a	1569a	1641ab
NT.No.Cover.Int	89a	1403a	1616ab
NT.Cover.Graze	18a	1398a	1210b
NT.Cover.No.Graze	27a	1606a	1342b
NT.Cover.Graze. Int	8a	1546a	1152b
NT.Cover.No.Graze.Int	55a	1622a	1215b

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Discussion

Cover Crop Performance

Although limited information is available for mixed species cover crop performance, our data were comparable to recent observations in Nebraska and Colorado where a mixture of cool- and warm-season cover crops produced variable biomass from year to year ranging from 2020 to 4790 kg dry biomass ha^{-1} (Nielsen et al., 2015), although seeding rates were much higher than used in our study (57.1 vs 28 kg ha^{-1}). Nielsen et al. (2015) also noted that cover crop mixtures can be dominated by 1-2 species, where 2 species of a 10-species mix comprised 69-92% of the total biomass over three growing seasons in Nebraska and Colorado, similar to what we observed.

The grass species in our cover crops mix, millets and sorghum, outperformed legumes. Dozier et al. (2008) reported cereal rye (*Secale cereale*) and wheat produced more biomass compared to vetch in Haskell, Texas. The grass dominated mixture gave rise to higher biomass C:N ratios. Foxtail millet was reported to have a C:N ratio of 44 (Creamer and Baldwin, 1999), and its residue was more persistent than that of soybean and buckwheat (Morse, 1995). Pearl millet has been shown to have a C:N ratio of more than 50 (Wang and Nolte, 2010). Some literature indicated that plant residues with C:N ratios ranging <20-25:1will fairly rapidly manifest net N mineralization (Tisdale and Nelson, 1975; Sarrantonio, 1994), while other literature observed N mineralization over a wider C:N range of 20-40:1, both in lab and field studies (Alexander, 1977; Franzluebbers et al., 1994 ; Iritani and Arnold, 1959 ; Justes et al., 2009; Vigil and Kissel, 1991). Microbial residue decomposition was reportedly slower where soil moisture was limiting, resulting in a higher effective N mineralization for residue with high C:N ratio (O'Connell et al., 2015). Environmental stress like limited soil moisture, decreases C use efficiency by combating microbial growth resulting is disparate rates of C and N integration (Herron et al., 2009).

Grazed cover crops added an average of up to 1400 kg total biomass ha^{-1} per year to the soil as surface residues during the study period, while non-grazed treatments averaged 3200 kg biomass ha^{-1} per year (Table 3.2). This difference approximated 560 kg C ha^{-1} and about 15 kg N ha^{-1} for grazed cover crops and 1300 kg C ha^{-1} and about 30 kg N ha^{-1} per year for non-grazed cover crops (Table 3.4). Part of the C was respired as CO_2 while a portion was sequestered into the soil. Cattle manure that was added in grazed treatments was not quantified.

Soil water

Cover crops depleted soil moisture significantly compared to fallowing during the entire period of this investigation. This result concurs with that of Nielsen at al. (2015) in the Central Great Plains where they found that cover crops mixtures or single species used more soil moisture in comparison to leaving the land fallow. Other studies in the Great Plains have reported similar results (Nielsen and Vigil, 2005; Burgess et al., 2014 and Holman et al., 2012). Although cover crops comparatively depleted soil moisture during their growth, upon termination, cover crop treatments after receiving precipitation recharged to comparable soil moisture contents of NT with no cover crops. Conversely, CT without cover crops recorded the least stored soil water content, which was particularly conspicuous in the final year of study just after seeding cover crops and during the wheat growth period (Figure 3.5). Soil tillage reduced soil aggregation and infiltration rates (Elliott et al., 1987). Surface soil sealing, and degraded soil structure and mesoporosity (soil pores with <60 µm diameter) has been reported for tilled soil (Fabrizzi et al., 2005; Elliott, 1986). Blanco-Canqui et al. (2012) also acknowledged the reduction by cover crops of available water to following crops but reiterated their capacity to increase water capture and curb runoff. In Indiana and Iowa during a severe drought in 2012, a rye cover crop reportedly increased stored soil water for the following corn crop (Daigh et al., 2014). A long-term study in China comparing CT without surface residues to NT with surface residues showed how the latter improved soil physical properties and soil water transmission in a monoculture winter wheat system (He et al., 2009).

No-till and cover crops can improve water transmission into soil and water holding capacity. Cover crops' roots potentially may improve soil structure and aggregate stability. Macropores formed in such a scenario can have a significant impact on water flux (Lin et al.,

1996). Conservation practices can increase the volume of macropores and their continuity, increasing saturated hydraulic conductivity (Lipiec and Stepniewski, 1995; Arvidsson, 1997). This was substantiated by higher infiltration rates that were recorded for NT and cover crops treatments. The cover crops roots may increase soil total porosity thus water holding capacity. The cover crops surface plant residues also provide mulch that reduces soil evaporation. A reduction in soil evaporation increases productive transpiration which enhances plant growth. The second year of cover crops showed on average 21% higher yields under NT and cover crops compared to CT.

Although grazing resulted in significant removal of cover crops biomass, no significant negative effects were observed from this practice. Intercropping with turnips and radishes did not yield any consistent significant differences upon which to draw conclusions and may partly be attributed to the deficient performance by radishes and turnips during the study period, except for the last year.

Wheat yields

Although cover crops conserved N, which will be discussed later, insufficient N (data shown in chapter 4) during this investigation negatively impacted wheat yields for NT cover crops treatments and was reflected in the yields for 2016 (Table 3.19). The no cover crops treatments, CT, NT.No.Cover and NT.No.Cover.Int, resulted in higher yields of 2067, 1641 and 1616 kg ha^{-1}, respectively compared to cover crops treatments which ranged from 1152 to 1342 kg ha^{-1} (Table 3.19; $p<0.05$). When using cover crops, N management becomes of paramount importance to avoid a soil N deficit for the following main crop due to immobilization and utilization by cover crops. No significant wheat yield differences were noted for the 2013/2014

and 2014/2015 seasons, though CT in the latter season had the least yield. Nielsen et al. (2016) noted a 10% average decrease in wheat yields after cover crops in comparison to following fallow, and the decrease was even higher when precipitation was limiting. We observed a 25% decrease in wheat yields following cover crops compared to NT following fallow and 40% lower yields when compared to CT following fallow in 2016. However, our yield results for 2015 were in contrast to the postulation of Nielsen et al. (2016). We observed a 4% increase in yields following cover crops compared to NT without cover crops following fallow, and 28% higher yield when compared to CT without cover crops following fallow. Cover crops decreased soil NO_3^-–N to wheat in the NT cover crops treatments compared to no cover crops treatments (data shown in chapter 4). Cover crops scavenged available inorganic N during their growth cycle. Upon termination, cover crops residues on the soil surface immobilized soil inorganic-N because of their high C:N ratio. The continued use of cover crops resulted in accumulation over time of plant residues with C:N ratios of up to 48, effectively immobilizing soil inorganic-N and reducing N available for uptake by wheat. This decreased N availability was partially reflected in wheat grain yields, with all cover crops treatments recording lower yields in the final year of the study 2015/2016 (Table 3.18; $p<0.05$). Some authors recommend applying higher rates of N fertilizer when using cover crops to offset possible N immobilization by cover crop residues (Bakermans and deWit, 1970; Bandel, 1979; Bandel et al., 1975). Thomsen and Christensen (1998) observed reduced barley yield and N uptake due a prolonged immobilization of N. Franzluebbers et al. (1995) reported a short-lived soil N reduction due to immobilization following addition of high C:N ratio fresh crop residues in sorghum production. In our study, the grasses that were included in the cover crop mixes tended to outperform legumes due to erratic and unreliable rainfall. Forage sorghum and foxtail and pearl millets, which produced high C:N

ratio biomass, did well compared to mung bean, guar and cowpeas at the time of termination, resulting in higher lignin- and cellulose-containing residues. Residues with high C:N ratios immobilize soil N and have been reported to have slower N release rates (Pink et al., 1945, 1948; Muller et al., 1988; Bowen et al., 1993; Quemada and Cabrera, 1995). Under more favorable growing conditions, legumes in the cover crops mixes might have counteracted the N deficiency that was witnessed. Balkcom and Reeves (2005) reported an average corn (*Zea mays* L.) yield of 6.9 Mg ha^{-1} following sunn-hemp (*Crotalaria juncea* cv), a legume, compared to 5.7 Mg ha^{-1} following winter fallow. Cover crops mix composition becomes of paramount importance in that including enough legumes in the mix and having sufficient growth is critical in maintaining sustainable net N mineralization to avert yield losses due to N deficiency.

Conclusion

Cover crops grown during the fallow period in continuous wheat systems produced biomass throughout the study period, even during the drought period, although some species in the mix failed every season. The biomass cycled N and C and other nutrients in the soil system and provided mulch. Cover crops however, depleted soil moisture during their growth period and negatively affected subsequent crop yields, through N deficiency due to nitrogen immobilization. Moisture depletion remains a deterrent to cover crop technology adoption, especially in semi-arid and drier regions. However, NT with or without a cover crop re-charged soil moisture to comparable contents regardless of treatment. Cover crops and NT helped improve soil physical properties, ultimately increasing water infiltration, transmission and holding capacity that was observed. Tillage (CT) showed adverse effects on soil physical properties and subsequent water infiltration and holding capacity compared to all NT treatments. Ultimately, NT with cover

crops, if strategically adopted, may have the potential to improve and sustain continuous wheat production systems common in the Southern Great Plains. Strategic planning considering times of planting and termination of cover crops, closely following short- and long-term rainfall forecasts, and possibly increasing N fertilization of wheat following covers, will all be keys to success.

CHAPTER IV

SOIL CYCLING OF N, P, K AND C IN CONTINUOUS WHEAT AS IMPACTED BY COVER CROPS, INTERCROPPING AND NO TILLAGE

Summary

Continuous cultivated winter wheat is a customary practice in the Southern Great Plains, although it poses potential hazards to soil ecosystem services and function. An increased understanding of nutrient dynamics associated with cover crop implementation is needed to maximize potential benefits and reduce risk. The objective of this study was to determine soil nutrient cycling in dryland wheat cropping systems as impacted by cover crops, grazing, intercropping, and tillage. The study was conducted at the Texas A&M AgriLife Research Smith Walker Ranch near Vernon, Texas for a period of 3 years. The soil type is Rotan clay loam (Fine, mixed, superactive, thermic Pachic Paleustolls). The investigation used a randomized complete block design with seven treatments replicated four times. Treatments were (1) conventional till (CT) without a cover crop; (2) no-till (NT) without a cover crop; (3) NT with intercropping; (4) NT with a cover crop; (5) NT with a grazed cover crop; (6) NT with a cover crop plus intercropping; and (7) NT with a grazed cover crop plus intercropping. Spring soil profile NO_3^-–N did not show any treatment differences for the first two growing seasons but did in the third season (2015/16), with CT recording highest KCl-extractable NO_3^-–N. The same trends were observed for Haney NO_3^-–N results. However, Haney organic N, C and available-N were lowest in the CT treatment. Standard soil test methods did not show any differences due to treatment for P, K and S for the duration of the study.

No-till cover crop treatments did not sequester additional soil C during the period of this investigation. Observed increases in soil organic C (SOC) were short-lived. No-till cover crops

treatments over time gradually increased Haney soil water extractable organic C (WEOC) compared to CT. No-till with cover crops has the potential to improve soil quality in continuous wheat systems in semi-arid regions of the Southern Great Plains.

Introduction and Literature Review

Cover crops can conserve soil N through converting mobile soil NO_3^-–N that is prone to leaching or denitrification into immobile plant proteins and other biomolecules, which may improve N recovery in cropping systems. In a 10-year classic study in Connecticut, Morgan et al. (1942) used lysimeters in a sandy loam soil to measure N leaching in continuous tobacco (*Nicotiana tabacum* L.) fertilized with 200 kg N ha^{-1} yr^{-1} from a combination of organic-N and inorganic fertilizer sources. Oats (*Avena sativa*.), rye (*Secale cereale*) and timothy grass (*Phleum pretense* L.) were planted as a cover crop within 10 days of harvesting tobacco each August. Rye cover cropping resulted in a 66% reduction in N leached compared to the no cover control. In comparison, N leaching was reduced by 57% with oats and 31% by timothy compared to the no cover control. The resultant N that was conserved increased soil organic matter by an average 0.33% in the top 15 cm of soil.

A two-year study by Shipley et al. (1992) in Maryland's Coastal Plain showed soil N conservation using rye, annual ryegrass (*Lolium multiflorum* L.), crimson clover (*Trifolium incarnatum* L.), and hairy vetch (*Vicia villosa*) cover crops. Labeled fertilizer ^{15}N at 300 kg N ha^{-1} was added to corn (*Zea mays* L.) to provide a pool of labeled residual N. Rye recovered 60% of the residual corn fertilizer N, while recovery by annual ryegrass was 40%, and hairy vetch and crimson clover each recovered less than 10%. The greater efficiency of grass cover crops was credited to their winter hardiness and deeper fall root growth. Therefore, grasses may be superior

to legumes in conserving residual soil N. Dabney et al. (2001) reported that the average reduction in soil NO_3^-–N leaching was directly related to species of cover crop, with grass or brassica species resulting in a 70% reduction and legumes about a 23% reduction. It is worth noting that in semi-arid regions, where precipitation is normally much lower than potential evapotranspiration under dryland agriculture, NO_3^-–N leaching may not be as great an issue (Westfall et al., 1996). However, Chaudhuri et al. (2012) suggested a negative impact of agriculture on NO_3^-–N groundwater concentrations in the Texas Rolling Plains, particularly under irrigated agriculture.

Cover crops significantly reduced NO_3^-–N leaching while at the same time mining NO_3^-–N from groundwater in Colorado (Delgado, 1998). A regional analysis using GIS 4.2 was used to generate NO_3^-–N leaching potentials across south central Colorado (Delgado, 1998). The analyses showed average NO_3^-–N leaching above 70 kg NO_3^-–N ha^{-1} across the region with no cover crops. The use of winter cover crops reduced leaching loss by 45 kg NO_3^-–N ha^{-1}. When summer cover crops were used, the average NO_3^-–N leaching losses dropped below 30 kg NO_3^-–N ha^{-1}.

While legume cover crops may not be as efficient at conserving soil N as grass cover crops, legume cover crops can directly add N to a cropping system, especially where fertilizer is scarce or expensive. Legumes have been documented to supply N to subsequent grass crops through symbiotic N_2 fixation (Clark et al., 1997). Research has shown that hairy vetch can supply 50-155 kg N ha^{-1} to a following corn crop (Holderbaum et al., 1990; Ranells and Wagger, 1996; Seo et al., 2000). Seo et al. (2006) showed legume crops resulted in greater soil N conservation compared to conventional N fertilizers. Post-harvest soil contained 38% labeled ^{15}N from hairy vetch residues compared to only 15% from applied fertilizer. However, other studies

reported fertilizer N being about two times as effective as legume residues in supplying N to a crop, while legume residues contributed two times as much N to the soil (Ladd and Amato, 1986; Harris et al., 1994; Janzen et al., 1990). These results may demonstrate how a combination of inorganic and organic nutrient planning may be exploited in developing more sustainable systems.

Nitrogen availability after cover crops is related to and controlled by the residue quantity, chemical composition and quality. Mature small grain residue immobilizes soil mineral N during decomposition because of its wide C:N ratio. Cotton [*Gossypium hirsutum* (L.)] planted in Alabama after a rye cover crop needed an additional 34 kg N ha^{-1} to achieve the same yields as cotton in a no cover crop system because of N immobilization (Brown et al., 1985). In another related study in Alabama, ^{15}N methodology showed that N immobilization in a rye-corn conservation tillage system reduced corn yield by 0.3 Mg ha^{-1} in 1990 when low cover crop biomass was produced and 3.5 Mg ha^{-1} the year that greater rye biomass was produced.

Cover crops left as surface residue also activate soil P cycling through plant uptake and subsequent decomposition. Nachimuthu et al. (2009) and Alamgir et al. (2012) estimated that P mineralization occurred at a carbon to phosphorus ratio (C:P) below 200:1 when the P residue concentration was greater than 0.24%, otherwise P immobilization would ensue. Horst et al. (2001) noted that where soil P was limiting, cover crops improved cycling by enhancing and concentrating P through uptake and decomposition. Exudation of organic acids by cover crops also was reported to acidify the rhizosphere, thereby releasing calcium-, aluminum- and iron-complexed P (Kamh et al., 1999). Eichler-Loebermann et al. (2008) reported greater P uptake by cereal crops after cover crops. Use of cover crops may mitigate potential loss of excess P through runoff more so after soil has reached the P saturation point (Pautler and Sims, 2000).

Winter cover crops produced above ground dry matter ranging 3 to 5 Mg ha^{-1} per year (Seo et al., 2000; Clark et al., 1995) with a potential of increasing soil C by 0.1 to 0.3 Mg C ha^{-1} per year (Dabney et al., 2010; Lal, 1999). Most plant residue C will be respired as CO_2 by soil microbes, but a significant portion may be sequestered into more recalcitrant SOC, particularly under reduced tillage management systems. Cover crops, crop rotations and no-tillage practices often increase soil microbial biomass and may also result in a more fungus-dominated soil community structure, increasing microbial-derived soil organic matter.

A recent study to evaluate effects on soil properties of replacing fallow with cover crops in semi-arid regions showed how single species cover crops improved soil aggregation, increased the SOC pool and reduced runoff loss of soil NO_3^-–N and total P (Blanco-Canqui et al., 2013). The intensified cropping system also reduced possible wind and water erosion. The benefits from cover crops residues were short-term, however, in the semi-arid climate. Only limited information is available concerning soil biogeochemical processes as impacted by multi-species cover crops in a semi-arid climate. This study was therefore initiated to determine nutrient cycling of soil N, P, K, C, and S in continuous wheat production systems as impacted by cover crops, intercropping and NT practices. Cover crops technology is hypothesized to increase soil N, P, K, C, and S cycling.

Materials and Methods

This study utilized a randomized complete block design, 4 replications, and 7 treatments utilizing a 2025 m^2 plot (replicate) size (Figure 2.2). The main crop was winter wheat which was intercropped with turnips and radishes. Winter wheat, turnips and radishes were all mixed and planted at rates of 65 kg ha^{-1}, 0.56 kg ha^{-1}, and 1.68 kg ha^{-1}, respectively, at a row spacing of 19 cm in 2014 and 25 cm in 2014 and 2015 (Table 2.2). The treatments were (1) conventional till

wheat without a cover crop (CT); (2) no-till wheat without a cover crop (NT.No.Cover); (3) no-till wheat with a grazed summer cover crop (NT.Cover.Graze); (4) no-till wheat with a terminated summer cover crop (NT.Cover.No.Graze); (5) no-till wheat intercropped with turnip/radish with grazed summer cover crop (NT.Cover.Graze.Int); (6) no-till wheat intercropped with turnip/radish with terminated summer cover crop (NT.Cover.No.Graze.Int); and (7) no-till wheat intercropped with turnip/radish without summer cover crop (NT.No.Cover.Int).

Soil cores were taken twice annually throughout the study after cover crop termination in the fall and after winter wheat harvest in the spring to a depth of 60 cm from each treatment using a tractor mounted hydraulic Giddings Machine (Giddings Machine Company, Inc., Windsor, Colorado, USA) with a 5-cm diameter soil probe. Samples were initially segmented into two depth increments in the first year: 0–15 and 15–60 cm, then 0–15, 15–30 and 30–60 cm in the 2nd year and later into four depth increments: 0–5, 5–15, 15–30, and 30–60 cm the 3rd year to capture more detail in analyses. Two soil cores from the same plot and depth at each sampling were composited, dried for 24 hours in a forced draft oven at 60°C, screened through a 2-mm sieve and analyzed using standard methods for pH (1:2 soil:water), conductivity (1:2 soil:water), NO_3^-, NH_4^+, P, K, S, total C, and total N. Phosphorus, K, and S soil analyses were conducted using Inductively coupled plasma (ICP) (Varian Vista-MPX axial flow ICP, Varian Inc., Palo Alto, California, USA) after extracting with Mehlich solution as described by Mehlich (1984). Inorganic N, NO_3^-–N and NH_4^+–N, was determined by extracting 2 grams of soil with 1 N KCl at 10:1 extractant to soil ratio using colorimetric methods after filtering through Whatman number 42 filter paper. Nitrate was analyzed following Cd reduction as summarized by Keeney & Nelson (1982), while NH_4^+–N was determined as described by Dorich & Nelson (1983). A

Skalar San-plus Analyzer (Skalar Analytical B.V., North Brabant, Netherlands) was used for NO_3^-–N and NH_4^+–N analysis. Soil total N, total C and organic C were analyzed using a Macro Elementar analyzer (Vario Max CN, Elementar Analysensysteme GmbH, Langenselbold, Germany) as described by McGeehan and Naylor (1988) after drying and grinding.

Four soil subsamples were randomly taken to a depth of 0-15 cm in each plot at each sampling using the Giddings Machine as outlined above and composited for the Haney Soil Health Assessment, also called the Soil Health Tool (Haney et al., 2006). Soil samples were air dried and shipped to the USDA-ARS laboratory in Temple, TX for analysis. The soil samples were oven dried at 50°C for 24 hours and ground to pass a 2-mm sieve. Soil samples were then extracted with water and the H^3A extractant using 4 g samples at a dilution factor of 10:1, one-part soil and 10 parts extractant. The samples were shaken for 10 minutes using a reciprocal shaker and centrifuged for 5 minutes before filtering them through Whatman 2V filter paper. The H^3A extracts were analyzed colorimetrically for NO_3^-–N, NH_4^+–N and P on a segmented flow analyzer (Haney et al., 2006). Water extracts were analyzed for water-extractable organic C (WEOC) and N (WEON) on an Elementar TOC Select Analyzer (Vario TOC Cube, Elementar Analysensysteme GmbH, Langenselbold, Germany), while H^3A extracts were additionally analyzed for Al, Fe, Ca and K on an Agilent MP-4200 Microwave Plasma Instrument (Agilent Technologies Inc., Santa Clara, California, USA) as described by Haney et al. (2006).

The Soil Health Tool provides a calculation for total plant available N, NO_3^-–N, and additional N. Beginning in spring 2014, only 70% of measured NO_3^-–N was credited and reported due to leaching and denitrification potential according to the Soil Health Tool. Available N was defined as the sum of water extractable NH_4^+–N plus microbial released N based on microbial activity and organic C:organic N ratio. Total plant available N was calculated

as the sum of 70% of measured NO_3^-–N and additional N. Soil Health Tool additional–N is the water extractable soil NH_4^+–N plus biological N component in the soil due to microbial degradation (Solvita 1-day CO_2–C). Phosphorus was reported as H^3A extractable ortho-phosphate and organic P was determined based on C:P ratio. Potassium was reported as H^3A extractable K.

Statistical Analysis

The collected data were analyzed by ANOVA using the general linear model procedure (SAS Institute, 2008) at $P<0.05$. Mean separations were accomplished using Fisher's protected least significant difference (LSD), also at $P<0.05$.

Results

Soil Nitrogen

a. KCl Extractable Nitrate and Ammonium

i. 2013/2014 Season

The first-year soil analysis following cover crops showed cover crop treatments with significantly lower KCl-extractable soil NO_3^-–N compared to no cover crop treatments at both 0-15 cm and 15-60 cm depths ($p<0.05$) in fall 2013 (Table 4.1). Within the top 15 cm, non-cover crop treatments ranged from 7.6 to 10.8 mg NO_3^-–N kg^{-1} while all cover crops treatments had concentrations below 0.48 mg NO_3^-–N kg^{-1}. A "mining" effect was also noted for the significantly lower NO_3^-–N levels for cover crop treatments in the profile to a depth of 60 cm after cover crop termination. Samples taken following winter wheat showed comparable soil NO_3^-–N values among treatments, with the exception of CT and NT.Cover.No.Graze.Int, where CT soil NO_3^-–N was significantly higher in the upper 15 cm (Table 4.1).

Traditional KCl-extractable soil NH_4^+–N was only minimally affected by treatment for both post cover crops and post wheat sampling in 2013/2014 (Table 4.1). Surface soils (0–15 cm) generally showed higher NH_4^+–N compared to subsurface soils. Although some differences were identified mainly in the subsurface soil horizons, no conclusions could be derived due to inconsistences in the patterns. Potassium chloride extracted NH_4^+–N following winter wheat was generally higher compared to the post cover crops period. Differences that were observed could not be formulated into meaningful conclusions and were attributed to random variation.

Table 4.1: Soil NO_3^-–N and NH_4^+–N by depth, Fall 2013 and Spring 2014.

Soil NO_3^-–N (mg kg^{-1})	**2013 Fall**		**2014 Spring**		
Treatment	0-15 cm	15-60 cm	0-15 cm	15-30 cm	30-60 cm
Conv. Till	9.5a†	3.1a	10.9a	1.7a	0.4a
NT.No.Cover	10.8a	2.6ab	5.9ab	1.3a	0.6a
NT.No.Cover.Int	7.6b	2.0b	6.5ab	1.0a	0.7a
NT.Cover.Graze	0.34c	0.62c	9.5ab	1.3a	0.3a
NT.Cover.No.Graze	0.48c	0.43c	4.3ab	0.7a	0.3a
NT.Cover.Graze. Int	0.29c	0.23c	2.9b	0.8a	0.5a
NT.Cover.No.Graze.Int	0.38c	0.57c	7.4ab	2.0a	0.3a
Soil NH_4^+–N (mg kg^{-1})					
Conv. Till	7.0ab†	4.1a	16.8a†	12.3ab	10.0ab
NT.No.Cover	6.4b	4.4a	14.0a	12.3ab	13.7a
NT.No.Cover.Int	5.8b	5.1a	12.8a	9.9b	9.3b
NT.Cover.Graze	10.7a	3.5a	15.6a	10.9ab	10.9ab
NT.Cover.No.Graze	6.2b	4.0a	21.1a	12.6ab	13.3a
NT.Cover.Graze. Int	5.5b	4.1a	18.1a	15.0a	11.7ab
NT.Cover.No.Graze.Int	5.4b	3.9a	15.4a	12.2ab	10.2ab

† Means within a column and N form followed by the same letter are not different by Fisher's protected LSD (0.05).

ii. 2014/2015 Season

In the second year of study, post cover crop KCl-extracted soil NO_3^-–N did not show distinct differences between treatments with or without cover crops (Table 4.2). In addition,

cover crop biomass production was higher in the second year than other years (Table 3.3). Thus, plant N uptake would be expected to be higher, resulting in decreased soil NO_3^-–N concentrations. The post wheat period in spring 2015 as in the first year resulted in similar soil NO_3^-–N contents in the soil profile for all treatments. Soil NH_4^+–N from fall 2014 samples did not differ among treatments for the upper 15 cm of the soil profile (Table 4.2). However, NH_4^+–N was significantly lower for cover crop treatments compared to non-cover crop treatments at the 30-60 cm depth following cover crop termination. This effect was not observed after wheat harvest. Soil NH_4^+–N concentrations were considerably greater in the second year of study possibly due to ammonification during mineralization.

Table 4.2: Soil NO_3^-–N and NH_4^+–N by depth, Fall 2014 and Spring 2015.

Soil NO_3^-–N (mg kg^{-1})	Fall 2014 soil NO_3^-–N (mg kg^{-1}) by depth (cm)				Spring 2015 soil NO_3^-–N (mg kg^{-1}) by depth (cm)			
Treatments	0-15	15-30	30-60		0-5	5-15	15-30	30-60
Conv. Till	13.5ab†	6.3a	4.0a		8.6a	7.2a	5.8a	7.8a
NT.No.Cover	10.0ab	3.8ab	2.5ab		8.0a	6.0ab	6.2a	5.1b
NT.No.Cover.Int	10.8ab	4.3ab	2.0ab		6.5a	5.7b	6.5a	5.8b
NT.Cover.Graze	13.3ab	3.8ab	0.3ab		6.8a	7.2a	6.0a	5.1b
NT.Cover.No.Graze	3.5b	3.0ab	0.3ab		6.5a	6.2ab	5.6a	6.7ab
NT.Cover.Graze. Int	5.0b	5.0ab	0.3b		7.6a	6.1ab	5.4a	6.6ab
NT.Cover.No.Graze.Int	18.8a	6.0a	4.3a		8.9a	6.6ab	6.7a	5.2b
Soil NH_4^+–N (mg kg^{-1})								
Conv. Till	22.5a	23.7a	15.8a		20.2b	17.3bc	20.0b	18.6a
NT.No.Cover	13.4a	15.5b	15.4a		36.9a	17.7bc	22.5ab	21.2a
NT.No.Cover.Int	20.7a	23.5a	20.2a		19.7b	15.0c	17.6b	14.4a
NT.Cover.Graze	17.4a	13.1b	8.0b		19.1b	19.2abc	19.5ab	16.9a
NT.Cover.No.Graze	16.3a	11.5b	8.9b		20.4b	19.5abc	20.1ab	20.7a
NT.Cover.Graze. Int	14.9a	10.7b	7.6b		23.3ab	23.3ab	21.2ab	18.4a
NT.Cover.No.Graze.Int	21.1a	13.5b	8.0b		22.2ab	26.6a	27.3a	22.6a

† Means within a column and N form followed by the same letter are not different by Fisher's protected LSD (0.05).

iii. 2015/2016 Season

In the final year of study, post cover crop KCl-extracted soil NO_3^-–N was significantly lower in cover crop treatments for each depth increment above 30 cm compared to CT and NT without a cover crop ($p<0.05$; Table 4.3). Conventional till had significantly higher NO_3^-–N throughout the soil profile compared to all other treatments at this time ($p<0.05$; Table 4.3). Soil NO_3^-–N was at least 1.7 times higher for CT compared to both NT without cover crop treatments and was much greater than all cover crops treatments. Soil NO_3^-–N remained significantly higher throughout the soil profile for CT post wheat harvest compared to all other treatments, although concentrations were much lower than the post cover crop period. There were no significant differences in NO_3^-–N among NT treatments post winter wheat.

Table 4.3: Soil NO_3^-–N and NH_4-N by depth, Fall 2015 and Spring 2016.

Treatments	Fall 2015 soil NO_3^-–N (mg kg^{-1}) by depth (cm)				Spring 2016 soil NO_3^-–N (mg kg^{-1}) by depth (cm)			
	0-5	5-15	15-30	30-60	0-5	5-15	15-30	30-60
Conv. Till	24.3a†	23.5a	8.8a	3.3a	5.4a	3.0a	2.2a	2.2a
NT.No.Cover	14.5b	8.8b	4.8b	1.0c	3.5b	0.8b	0.4b	0.4b
NT.No.Cover.Int	9.5bc	6.8bc	3.3b	1.5b	3.9b	0.9b	0.3b	0.3b
NT.Cover.Graze	3.0c	2.0cd	0.8c	0.8bc	3.3b	0.8b	0.6b	0.5b
NT.Cover.No.Graze	5.0c	1.5cd	0.3c	0.3c	3.8b	1.0b	0.3b	0.3b
NT.Cover.Graze. Int	5.0c	1.8cd	0.8c	1.0bc	2.9b	1.2b	0.7b	0.4b
NT.Cover.No.Graze.Int	3.3c	1.0d	0.5c	0.8bc	2.8b	1.3b	0.7b	0.6b
Soil NH_4^+–N (mg kg^{-1})								
Conv. Till	11.2a	6.3a	5.8ab	1.4b	5.7ab	5.3ab	4.3a	6.4a
NT.No.Cover	9.7a	5.1a	4.7bc	3.0ab	6.6ab	3.5ab	2.9a	3.5b
NT.No.Cover.Int	11.5a	4.8a	8.0a	3.3ab	2.9b	3.6ab	5.0a	3.8b
NT.Cover.Graze	14.6a	8.0a	3.1bc	2.1ab	9.5a	3.3ab	5.6a	2.7b
NT.Cover.No.Graze	14.2a	3.9a	2.7c	3.4ab	4.1ab	5.9a	7.5a	9.8a
NT.Cover.Graze. Int	12.3a	8.6a	4.3bc	5.1a	4.3ab	2.2b	3.1a	1.9b
NT.Cover.No.Graze.Int	12.9a	5.5a	3.1bc	4.6ab	8.9a	4.6ab	3.2a	3.9b

† Means within a column and N form followed by the same letter are not different by Fisher's protected LSD (0.05).

Ammonium-N was relatively comparable among treatments throughout the season though Fall 2015 recorded comparatively higher NH_4^+–N than spring 2016.

b. Soil Health Test (SHT) Nitrate

Results for the Haney test soil NO_3^-–N in 0-15 cm samples followed similar trends as above, with treatments without cover crops having the highest soil NO_3^-–N compared to cover crop treatments for the Fall study periods of 2013-2015 (Table 4.4). Soil Health Tool NO_3^-–N in no cover treatments was more than 10 times higher compared to cover treatments in Fall 2013, declining to at least 3 times higher in Fall 2015. In Fall 2015, no cover crops treatments exhibited significantly higher SHT NO_3^-–N compared with all cover crops treatments ($p<0.05$) (Table 4.4). No differences were observed in SHT NO_3^-–N among cover crops treatments, with CT having the highest concentration. Total SHT N followed similar trends.

Table 4.4: Fall Haney soil test results (0-15 cm) for NO_3^-–N, Additional-N (Add-N) and Total Available Nitrogen (water extractable) (TN) (mg kg^{-1}).

Treatment	Fall 2013			Fall 2014			Fall 2015		
	NO_3^-–N	Add-N	TN	NO_3^-–N	Add-N	TN	NO_3^-–N	Add-N	TN
Conv. Till	13.2a†	3.6c	16.8a	18.5a	13.7ab	32.2a	21.5a	7.2b	28.7a
NT.No.Cover	14.0a	5.9abc	20.0a	12.7b	20.9a	33.2a	10.9b	12.4ab	23.3b
NT.No.Cover.Int	12.4a	5.7abc	18.1a	10.0bc	8.7b	18.7b	9.1b	9.7ab	18.8bc
NT.Cover.Graze	0.8b	5.7ab	6.5b	4.0d	14.5ab	18.5b	3.3c	10.3ab	13.6c
NT.Cover.No.Graze	1.1b	9.6a	10.7b	3.6d	13.3ab	17.0b	3.0c	11.3ab	14.2c
NT.Cover.Graze. Int	0.6b	5.2abc	5.8b	5.2cd	13.3ab	18.5b	3.2c	14.0a	17.2c
NT.Cover.No.Graze.Int	0.9b	8.4ab	9.3b	3.7d	14.8ab	18.5b	2.3c	11.6ab	14.0c

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Post winter wheat SHT NO_3^-–N results showed no significant treatment differences for Spring 2014 and Spring 2015, and only minor differences in Spring 2016 (Table 4.5). Soil Health Tool TN was not different for any treatment after wheat harvest in all years.

Table 4.5: Spring Haney soil test results (0-15 cm) for NO_3^-–N, Additional-N (Add-N) and Total Available Nitrogen (TN) (mg kg^{-1}).

Treatment	Spring 2014			Spring 2015			Spring 2016		
	NO_3^-–N	Add-N	TN	NO_3^-–N	Add-N	TN	NO_3^-–N	Add-N	TN
Conv. Till	9.7a†	4.4a	14.1a	11.6a	2.7b	14.3a	5.9a	11.9b	17.8a
NT.No.Cover	4.4a	6.0a	10.4a	6.7a	7.2a	13.9a	3.2b	17.4a	20.6a
NT.No.Cover.Int	4.2a	6.2a	10.4a	10.1a	5.5ab	15.6a	3.3ab	15.9ab	19.2a
NT.Cover.Graze	5.5a	5.9a	11.4a	7.7a	4.5ab	12.2a	3.9ab	16.3a	20.4a
NT.Cover.No.Graze	4.0a	6.3a	10.3a	5.7a	4.1b	9.8a	2.8ab	17.3a	21.3a
NT.Cover.Graze. Int	2.3a	6.6a	9.0a	6.9a	5.4ab	12.3a	2.8b	16.3a	19.1a
NT.Cover.No.Graze.Int	9.8a	8.6a	18.4a	10.1a	5.1ab	15.9a	3.4ab	16.0ab	19.4a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

c. Soil Health Tool Additional-N

Soil Health Tool additional–N is the water extractable soil NH_4^+–N plus biological N component in the soil though microbial activity (Solvita 1-day CO_2-C). Additional N (Add-N) was usually lowest in the CT treatment in all post cover crops and post winter wheat samplings (Tables 4.4 and 4.5). The NT.Cover No.Graze Int. treatment showed the highest Add–N of about 10 mg kg^{-1} in Fall 2013, and in Fall 2015 NT.Cover.Graze. Int was highest with 14 mg Add–N kg^{-1}. The post cover crops sampling in Fall 2014 showed no differences among all treatments for soil Add–N.

Post winter wheat water extractable soil Add–N was lowest in CT with 2.7 and 11.9 mg kg^{-1} in Spring 2015 and Spring 2016 compared to NT.No.Cover, NT.Cover.Graze,

NT.Cover.No.Graze, and NT.Cover.Graze.Int (Table 4.5). No significant treatment differences in post wheat Spring 2014 soil Add–N were detected.

Soil Carbon

Soil organic C analysis showed minimal treatment effects following cover crops (Table 4.6) or following wheat (Table 4.7) during this investigation.

Table 4.6: Soil organic (g kg^{-1}) with depth following summer cover crops.

Treatments	Soil organic carbon (g kg^{-1})							
	Fall 2013			**Fall 2014**			**Fall 2015**	
Depth	**0-15**	**15-60**		**0-15**	**15-60**		**0-15**	**15-60**
Conv. Till	8.2a†	6.1a		6.5a	4.7a		8.1a	6.4a
NT.No.Cover	8.2a	5.0ab		5.9a	4.8a		8.4a	5.6a
NT.No.Cover.Int	8.5a	4.8ab		6.5a	4.7a		7.8a	5.4a
NT.Cover.Graze	8.4a	4.9ab		6.5a	5.5a		9.3a	5.9a
NT.Cover.No.Graze	9.6a	5.1ab		6.8a	4.8a		8.8a	5.9a
NT.Cover.Graze. Int	9.7a	5.2ab		6.7a	4.9a		9.4a	6.2a
NT.Cover.No.Graze.Int	10.2a	4.4b		6.5a	4.8a		8.1a	5.2a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

The NT.Cover.Graze treatment showed the highest SOC of 12.2 g kg^{-1} at 0-15 cm in the final spring of the study in 2016 compared to rest of the treatments, but no differences among the other treatments were noted ($p<0.05$; Table 4.7).

Table 4.7: Soil organic carbon (g kg^{-1}) with depth following winter wheat.

Treatments	Soil organic Carbon (g kg^{-1})							
	Spring 2014			**Spring 2015**			**Spring 2016**	
Depth(cm):	**0-15**	**15-60**		**0-15**	**15-60**		**0-15**	**15-60**
Conv. Till	7.2abc	5.5a†		6.5ab	5.5a		8.4b	7.8a
NT.No.Cover	6.6bc	5.4a		5.45b	5.2a		9.0b	6.4a
NT.No.Cover.Int	6.5c	6.1a		5.8b	4.7a		8.3b	6.9a
NT.Cover.Graze	8.0ab	5.9a		7.4ab	5.3a		12.2a	7.7a
NT.Cover.No.Graze	6.8abc	6.1a		6.5ab	5.0a		8.7b	6.6a
NT.Cover.Graze. Int	8.1a	6.1a		9.7a	5.8a		9.5b	7.2a
NT.Cover.No.Graze.Int	7.1abc	5.9a		7.9ab	5.9a		9.5b	8.1a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

This study did not show any consistent treatment effects for SOC due to grazing, tillage, cover crops or intercropping. The research site had been under no till since 2001 prior to initiation of this investigation in 2013 and may be one reason why few differences were observed.

Soil Phosphorus

No significant treatment differences were observed for post cover crops Mehlich III P at 0-15 cm for the 2013/14 growing season (Table 4.8), and similar results were noted following the winter wheat crop. The soil P concentrations in the top 0-15 cm both post cover crops and post wheat periods were very comparable for the 2013/2014 period.

Table 4.8: Mehlich III soil phosphorus, Fall 2013 and Spring 2014.

Treatments	Fall 2013 soil P by depth (mg kg^{-1})		Spring 2014 soil P by depth (mg kg^{-1})		
	0-15cm	**15-60cm**	**0-15cm**	**15-30cm**	**30-60cm**
Conv. Till	17.5a†	4.0ab	20.9a	8.1a	2.9a
NT.No.Cover	24.8a	4.3a	27.2a	9.1a	3.3a
NT.No.Cover.Int	20.0a	4.3a	21.9a	6.3a	3.3a
NT.Cover.Graze	18.5a	3.3ab	27.2a	7.3a	3.1a
NT.Cover.No.Graze	26.3a	3.3ab	22.1a	9.7a	3.8a
NT.Cover.Graze. Int	20.3a	2.8b	19.6a	7.9a	3.1a
NT.Cover.No.Graze.Int	22.0a	3.0ab	23.0a	8.9a	2.8a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

The 2014/15 Mehlich soil P tests also did not show any meaningful differences for samples from post cover crops and winter wheat periods (Table 4.9). Samples taken following winter wheat in some treatments showed higher soil P compared to after cover crops. The different surface sampling depths could be one reason for the differences that were observed following cover crops and wheat sampling periods.

Table 4.9: Mehlich III soil phosphorus, Fall 2014 and Spring 2015.

Treatments	Fall 2014 soil P by depth (mg kg^{-1})				Spring 2015 soil P by depth (mg kg^{-1})			
	0-15cm	**15-30cm**	**30-60cm**		**0-5cm**	**5-15cm**	**15-30cm**	**30-60cm**
Conv. Till	20.5a†	5.3a	4.5a		21.0a	8.1a	8.8a	18.6a
NT.No.Cover	22.0a	5.3a	5.0a		45.8a	13.3a	7.6a	3.8b
NT.No.Cover.Int	24.8a	5.0a	4.3a		11.6a	6.4a	7.4a	3.3b
NT.Cover.Graze	17.0a	5.5a	3.3a		38.8a	15.0a	13.8a	4.1b
NT.Cover.No.Graze	20.0a	4.5a	3.8a		21.7a	9.7a	6.2a	10.5ab
NT.Cover.Graze. Int	20.0a	4.3a	3.0a		34.6a	8.4a	4.2a	7.5ab
NT.Cover.No.Graze.Int	19.3a	5.0a	4.0a		27.2a	12.7a	10.1a	5.2b

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Mehlich III soil P in post cover crops and post wheat samples again did not show any significant systematic variation due to treatment effects during the final year of study, although the CT treatment without cover crops trended lowest in 0-5 cm samples during the 2015/2016 growing season (Table 4.10). Wheat reportedly absorbs between 10 to 30 percent of available

soil P during its growth cycle (Hergert and Shaver, 2009). The considerably higher P values observed in the final year could possibly be due to mineralization of plant residues.

Table 4.10: Mehlich III soil phosphorus, Fall 2015 and Spring 2016

Treatments	Fall 2015 soil P by depth (mg kg^{-1})				Spring 2016 soil P by depth (mg kg^{-1})			
	0-5cm	**5-15cm**	**15-30cm**	**30-60cm**	**0-5cm**	**5-15cm**	**15-30cm**	**30-60cm**
Conv. Till	27.8a†	12.5a	3.8a	1.3a	27.9a	15.0ab	4.9a	3.5a
NT.No.Cover	50.8a	10.5a	3.0a	3.5a	46.0a	12.4ab	4.1ab	3.6a
NT.No.Cover.Int	35.0a	8.8a	2.3a	2.5a	33.2a	11.2b	4.5a	3.2a
NT.Cover.Graze	38.8a	11.3a	4.0a	3.5a	32.7a	13.0ab	4.2ab	3.2a
NT.Cover.No.Graze	35.8a	8.0a	4.0a	5.0a	36.1a	16.0a	4.5a	4.5a
NT.Cover.Graze. Int	35.0a	9.8a	2.3a	1.5a	32.0a	11.2b	3.2b	3.0a
NT.Cover.No.Graze.Int	32.3a	8.0a	3.0a	1.8a	34.8a	14.3ab	4.2ab	3.2a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

a. Soil Health Tool P

Soil Health Tool P is Haney's H^3A-extracted soil P. The SHT P did not show any significant differences in 0-15 cm samples at inception of the study in either post cover crops or post wheat periods in 2013/14 and 2015/16, nor in the post wheat period in 2015 (Table 4.11). Post cover crops samples for CT in Fall 2014 had the lowest SHT P, while NT.Cover.No.Graze had the highest (Table 4.11; $p<0.05$). Few significant differences were observed among all NT treatments, cover or no cover crops, grazed or non-grazed and intercropped or non-intercropped treatments. Mehlich III extractable P tended to be greater than SHT P.

Table 4.11: Soil Health Tool extractable P in 0-15cm, post cover Fall and post wheat Spring soil samples.

Treatment	2013/2014 Season (mg kg^{-1})			2014/2015 Season (mg kg^{-1})			2015/2016 Season (mg kg^{-1})	
	Fall 2013	Spring 2014		Fall 2014	Spring 2015		Fall 2015	Spring 2016
Conv. Till	9.8a†	9.7a		7.5b	4.1a		4.3a	18.7a
NT.No.Cover	9.7a	8.4a		10.3ab	5.9a		4.8a	16.0a
NT.No.Cover.Int	10.0a	8.5a		10.8ab	5.4a		6.1a	17.7a
NT.Cover.Graze	10.4a	9.0a		9.8ab	3.5a		4.6a	10.1a
NT.Cover.No.Graze	12.3a	8.7a		13.0a	4.6a		6.5a	19.9a
NT.Cover.Graze. Int	7.1a	5.6a		8.3ab	5.5a		6.0a	13.1a
NT.Cover.No.Graze.Int	11.4a	9.2a		10.1ab	4.3a		4.9a	19.4a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Soil Potassium

Mehlich III extractable soil potassium (K) generally varied little from 2013 to 2016 due to treatment. The first and second years of cover crops treatments did not show any differences in Mehlich III extracted soil K (see appendix) for both post cover crops and post wheat periods. Samples from the final growing season of 2015/16 showed comparable soil potassium contents after 3 years regardless of cover crops, grazing and intercropping treatments. Although not significant, the CT treatment had the least extractable soil K in the top 5 cm of soil in post cover crop samples (Table 4.12). Other research has shown no difference in soil K between no-till and conventional till (Karlen, et al., 1989).

Table 4.12: Mehlich III extractable soil potassium, Fall 2015 and Spring 2016.

Treatments	Fall 2015 soil K (mg kg^{-1}) by depth (cm)				Spring 2016 soil K (mg kg^{-1}) by depth (cm)			
	0-5	**5-15**	**15-30**	**30-60**	**0-5**	**5-15**	**15-30**	**30-60**
Conv. Till	222a†	187a	187a	166a	252a	180a	180a	167a
NT.No.Cover	255a	191a	191a	169a	252a	174a	174a	168a
NT.No.Cover.Int	254a	176a	176a	165a	270a	169a	169a	171a
NT.Cover.Graze	268a	185a	185a	171a	261a	186a	186a	167a
NT.Cover.No.Graze	245a	177a	177a	164a	263a	171a	171a	166a
NT.Cover.Graze. Int	268a	171a	171a	153a	257a	178a	178a	168a
NT.Cover.No.Graze.Int	260a	191a	191a	164a	284a	183a	183a	191a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

a. Soil Health Tool Potassium

Haney et al. (2006) extractable soil K is based on H^3A extraction which theoretically mimics root exudates released into the rhizosphere. Although SHT results showed no treatment differences in soil K in the top 15 cm of soil in the 2013/14 season, some interesting effects due to treatments were observed in samples collected in the 2015/16 post wheat period (Table 4.13). Soil available K was least in CT at this time compared to the rest of the treatments (Table 4.13; $p>0.05$), possibly because of greater wheat yield with this treatment in 2016. There were no significant differences among all NT treatments, with or without cover crops, grazed or non-grazed, or due to intercropping (Table 4.13).

Table 4.13: Soil Health Tool extractable potassium (0-15 cm).

Treatment	2013/14 season-K (mg kg^{-1})		2014/15 season-K (mg kg^{-1})		2015/16 season-K (mg kg^{-1})	
	Fall 2013	**Spring 2014**	**Fall 2014**	**Spring 2015**	**Fall 2015**	**Spring 2016**
Conv. Till	24.2a†	28.2a	25.1a	16.0c	10.3b	25.3b
NT.No.Cover	46.3a	59.4a	41.6a	20.9abc	12.6ab	35.1a
NT.No.Cover.Int	31.7a	47.4a	25.1a	20.4abc	12.0ab	34.1a
NT.Cover.Graze	40.6a	51.6a	41.1a	20.2abc	9.3b	34.2a
NT.Cover.No.Graze	44.9a	37.5a	35.9a	17.9bc	10.5b	34.4a
NT.Cover.Graze. Int	48.4a	71.1a	46.7a	26.1a	18.2a	42.1a
NT.Cover.No.Graze.Int	35.1a	65.1a	39.2a	22.7ab	14.7ab	35.3a

† Means within a column followed by the same letter are not different by LSD (0.05).

Soil Sulfur

Mehlich extractable soil S concentrations in surface horizons were not affected by treatment during the entire period of this study. Although some differences were noted in subsurface horizons, they did not follow any discernible pattern. The first two years of study data is shown in the appendix. Extractable S values in the final year of investigation, 2015/16, showed considerable variability, especially in the 30 to 60 cm depth, and no meaningful interpretations could be drawn from the data (Table 4.14).

Table 4.14: Mehlich Extractable soil sulfur in Fall 2015 and Spring 2016.

Treatments	Fall 2015 soil S (mg kg^{-1}) by depth (cm)				Spring 2016 soil S (mg kg^{-1}) by depth (cm)			
Depth (cm):	**0-5**	**5-15**	**15-30**	**30-60**	**0-5**	**5-15**	**15-30**	**30-60**
Conv. Till	8.8a†	5.8a	7.3b	18.3c	9.5a	6.6a	8.0a	14.4b
NT.No.Cover	8.0a	6.0a	12.5ab	120.5a	11.5a	5.4a	10.8a	85.5ab
NT.No.Cover.Int	6.3a	4.5a	24.5ab	64.3abc	7.9a	6.4a	9.8a	25.6b
NT.Cover.Graze	8.5a	6.8a	19.5ab	113.3ab	10.5a	6.8a	20.3a	55.5ab
NT.Cover.No.Graze	7.8a	4.5a	31.3a	91.5abc	12.0a	7.7a	19.0a	285.4a
NT.Cover.Graze. Int	8.3a	4.5a	3.8b	19.8bc	10.9a	5.8a	8.5a	10.3b
NT.Cover.No.Graze.Int	6.3a	5.5a	6.5b	17.3c	10.5a	6.8a	12.2a	180.9ab

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Discussion

Nutrient cycling

a) Nitrogen

The variation in soil NO_3^-–N observed among treatments may be explained by cover crops growth, residues and tillage effects (Figure 4.1). Cover crops exerted a direct impact on soil nitrate observed in this investigation right from inception because of their uptake of NO_3^- for growth and subsequent reduction in soil NO_3^- concentration. The indirect impact was noted

when cover crops were terminated and became surface residue. Cover crop residues with high C:N ratios of up to 48 in the 2015/16 season immobilized soil NO_3^-, and the applied N fertilizer was not sufficient to curtail immobilization and the deficit created by utilizing NO_3^- during growth. The higher C:N ratios observed in cover crops biomass, particularly in the 2015/16 growing season, contributed to the soil NO_3^-–N deficit that likely reduced yields of the following wheat crop.

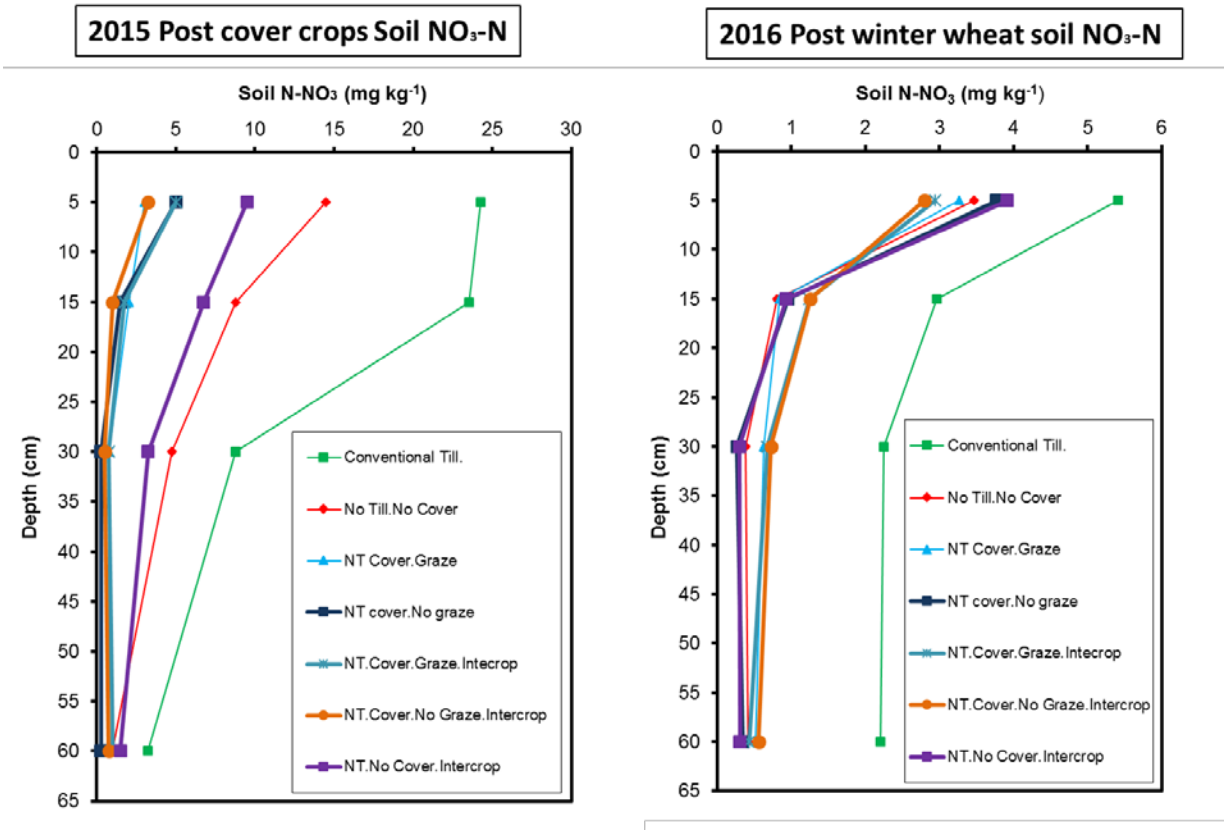

Figure 4.1: Soil nitrate-N in post in post cover crops and post winter wheat samples in 2015/16. *Significant at P<0.05.

The depletion of NO_3^-–N by non-leguminous cover crops observed in this study has also been reported in many other studies (Richards et al., 1996; Jackson et al., 1993; Francis et al.,

1998; Thorup-Kristensen, 1994). Pink et al. (1948) reported N immobilization by residues with C:N ratios higher than 35 and subsequently a slower rate of N mineralization. Immobilization of N, if synchronous with crop demand, increases fertilizer N requirements for economic yields to be realized (Holderbaum et al., 1990; Sullivan et al., 1991; Decker et al., 1994). Generally, legume cover crops have C:N ratios less than 20, which reduces immobilization and applied fertilizer N requirements (Doran and Smith, 1991; Ebelhar et al., 1984). The failure of legumes in our cover crops mix decreased the potential for symbiotic N_2 fixation, and increased fertilizer N requirements.

The greater soil NO_3^-–N witnessed in the CT treatment probably was a result of rapid microbial activity initiated by plowing which increased organic matter mineralization (Alvear et. al., 2005). In a related study, Reicosky et al. (1997) recorded increases in soil inorganic N after cultivation, with NT being intermediate and NT with coastal bermudagrass [*Cynodon dactylon* (L.) Pers.] being lowest with sorghum as the main crop. Surface residues under NT immobilize nutrients and are slower to decompose because of less intimate residue/soil contact (Pankhurst et al., 2002). Our study site was under NT for 12 years prior to effecting the CT treatment. Cover crops scavenge N from the soil and convert inorganic N to organic N as they grow (Reese et al., 2014; Dabney et al., 2007). Wagger and Mengel (1988) found that non-legume cover crops reduced soil inorganic N supply during their growth. Shipley et al. (1992) reported the lowest soil NO_3^-–N values in their study following cover crops, thereby potentially conserving N.

Additional N as reported via the Soil Health Tool, comprising biological N and water extractable NH_4^+–N, was consistently lowest under CT during this study. The lower soil NH_4^+–N prevalent in the CT treatment might be attributed to the rapid conversion of NH_4^+ to NO_3^- under tillage. This observation is substantiated by the general highest NO_3^-–N observed under

CT during this investigation. Tillage tends to increase soil microbial activity, thereby stimulating more rapid nutrient cycling. Quemada and Cabrera (1997) reported NH_4^+ from cover crops surface residues being leached into soil. However, to the contrary, Steenwerth and Belina (2008) found increased mineralization and nitrification under cover crops.

b) Phosphorus, potassium and sulfur cycling

The final year results began showing the impact of cover crops on Mehlich III extracted soil P, although differences were not significant. The numerically lowest soil P in the 0-5 cm depth for CT may have been due to mixing lower, more P-depleted soil layers with the upper layer during tillage (Table 4.12 & Figure 4.2). Intermediate values seen for cover crops treatments could be due to cover crops mining soil P from lower horizons and depositing it in organic matter near the soil surface.

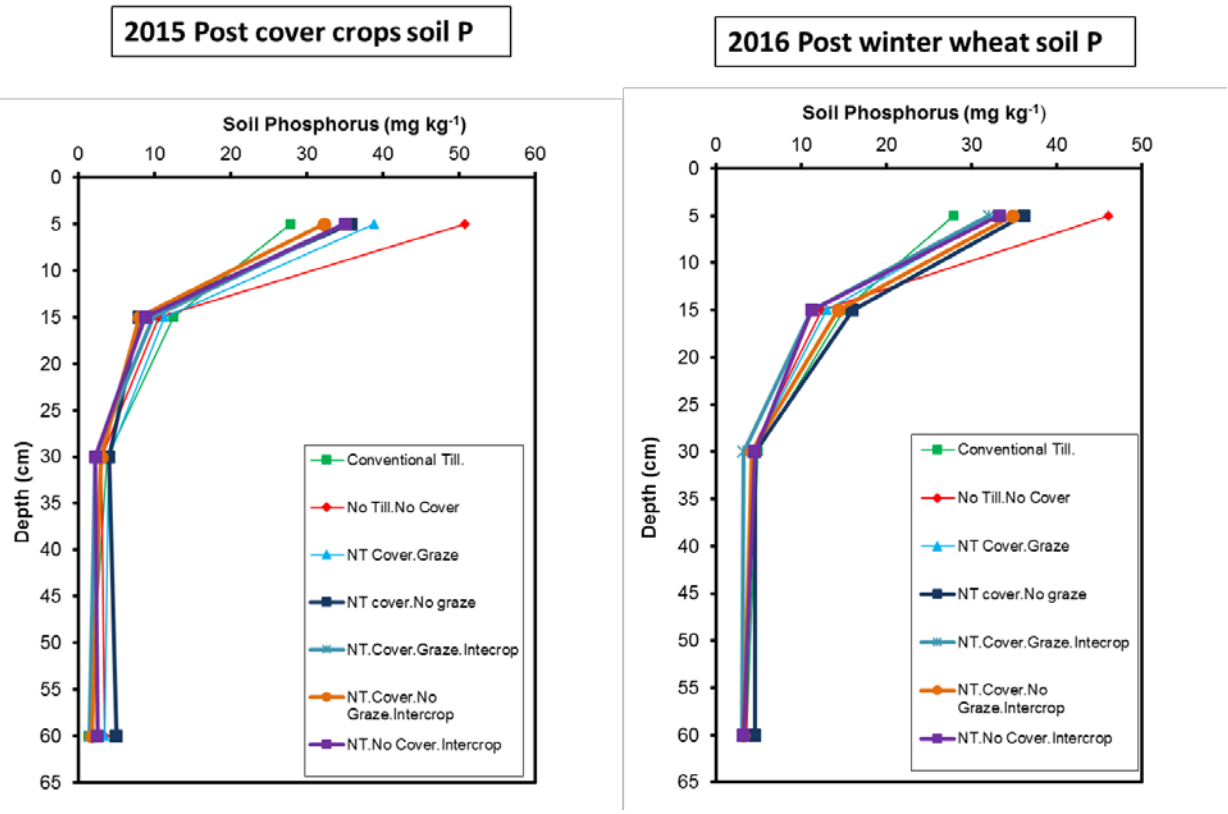

Figure 4.2: Mehlich III extractable soil phosphorus in post cover crops and post wheat samples in 2015/2016.

The highest Mehlich III soil P value observed with the NT no cover crops treatment might have been associated with soil P stratification, and subsequently higher soil P concentrations in the surface layer. Through root uptake of P and deposition on the soil surface, surface applications of P fertilizers, and the inherent insolubility of P in soils, agroecosystems may exhibit P accumulation in surface soils and increased vulnerability to losses into the environment (Simpson et. al., 2011). Sharpley and Smith (1991) reported reduced P leaching under legume and grass mixtures as well as in pure grasses. At the inception of the study, surface and subsurface soil P was comparable regardless of treatment. Research has shown P stratification under NT compared to CT which has a mixing of surface soil (Franzluebbers and Hons, 1996;

Robbins and Voss, 1991; Karlen et al., 1991; Follett and Peterson, 1988). However, the SHT P analysis did not show any notable patterns of SHT P during the study period. The lack of effect of cover crops on soil P dynamics was consistent with other reported studies (Takeda et al., 2009; Kuo et al., 2005), where cover crops had no effect on evaluation of available P in a water quality and protection study.

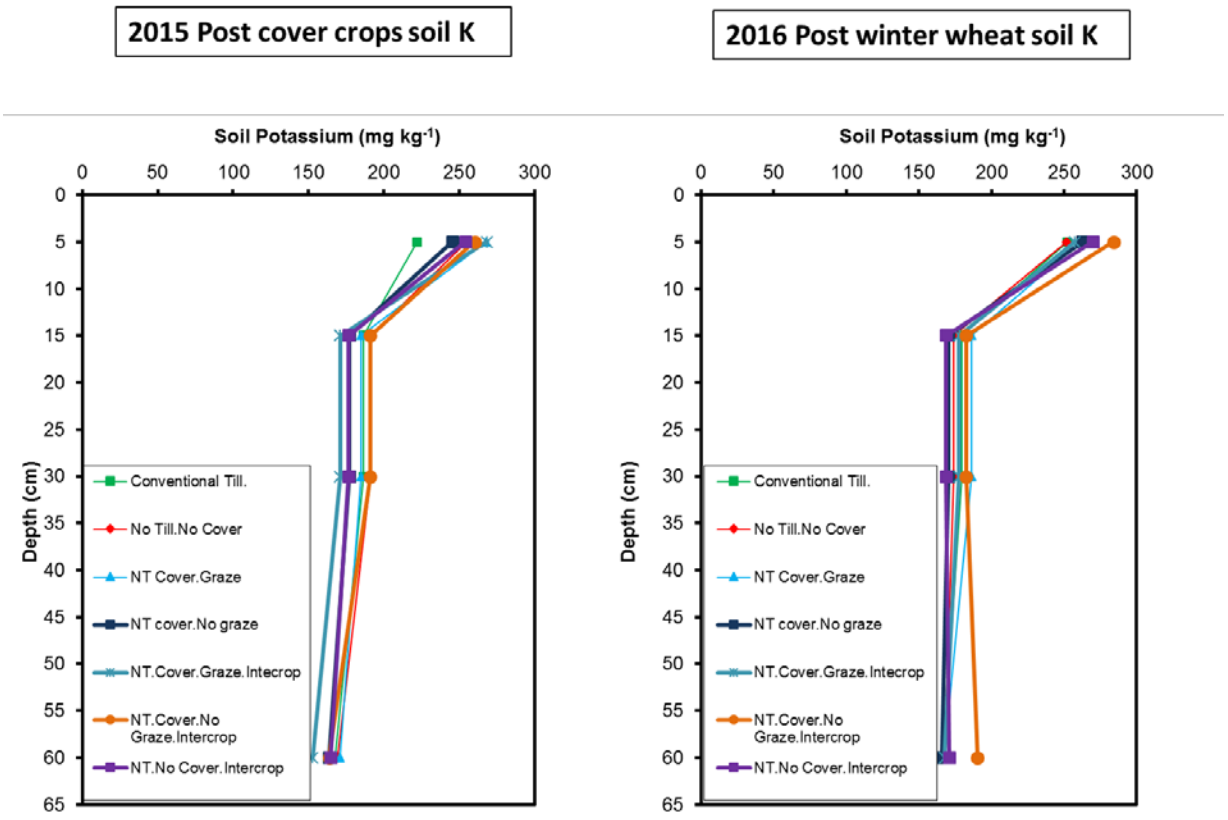

Figure 4.3: Mehlich III extractable soil potassium in post cover crops and post wheat samples in 2015/16.

Soil K is generally not limiting for crop production in the area of this study. Mehlich III extracted soil K varied little over the study period. In contrast, SHT K for CT characteristically trended lowest during this investigation. The consistently lower soil K under CT, significant in

final spring season of 2016, (Table 4.13 & Figure 4.3) may be related to NT concentrating K in the top soil layer (Eckert and Johnson, 1985; Follett and Peterson, 1988) or the dilution of K in the surface layer by mixing with lower K-containing layers during tillage. Bauder et al. (1985) also reported lower K concentrations under CT compared to NT. Comia et al. (1994) reiterated the same findings.

c) Soil Organic Carbon (SOC)

No significant treatment effects on total SOC were observed during this investigation, except for the NT.Cover.Graze treatment which was highest at the end of the study. Our finding on no significant increase in SOC was similar to that of Schwartz et al. (2015) who showed minimal change in SOC over 25 years of NT on a clay loam soil in a semi-arid region. West and Post (2002) also reported insignificant increases in SOC under sites that had been under long-term NT, concluding that steady state conditions had already been reached. Our research site had been under no-till since 2001. However, in a related study, NT increased near surface SOC in wheat management systems after 10 years (Franzluebbers et al., 1994). Johnson et al. (1995) also observed that soils that had been intensively cultivation showed significant SOC sequestration when converted to NT.

The overall impact of cover crops on SOC may not be easily detected in the short term (Blanco-Canqui et al., 2014; Acuna and Villamil, 2014), although they increased SOC concentrations. Blanco-Canqui et al. (2015) postulated that SOC benefits from cover crops may not persist in semi-arid climates and suggested continuing use of cover crops to realize full benefits. A three-year rye-vetch cover crops evaluation under NT in Fort Valley, Georgia reported a 6-8% increase in SOC at 0-10 cm depth compared to no cover crops treatments,

whether tilled or NT. This result was achieved with the addition of 120 to 130 kg fertilizer N ha^{-1} (Sainju et al., 2006). The research site had been under tillage to a depth of 20 cm with chisel plows and disc harrows prior to establishment of the study.

Conclusion

Cover crops grown during the fallow period in continuous wheat systems potentially conserved N through immobilization into organic soil N and soil mining to reduce leaching. However, it is also important to strike a balance in N management of such systems to prevent N deficiency to the main crop as was likely observed in this investigation. No significant effects of cover crops treatments were measured for soil P, K and S. No significant effects of grazing on nutrient cycling were recorded despite significant removal of biomass that otherwise would be left as surface residue. Intercropping also was not significant when compared to other NT treatments. Conventional till effects on nutrient cycling were rather conspicuous. This site had been under NT since 2001, tillage in 2013 initially likely enhanced microbial activity, resulting in a mineralization spike and higher soil NO_3^-–N with the CT treatment. Lower extractable soil K and P in surface soil under CT likely occurred due to mixing of surface soil with underlying soil containing less K and P. No treatment effects were recorded for extractable soil S. Some research has shown that cover crops may need to be grown for a period longer than 5 years for detection of significant effects on soil chemical constituents (Thomsen and Christensen, 2004; Abdollahi and Munkholm, 2014).

CHAPTER V

COMPARATIVE ANALYSIS OF SOIL HEALTH INDICATORS UNDER CONTINUOUS WHEAT

Summary

Continuous wheat production under conventional tillage (CT) for both forage grazing and grain harvest is a common practice, which may potentially have detrimental effects on soil ecosystem services and function. Cover crop use has shown increased nutrient use efficiency and soil microbial diversity, though literature is limited. This study quantified the effects of no till, cover crops, grazing and intercropping in monoculture wheat (*Triticum aestivum*) on soil microbial diversity and nutrient cycling in the Texas Rolling Plains. The study utilized a randomized complete block design with seven treatments replicated four times. Treatments were (1) CT wheat without a cover crop; (2) no-till (NT) wheat without a cover crop; (3) NT wheat with a terminated summer cover crop; (4) NT wheat with a grazed summer cover crop; (5) NT wheat intercropped with turnip (*Brassica rapa subsp. Rapa*)/radish (*Raphanus sativus*) without summer cover crop; (6) NT wheat intercropped with turnip/radish with terminated summer cover crop; and (7) NT wheat intercropped with turnip/radish with grazed summer cover crop. Phospholipid fatty acid (PLFA) analysis was used to assess soil microbial community structure. Soil samples were taken at 0-7.5 cm next to wheat plants near roots and after harvesting wheat and after terminating summer cover crops. PLFAs of post cover crops samples showed changes in the soil ecosystem due to NT with cover crops, grazing and intercropping. Total living microbial mass, total bacteria, total fungi, gram (+) and gram (-) bacteria, arbuscular mycorrhizal, saprophytes, protozoa, and undifferentiated biomass were higher for NT systems

compared to CT. No-till wheat intercropped with turnip/radish with a terminated summer cover crop resulted in the highest microbial biomass, with no cover crop treatments trending lower compared to those with cover crops. Fungi:bacteria ratios were consistently lowest under CT compared to NT treatments. Relatively higher fungi:bacteria ratios were recorded for NT treatments with cover crops, grazing and intercropping. Solvita 1-day CO_2–C was positively related with PLFA biomass. No treatment effects were found for soil organic phosphorus (SOP). No till produced cover crops had positive effects on soil microbial community structure and nutrient cycling. No till cover crops use has the potential to ameliorate continuous wheat systems prevalent in the Texas Rolling Plains by promoting diversity, soil microbial proliferation and community structure, nutrient cycling and overall soil quality in soil ecosystem for sustainable agroecosystems and sequestration of C in agroecosystems. Intensive soil cultivation in agricultural systems contributes about 55 Pg C per year through atmospheric release of CO_2 (Cole et al., 1997).

Introduction and Literature Review

Conservation practices coupled with the use of cover crops has been reported to improve soil quality, fertility and productivity. Cover crops, no-till and crop rotations bring about soil ecosystem diversity that stimulates soil microbial proliferation (Dick, 1992). Diverse soil microbial communities and their associated functional capabilities are important for organic matter decomposition and subsequent nutrient cycling. Microbial processing of organic materials is central in building soil structure, and enhancing soil physical, chemical and microbial properties. Practices that leave crop residue on the soil surface provide substrates for soil microbes, reduce soil evaporation, conserve soil moisture, and create conditions conducive for microbial growth and activity. Cover crops, crop rotations and organic amendments, such as crop residue and animal excreta, promote microbial diversity and activity in the soil ecosystem (Dick, 1992; Bunemann et al., 2006; Nicolardot et al., 2007; Pascault et al., 2010).

Over 90% of soil microbial biomass is made up of bacteria and fungi. Some common soil bacteria include actinomycetes and rhizobia, while common fungi include arbuscular mycorrhizae and saprophytes. Fungi and bacteria are very crucial in plant and animal litter decomposition and associated nutrient cycling. Fungi are early colonizers of fresh litter and are found in abundance at initiation of the decomposition process (Osono, 2002; Koide et al., 2005). Fungi possess the unique ability to decompose lignocellulose, which other organisms cannot readily decompose (Swift et al., 1979; Cooke and Rayner, 1984). Fungi are more efficient in C substrate utilization and have higher growth yield efficiency compared to bacteria (Parton et al., 1987; Holland and Coleman, 1987). Fungi also play a pivotal role in soil structure modification (Tisdall and Oades, 1982) through promoting soil aggregation that protects SOC from decomposition (Simpson et al., 2004). Arbuscular mycorrhizal fungi (AMF) are instrumental in

the formation and stability of soil aggregates (Rilling and Mummey, 2006), and soil aggregates define soil structure. Soil particles comprising aggregates strongly adhere to each other in comparison to soil particles around them (Kemper and Rosenau, 1986). AMF are credited for formation and stabilization of soil aggregates through biological, biochemical and biophysical processes. Biological processes involve the interaction of AMF with plant roots and many other organisms. AMF deposits mycelial products, substrates that stimulate fungal and bacterial growth and are important in soil aggregation (Bezzate et al., 2000; Mansfel-Giese et al., 2002). Biochemically, AMF are linked to production of glomalin and glomalin-related soil protein (Wright and Upadhyaya, 1996) which technically acts as 'glue' and attaches soil particles together. Biophysically, AMF resemble roots, but at a smaller scale with their hyphae entangling and enmeshing soil particles into small aggregates, ultimately resulting in macroaggregates (Hart and Reader, 2005). Fungal dominated soil ecosystems also generally sequester more C compared to bacterial dominated systems (Six et al., 2005).

Fungi:bacteria ratio is an important ecosystem service characterization parameter, comparing fungi to bacteria relative to microbial community proportions. Low fungi:bacteria ratio usually signifies high soil disturbance through cultivation often associated with high C losses (Bailey et al., 2002; Frey et al., 1999). Intensive cultivation physically disrupts soil aggregates and AMF hyphae, accelerating SOC decomposition. Intensive grazing has also been linked to low fungi:bacteria ratios (Bardgett et al., 1996). Intensive grazing depletes high lignin and cellulose biomass which ultimately lowers fungal microbiota. High fungi:bacteria ratios have been reported in soils under conservation practices with minimum disturbances (Klein et al., 1996).

Doran (1980) evaluated soil microbial and biochemical shifts associated with reduced tillage across several locations in the USA and showed higher soil microbial populations under NT compared to CT in the top 7.5 cm soil depth. Fungi and bacteria had the highest counts among total aerobic organisms. No-till had the highest aerobic and autotrophic nitrifiers (NH_4^+ and NO_2^- oxidizers). Analyses of subsurface (7.5 to 30 cm) soil showed higher or similar microbial populations for CT in comparison to NT, except for actinomycetes. Soil water content in the top 7.5 cm was significantly higher under NT compared to CT. Soil moisture content generally has a positive effect on substrate availability and a direct impact on fungal biomass and fungal:bacterial ratios in soil environments (Frey et al., 1999). The soil microbial populations correlated with SOC and SON levels. Soil organic C and N pools are directly impacted by agricultural practices and cropping systems (Havlin et al., 1990). Labile SOC and SON pools are usually more sensitive to agronomic practices compared to total pools (Haynes, 2005).

Wawrik et al. (2005) demonstrated how bacteria in soil were increased in diversity in response to enriching soil ecosystems with chemically diverse sources of C. Substrate quality based on C:N has a strong bearing on fungal:bacterial ratio dynamics (Bossuyt et al., 2001). Low quality substrates which are high C:N are conducive to fungal proliferation, and higher substrate quality, i.e. low C:N, favor bacterial multiplication. Leguminous cover crops fix N from the atmosphere through a symbiotic association with Rhizobia bacteria, adding N to soil for following crops (Clark et al., 1994). Non-leguminous plants add biomass to soil providing organic C to soil systems (Sainju et al., 2000; Kuo et al., 1997). A well-balanced cover crop mix of leguminous and non-leguminous plants is critical in soil C and N dynamics and for sustainably maintaining soil fertility.Leveraging the apparent synergies that exist among plant biomass, soil microbial communities and grazing is critical for developing and maintaining

functional soil ecosystems. Cover crops can provide essential substrates that are utilized by soil microbes in facilitating nutrient cycling for ecosystem services and functions. Winter wheat grazing is a customary practice despite possible associated risks like soil erosion, compaction and reduced infiltration (Van Haveren, 1983; Daniel and Phillips, 2000; Daniel et al., 2002; Wheeler et al., 2002). Turnips (*Brassica rapa subsp. Rapa*) and radishes (*Raphanus sativus)* have been shown to potentially reduce these negative effects (Kennedy, 2012) by opening subsoil and providing root biomass and carbon sequestration. This part of the study included a comparative analysis of soil microbial community structure and diversity and relationships with nutrient cycling under continuous wheat systems as influenced by cover crops, grazing, and intercropping with turnips and radishes under NT practices.

Materials and Methods

This 3-year study was conducted at the Texas A&M AgriLife Research Smith/Walker Ranch near Vernon, Texas. The site has been under NT continuous dual-purpose wheat system since 2001 and was grazed whenever there was adequate forage during that period. The soil type is Rotan clay loam (Fine, mixed, superactive, thermic Pachic Paleustolls). The experimental design was a randomized complete block design with 7 treatments replicated 4 times. Individual plot size was 2025 m^2. A cover crops mix (Table 2.1) was grown during summer months while mixed intercropping (wheat plus turnips and radishes) was grown in winter. The treatments were (1) CT wheat without a cover crop (Conv.Till); (2) NT wheat without a cover crop (NT.No.Cover); (3) NT wheat with a grazed summer cover crop (NT.Cover.Graze); (4) NT wheat with a terminated summer cover crop (NT.Cover.No.Graze); (5) NT wheat intercropped with turnip/radish with grazed summer cover crop (NT.Cover.Graze.Int); (6) NT wheat

intercropped with turnip/radish with terminated summer cover crop (NT.Cover.No.Graze.Int); and (7) NT wheat intercropped with turnip/radish without summer cover crop (NT.No.Cover.Int).

Soil samples were taken to 0-15 cm depth after cover crop termination in October and prior to wheat planting each year for Haney tests. Two 5 cm diameter soil cores per plot were composited, dried at 50 °C overnight and ground to pass through a 2-mm sieve. Samples were analyzed for water extractable organic C, N, P (Haney et al., 2012) while the Solvita gel system was used for 24 hr soil CO_2 analysis following rewetting of dry soil (Haney et al., 2008). The Solvita 1-day CO_2-C measurement gives a rapid measure of soil microbial activity.

The phospholipid-linked fatty acid (PLFA) method was used in assessing the soil total living microbial community structure and diversity (Frostegard, 1996; Frostegard and Baath, 1996). PLFA soil samples were taken to a 0-7.5 cm depth in the plant rooting zone and immediately stored at 4°C and shipped same day. Ten random 2 cm diameter soil cores were composited from each treatment plot. PLFA analyses were done 4 times: when wheat was actively growing in February 2015 (Winter), after harvesting wheat in June 2015 (Summer), after terminating cover crops in October 2015 (Autumn) and when wheat was actively growing in February 2016 (Winter). Soil samples were sent to Ward Laboratories, Kearney, Nebraska for PLFA analyses. PLFA analysis generally assesses relative biomass of fungi and bacteria. The fungi:bacteria ratio (FBR) estimation used PLFA 18:2ω6,9 for measuring fungal biomass and the sum of 13 bacteria-specific PLFAs for bacterial biomass (Frosteguard and Baath, 1996). Phospholipids, common in every living cell, are used as biomarkers, and also degrade rapidly upon death of a cell, making them a good gauge of the living microbial biomass in the soil (Bardgett and McAlister, 1999). This method, therefore, captures the living microbial

community. Microbial populations that are different have characteristic lipid profiles which are unique to each population, with different phospholipids having different fatty acid chain structures. The method utilizes fatty acid branching, chain length and saturation as a 'fingerprint' of the soil community (Fang et al., 2001; Steer and Harris, 2000).

The PLFA method quantifies the living and actively involved organisms that are critical in nutrient cycling. Total biomass (TB), total bacteria biomass (TBB), actinomycetes biomass (AB), gram (-) biomass (GNB), rhizobia biomass (RB), gram (+) biomass (GPB), total fungal biomass (TFB), arbuscular mycorrhizal biomass (AMB), saprophytes biomass (SB), protozoan biomass (PB), undifferentiated biomass (UB), and fungi:bacteria ratio (FBR) were evaluated. Table 5.1, shows PLFAs that were used in evaluating each group.

Table 5.1: PLFA Biomarkers used in characterization

PLFA/FAME Biomarkers	**Specific Group**	**Family**	**Class**
10:0 2OH		Gram -	Bacteria
10:0 3OH		Gram -	Bacteria
11:0 iso 3OH		Gram -	Bacteria
12:0 2OH		Gram -	Bacteria
14:0 iso		Gram +	Bacteria
14:0 2OH		Gram -	Bacteria
14:0 iso 3OH		Gram -	Bacteria
15:0		Gram +	Bacteria
15:0 iso		Gram +	Bacteria
15:0 anteiso		Gram +	Bacteria
16:0 iso		Gram +	Bacteria
16:1 w5c	Arbuscular Mycorrhizal		Fungi
16:1 w7c		Gram -	Bacteria
16:1 w9c		Gram -	Bacteria
16:0 2OH		Gram -	Bacteria
16:0 10-methyl	Actinomycetes	Gram +	Bacteria
17:0		Gram +	Bacteria
17:0 iso		Gram +	Bacteria
17:0 anteiso		Gram +	Bacteria
17:0 10-methyl	Actinomycetes	Gram +	Bacteria
17:0 cyclo		Gram -	Bacteria
18:0 10-methyl	Actinomycetes	Gram +	Bacteria
18:1 w5c		Gram -	Bacteria
18:1 w7c		Gram -	Bacteria
18:1 w9c	Saprophytes		Fungi
18:2 w6c	Saprophytes		Fungi
18:3 w3c	Saprophytes		Fungi
19:0 iso		Gram -/Gram +	Bacteria
19:0 anteiso		Gram -/Gram +	Bacteria
19:0 cyclo w8c	Rhizobia	Gram -	Bacteria
19:0 cyclo w9		Gram -	Bacteria
19:0 cyclo w6		Gram -	Bacteria
20:1 w9c	Arbuscular Mycorrhizal		Fungi
20:2 w3c			Protozoa
20:2 w6c			Protozoa
20:3 w3c			Protozoa
20:4 w6c			Protozoa
22:1 w9c	Arbuscular Mycorrhizal		Fungi
20:5 w3c	Saprophytes		Fungi

Statistical Analysis

The collected data were analyzed by ANOVA using the general linear model procedure (SAS Institute, 2008) at $P<0.05$. Mean separations were accomplished using Fisher's protected least significant difference (LSD) also at $P<0.05$.

Results

PLFA results indicated significant treatment effects on the measured microbial parameters in post cover crops soil samples (Autumn) and was variable in those collected during the wheat periods.

Soil Microbial Biomass

a. Total Biomass (TB)

Conventional till without a cover crop trended lowest in total microbial biomass during the periods under investigation and were significantly lower in winter and autumn 2015 partly because of recent tillage prior to seeding wheat (Table 5.2; $p<0.05$). The post cover crops period, autumn 2015, showed significant interactions amongst treatments. The no cover crops treatments Conv.Till and NT.No.Cover. were significantly lowest in TB in autumn 2015 after cover crop termination, compared to all other treatments (Table 5.2; $p<0.05$). For cover crop treatments, grazed/ungrazed and intercropped, TB was 38–57 % higher than CT and NT no cover crop treatments following cover crop termination (Table 5.2; $p<0.05$).

Table 5.2: Total living soil biomass in soil samples collected post cover crops and post and active wheat growth.

Treatment	Total Living microbial biomass (ng g^{-1})			
	Winter 2015	**Summer 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	1283c†	1266b	1528d	1545a
NT.No.Cover	2656ab	1474ab	2230c	1672a
NT.No.Cover.Int	2251ab	1580ab	3002b	1369a
NT.Cover.Graze	3192a	1738a	2687b	1669a
NT.Cover.No.Graze	2760ab	1490ab	2505b	1460a
NT.Cover.Graze.Int	1561bc	1694ab	2517b	1627a
NT.Cover.No.Graze.Int	2153ab	1531ab	3587a	1727a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

No-till wheat intercropped with turnip/radish with a terminated summer cover crop (NT.Cover.No.Graze.Int.) resulted in the highest TB of 3587 ng g^{-1}, 135 % more than CT wheat without a cover crop (Conv.Till) and 61% higher than NT.No.Cover (Table 5.2). Turnip and radish production was erratic expect for the last year of study when they did well. The increase that was observed in TB in post cover crops samples diminished when wheat was actively growing in winter 2016. Relatively few differences were observed among NT cover crops and grazed treatments.

b. Total Bacteria Biomass (TBB)

A general uniformity in total bacteria biomass (TBB) was observed among treatments in samples taken during active wheat periods of winter 2015 and 2016 (Table 5.3). Active growth stages of wheat seemed to create a more uniform soil ecosystem which was not conducive to proliferation of soil microbiota. Balota et al. (2003) noted that changing the diversity of a

cropping sequence can affect SOC levels just as much the chemical composition of residues added to soil. These both influence soil microbiota proliferation and growth.

Total bacteria biomass was significantly lower in autumn 2015 CT samples compared with all other treatments (Table 5.3; $p<0.05$). The NT wheat with a terminated summer cover crop (NT.Cover.No.Graze.Int) treatment at this time had the highest TBB of 1706 ng g^{-1}, more than double that of CT and 37–56% higher than NT no cover crop treatments (Table 5.3; $p<0.05$). No significant effects were observed for grazing.

Table 5.3: Total bacteria biomass in soil samples collected post cover crops and post and active wheat growth.

Treatment	**Total Bacteria Biomass (ng g^{-1})**			
	Winter 2015	**Summer 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	618b†	730c	759d	698a
NT.No.Cover	942ab	819bc	1070c	719a
NT.No.Cover.Int	946ab	900ab	1160bc	595a
NT.Cover.Graze	1251a	981a	1201b	744a
NT.Cover.No.Graze	1087ab	873ab	1177bc	603a
NT.Cover.Graze.Int	699b	979a	1162bc	728a
NT.Cover.No.Graze.Int	976ab	875ab	1706a	762a

† Means within a column followed by the same letter are not different by LSD (0.05).

c. Actinomycetes Biomass (AB)

Post cover crops samples of NT wheat intercropped with turnip/radish with terminated summer cover crop (NT.Cover.No.Graze.Int) had significantly higher AB than all other treatments at this sampling, except that same treatment with no cover crop (Table 5.4; $p<0.05$). The least AB at this time was associated with the CT treatment. There were no significant

differences among the remaining NT treatments. However, NT.Cover.No.Graze.Int in autumn 2015 samples was 56% higher AB compared to NT.Cover.Graze.Int, possibly due to grazing. Samples collected during wheat periods generally did not show discernible differences in AB.

Table 5.4: Actinomycetes biomass in soil samples collected post cover crops and post and active wheat growth.

Treatment	Actinomycetes Biomass (ng g^{-1})			
	Winter 2015	**Spring 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	113b†	162c	142d	154a
NT.No.Cover	141ab	185abc	209bc	139a
NT.No.Cover.Int	154ab	182bc	252ab	116a
NT.Cover.Graze	203a	199ab	205bc	141a
NT.Cover.No.Graze	168ab	183abc	195bc	106a
NT.Cover.Graze.Int	119a	211a	193bc	150a
NT.Cover.No.Graze.Int	171ab	181bc	301a	156a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Actinomycetes resemble fungi, although they are bacteria, and like fungi, they also form multicellular filaments capable of binding soil particles together into stable aggregates. Actinomycetes are credited with degrading cellulose and solubilizing lignin and are more tolerant to higher temperatures than fungi, although their degradation ability is not as great (Crawford, 1983; Godden et al., 1992). The ability of these microbes to mineralize lignin is limited (Eriksson et al., 1990; Godden et al., 1992), and are generally more efficient at degrading grass lignin compared to wood lignin (Buswell and Odier, 1987).

d. Gram (-) Bacterial Biomass (GNB)

Gram negative bacterial biomass was greatest for the NT.Cover.No.Graze.Int treatment in samples collected in autumn 2015 following cover crops, which was more than twice that of the CT treatment (Table 5.5; $p<0.05$). Cover crops, grazed/ungrazed and intercropped treatments showed 46–61 % higher GNB compared to the no cover crops treatments. Though not always significant, the CT treatment generally resulted in the least GNB at all sampling times. Fewer differences in GNB were observed in samples taken during active wheat growing periods. Wheat appeared to create a more uniform environment for soil microbes, regardless of treatment, compared to cover crops (Franzluebbers et al., 1995). Finney et al. (2017) reported an increase in GNB following a cover crop mix compared to an untilled control without a cover crop.

Table 5.5: Gram (-) bacterial biomass in soil samples collected post cover crops and post and active wheat growth.

Treatment	Gram (-) Biomass (ng g^{-1})			
	Winter 2015	**Spring 2015**	**Autumn 2015**	**Winter 2016**
Treatment	**Active Wheat**	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	271b†	196c	270d	288a
NT.No.Cover	496ab	238bc	373cd	331a
NT.No.Cover.Int	473ab	319a	520b	265a
NT.Cover.Graze	646a	305ab	500b	339a
NT.Cover.No.Graze	545ab	262abc	476bc	282a
NT.Cover.Graze.Int	323ab	295ab	428bc	278a
NT.Cover.No.Graze.Int	485ab	289ab	685a	354a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

The impact of grazing was also observed in intercropped treatments in autumn 2015 samples. The NT.Cover.No.Graze.Int. had significantly higher GNB compared to the grazed

treatment NT.Cover.Graze.Int. (Table 5.5; $p<0.05$). Grazing reduced surface residue by 58% (Table 3.3), possibly reducing substrate available for microbes.

e. Gram (+) Bacterial Biomass (GPB)

The NT.Cover.No.Graze.Int. treatment also resulted in the highest GPB in autumn 2015 post cover crops samples and was 108% greater than that of the Conv. Till treatment, which had the least GPB (Table 5.6; $p<0.05$). Gram (+) bacteria in the NT.Cover.No.Graze.Int. treatment were also greater than in all other treatments, and all no till treatments had GPB biomass greater than Conv. Till. Treatments with cover crops, grazed/non-grazed and intercropping in autumn 2015 had 32 - 52% higher GPB compared to the no cover crops treatments of Conv. Till and NT.No.Cover. Fewer treatment differences were observed in samples taken during wheat periods, but Conv. Till again tended to have the lowest GPB (Table 5.5).

Table 5.6: Gram (+) bacterial biomass in soil samples collected post cover crops and post and active wheat growth.

Treatment	Gram (+) Biomass (ng g^{-1})			
	Winter 2015	**Spring 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	347c†	535b	490c	410a
NT.No.Cover	446abc	581b	697b	387a
NT.No.Cover.Int	473abc	581b	802b	329a
NT.Cover.Graze	606a	677a	782b	405a
NT.Cover.No.Graze	542ab	611ab	740b	322a
NT.Cover.Graze.Int	376bc	684a	752b	450a
NT.Cover.No.Graze.Int	490abc	585b	1021a	408a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

f. Total Fungal Biomass (TFB)

The NT.Cover.No.Graze.Int treatment had the highest TFB in autumn 2015 post cover crops samples, which was about 5 times greater than the Conv. Till treatment (Table 5.7; $p<0.05$). Cover crops, grazed/ungrazed and intercropped treatments increased TFB by 48–82 % compared to no cover crops treatments (Conv. Till and NT.No.Cover). No significant differences in TFB were observed at this time among the rest of the NT treatments. Total fungal biomass at this sampling for NT.Cover.Graze.Int was reduced by 54% compared to NT.Cover.No.Graze.Int. (Table 5.7; $p<0.05$), and likely can be attributed to the 47% cover crops biomass reduction due to grazing that was observed during that period (Table 3.3).

Table 5.7: Total fungal biomass in soil samples collected post cover crops and post and active wheat growth.

Treatment	Total Fungal Biomass (ng g^{-1})			
	Winter 2015	**Spring 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	66b†	51b	97d	127a
NT.No.Cover	245ab	146a	286bc	170a
NT.No.Cover.Int	268a	141a	375b	141a
NT.Cover.Graze	283a	103ab	346b	169a
NT.Cover.No.Graze	308a	107ab	313b	117a
NT.Cover.Graze.Int	184ab	149a	257bc	140a
NT.Cover.No.Graze.Int	293a	123ab	553a	195a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Fewer significant treatment differences for TFB were observed in samples from wheat growth periods, although the Conv. till treatment again tended to be lowest.

g. Arbuscular Mycorrhizal Biomass (AMB)

In samples collected in autumn 2015, the third year following cover crops, the NT.Cover.No.Graze.Int treatment also exhibited the greatest AMB, which was about 6 times higher than the CT treatment with the least (Table 5.8; $p<0.05$). Cover crops, grazed/ungrazed and intercropped treatments had 69–84 % higher AMB compared to no cover crops treatments (Conv. Till and NT.No.Cover). Conventional tillage had numerically the lowest AMB at all sampling periods. No till with or without cover crops was generally conducive to AMB growth.

Table 5.8: Arbuscular mycorrhizal biomass in soil samples collected post cover crops and post and active wheat growth.

Treatment	Arbuscular Mycorrhizal Biomass (ng g^{-1})			
	Winter 2015	**Spring 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	16b†	12b	19d	15c
NT.No.Cover	35ab	42a	37dc	33bc
NT.No.Cover.Int	48ab	22ab	67b	39abc
NT.Cover.Graze	73a	22ab	72b	52ab
NT.Cover.No.Graze	67a	30ab	55bc	41abc
NT.Cover.Graze.Int	40ab	38ab	54bc	56ab
NT.Cover.No.Graze.Int	66a	38ab	119a	66a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

An evaluation of aggregate size distribution and mean weight diameter (MWD) in the top 5 cm of soil showed all no-till treatments having higher large macroaggregates and MWD compared to the Conv. Till treatment (Table 2.4). Cover crops treatments trended numerically higher for this parameter compared to no cover crops treatments. The AMB data is discussed relative to aggregate sizes and MWD in Chapter II. A correlation analysis of AMF and MWD in the top 5 cm showed a R^2 of 0.75.

h. Saprophytes Biomass (SB)

As opposed to results for other microorganisms during active wheat growing periods, SB was the least in samples from winter 2015, which was significantly lower than all other treatments except NT.Cover.Graze.Int (Table 5.9; $p<0.05$). Saprophytes biomass in post cover crops samples from autumn 2015 was highest for the NT.Cover.No.Graze.Int treatment (323 ng g^{-1}), about 4 times that of Conv. Till without a cover crop (79 ng g^{-1}). There were no significant differences among the rest of the NT treatments. Saprophytes are heterotrophic microorganisms whose sources of energy and C are primarily dead and decaying organic materials. Cover crops residues and root biomass from radish and turnip intercrops may have enhanced SB. Turnips and radishes add root C which is generally more stable than residue C (Kong and Six, 2010; Kong et al., 2011).

Table 5.9: Saprophytes biomass in soil samples collected post cover crops and post active wheat growth.

Treatment	**Saprophytes Biomass (ng g^{-1})**			
	Winter 2015	**Spring 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	51b†	38b	79c	104a
NT.No.Cover	209a	104a	249b	137a
NT.No.Cover.Int	220a	118a	256b	107a
NT.Cover.Graze	209a	82ab	274ab	131a
NT.Cover.No.Graze	242a	76ab	258b	86a
NT.Cover.Graze.Int	144ab	111a	201b	99a
NT.Cover.No.Graze.Int	227a	85ab	323a	139a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

i. Protozoa Biomass (PB)

Protozoa biomass was lowest for Conv. Till at all samplings, except winter 2016 (Table 5.10). Protozoa biomass was highest in autumn 2015 post cover crops samples, with NT.Cover.No.Graze.Int showing the highest PB, which was significantly greater than all other treatments, and Conv. Till without a cover crop being significantly lower than other treatments ($p<0.05$). There were no significant differences among the rest of the no-till treatments.

Table 5.10: Protozoa biomass in soil collected post cover crops and post and active wheat growth.

Treatment	**Protozoa Biomass (ng g^{-1})**			
	Winter 2015	**Spring 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	0.0c†	0.0c	1.0d	7.3b
NT.No.Cover	14abc	6.2abc	12bc	6.6b
NT.No.Cover.Int	17abc	7.1ab	17bc	15ab
NT.Cover.Graze	30a	3.7bc	21b	15ab
NT.Cover.No.Graze	18abc	3.0bc	18bc	4.6b
NT.Cover.Graze.Int	9.2bc	11a	11bc	11ab
NT.Cover.No.Graze.Int	24ab	5.8abc	39a	25a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

j. Undifferentiated Biomass (UB)

Undifferentiated biomass is from the leftover fatty acids from a sample that cannot be linked to any particular functional group using biomarkers. Samples from the post cover crops period in autumn 2015 for Conv. Till and no-till wheat without cover crops had the least UB compared all other treatments (Table 5.11; $p<0.05$). The NT.Cover.No.Graze.Int treatment, in contrast, had the highest UB in these samples, while there were no significant differences among

the rest of the no till treatments (Table 5.11). Cover crops, grazed or ungrazed and intercropping increased UB by 33–48 % over no cover crop treatments. Few readily explainable treatment differences were observed in samples collected during wheat growth periods.

Table 5.11: Undifferentiated biomass in soil samples collected post cover crops and post and active wheat growth.

Treatment	Undifferentiated Biomass (ng g^{-1})			
	Winter 2015	**Summer 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	599d†	485a	671c	713a
NT.No.Cover	1455ab	503a	862c	776a
NT.No.Cover.Int	1020bdc	532a	1288a	618a
NT.Cover.Graze	1627a	650a	1118ab	741a
NT.Cover.No.Graze	1346abc	507a	1062ab	735a
NT.Cover.Graze.Int	668d	555a	1089ab	748a
NT.Cover.No.Graze.Int	861dc	528a	1289a	745a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

k. Fungi: Bacteria ratio (FBR)

The highest FBR of 0.37 was found in samples for NT.Cover.No.Graze.Int from autumn 2015 post cover crops sampling (Table 5.12; $p<0.05$). Conventional till wheat without a cover crop had the lowest FBR for each sampling period and was significantly lower than all others treatments in this sampling plus in the winter 2015 wheat sampling. FBR is expressed as the fungal sum divided by the bacterial sum (Frostegard and Baath, 1996). The PLFA concentrations in these analyses are not converted to absolute biomass values, and the FBR shown is therefore a biomass index, showing only relative changes in the ratio of fungal to bacteria biomass. The FBR determined by PLFA are therefore usually less than 1.0. (Frostegard and Baath, 1996).

Table 5.12: Fungi:bacteria ratio in soil samples collected post cover crops and post and active wheat growth.

Treatment	Fungi: Bacteria ratio (ng g^{-1})			
	Winter 2015	**Spring 2015**	**Autumn 2015**	**Winter 2016**
	Active Wheat	**Post Wheat**	**Post Cover Crops**	**Active Wheat**
Conv. Till	0.11b†	0.06c	0.10c	0.12b
NT.No.Cover	0.26a	0.18a	0.22ab	0.23ab
NT.No.Cover.Int	0.28a	0.15ab	0.27ab	0.25ab
NT.Cover.Graze	0.21ab	0.10bc	0.28a	0.26a
NT.Cover.No.Graze	0.29a	0.12abc	0.26ab	0.22ab
NT.Cover.Graze.Int	0.27a	0.14ab	0.19b	0.22ab
NT.Cover.No.Graze.Int	0.27a	0.14ab	0.37a	0.27a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Solvita Soil Test (1-day CO_2-C)

The flush of CO_2 1 day after rewetting dried soil showed the Conv. Till treatment consistently resulting in the lowest CO_2-C values (Table 5.13) and corresponded with TBB (Table 5.3) and TFB (Table 5.7) with R^2 values of 74 and 57 respectively following cover crops. Various NT treatments resulted in the greatest 1-day CO_2 evolution (Table 5.13). Solvita 1-day CO_2–C for the Conv. Till treatment in the first year of study in fall 2013 implementing tillage dropped by 26 % from 23 mg kg^{-1} prior to study initiation to 17 mg kg^{-1} after the very first tillage operation. Water extractable organic C (WEOC) dropped by 14% from 153 mg kg^{-1} to 132 mg kg^{-1}, while water extractable organic N (WEON) fell by 10% from 10 mg kg^{-1} to 9 mg kg^{-1}. The first year of cover crops mix under NT recorded spikes of 30%, 8% and 20% in Solvita 1-day CO_2–C (Table 5.13), soil WEOC (SOC) (Table 5.14) and WEON (SON) (Table 5.15), respectively.

Table 5.13: Solvita 1-day CO_2-C from soil samples from fall 2013 through spring 2016. Values are in mg kg^{-1}.

Treatment	Fall 2013	Spring 2014	Fall 2014	Spring 2015	Fall 2015	Spring 2016
Conv. Till	17b†	12b	15a	9c	28b	47b
NT.No.Cover	29ab	15ab	27a	23a	62a	104ab
NT.No.Cover.Int	29ab	15ab	11a	19ab	30b	113a
NT.Cover.Graze	25ab	15ab	22a	13bc	30b	69ab
NT.Cover.No.Graze	38a	18ab	27a	12bc	29b	109a
NT.Cover.Graze. Int	23ab	18ab	20a	15abc	35ab	76ab
NT.Cover.No.Graze.Int	37a	27a	23a	16abc	30b	90ab

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Water extractable organic C (WEOC)

Soil samples from Conv.Till wheat without a cover crop exhibited numerically lower WEOC over the entire study period compared to no-till treatments with or without cover crops (Table 5.14). Soil from the first sampling after cover crops (Fall 2013) showed the NT.Cover.No.Graze treatment with the highest WEOC of 189 mg kg^{-1} and was significantly greater compared to all no cover crops treatments (Conv.Till and NT.No.Cover). (Table 5.14; $P<0.05$). Soil from second and third samplings after cover crops (Fall 2014 and Fall 2015) again showed analogous treatment effects. Samples from wheat growth periods (Spring 2014, 2015 and 2016) seemed to exhibit fewer distinct treatment differences. A gradual increase in WEOC due to no-till, cover crops and intercropping was observed.

Table 5.14: water extractable organic C from soil samples from fall 2013 through spring 2016. Values are in mg kg^{-1}.

Treatment	Fall 2013	Spring 2014	Fall 2014	Spring 2015	Fall 2015	Spring 2016
Conv. Till	132b†	127a	107b	186c	114b	140b
NT.No.Cover	135b	130a	126ab	230ab	142ab	217a
NT.No.Cover.Int	155ab	125a	111b	239a	127ab	191ab
NT.Cover.Graze	164ab	136a	135a	196bc	122ab	197ab
NT.Cover.No.Graze	189a	159a	128ab	191bc	151ab	199ab
NT.Cover.Graze. Int	167ab	137a	137a	210abc	163a	184ab
NT.Cover.No.Graze.Int	181ab	135a	132ab	217abc	143ab	191ab

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Water extractable organic N (WEON)

Soil samples from the first sampling after cover crops (Fall 2013) showed Conv. Till and NT.No.Cover crop treatments with lower WEON compared to cover crop treatments (Table 5.15; $p>0.05$). The NT.Cover.No.Graze.Int treatment showed the highest WEON in these samples of 15.4 mg kg^{-1} (Table 5.15), which was greater than no cover crops treatments. Soil from no till treatments with cover crops was again greater in WEON than the Conv. Till treatment without cover crops in Fall 2015. Fewer significant treatment effects were noted in post wheat samples. WEON is easily transformed by soil biota into inorganic N (Haney et al., 2012). Soil WEON and WEOC are normally highly correlated. The WEON and WEOC in post cover crops samples were statistically correlated, with average $R^2=0.84$. The impact of no-till with cover crops on soil in continuous wheat systems seemed to be gradual. Soil organic C and N drives microbial growth and proliferation and subsequent nutrient cycling that improves soil quality and sustainable ecosystem services (Dalal et al., 1991; Saffigna et al., 1989; Kapkiyai et al., 1999).

Table 5.15: Water extractable organic N from soil samples from fall 2013 through spring 2016.Values are in mg kg^{-1}.

Treatment	Fall 2013	Spring 2014	Fall 2014	Spring 2015	Fall 2015	Spring 2016
Conv. Till	8.9e†	9.5a	24.6a	10.0b	9.5c	11.7b
NT.No.Cover	9.4ed	11.2a	24.3ab	14.2a	12.1bc	15.8a
NT.No.Cover.Int	10.7cde	11.4a	22.0ab	14.6a	10.8bc	15.4ab
NT.Cover.Graze	12.7abc	11.8a	21.7ab	13.9a	13.4ab	16.8a
NT.Cover.No.Graze	15.4a	11.9a	20.0b	13.7ab	13.7ab	16.9a
NT.Cover.Graze. Int	12.1bcd	11.5a	22.1ab	15.7a	16.6a	15.7a
NT.Cover.No.Graze.Int	14.2ab	10.9a	21.3ab	14.3a	13.7ab	15.7a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Soil Organic Phosphorus

The Haney H^3A extractant was used for soil P extraction (Haney et. al., 2006). Organic P was calculated as total P minus inorganic P. No significant differences in Haney soil organic P due to treatment were noted for the duration of the study (Table 5.16).

Table 5.16: Haney Soil Organic P extracted from soil samples from fall 2013 through spring 2016. Values are in mg kg^{-1}.

Treatment	Fall 2013	Spring 2014	Fall 2014	Spring 2015	Fall 2015	Spring 2016
Conv. Till	5.90a†	13.8a	1.22a	0.53a	3.61a	18.6a
NT.No.Cover	4.92a	14.3a	2.89a	1.91a	4.65a	13.9a
NT.No.Cover.Int	5.76a	16.8a	1.85a	2.41a	4.70a	19.4a
NT.Cover.Graze	4.51a	13.7a	2.20a	1.23a	4.62a	12.1a
NT.Cover.No.Graze	5.52a	13.3a	3.68a	1.95a	3.97a	19.9a
NT.Cover.Graze. Int	2.22a	13.0a	3.51a	2.85a	4.47a	13.1a
NT.Cover.No.Graze.Int	4.70a	15.5a	2.07a	2.20a	3.89a	20.0a

† Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

Discussion

Tillage had a direct impact on total living microbial biomass (TBB). Conventional tillage affects soil moisture and temperature by speeding up the drying process and negatively affecting soil biota multiplication (Frey et al. 1999; Spedding et al. 2004). Six et al. (2001) observed a general decrease in C under CT compared to NT in both temperate and tropical soils. Hungria et al. (2009) concluded that soil microbiota was more deficient in C under CT. The NT cover crop practice created better conditions for TBB proliferation by providing substrates, and more favorable temperatures and moisture contents. Exudates from roots, residue decomposition and turnover of fine roots can add C to soil ecosystems that increases soil microbial biomass (Buyer et al. 2010; Maul and Drinkwater 2010; Kong and Six 2012).

Surface residues and root biomass in no till cover crops treatments significantly increased TBB compared to no cover crops treatments (Table 5.3). Brennan and Acosta-Martinez (2017) noted that increasing cover cropping intensity increased bacterial phyla in a study in California using legume-rye, mustard (*Brassica sp*.), or rye only as cover crops.

The combination of no soil disturbance and residue addition fostered actinomycetes proliferation (Table 5.4), which agrees with other studies (Gonzalez-Chavez et al., 2010; Ladd et al., 1994). Actinomycetes resemble fungi, although they are bacteria, and like fungi, they also form multicellular filaments capable of binding soil particles together into stable aggregates. Actinomycetes are credited with degrading cellulose and solubilizing lignin and are more tolerant to higher temperatures than fungi, although their degradation ability is not as great (Crawford, 1983; Godden et al., 1992). The ability of these microbes to mineralize lignin is limited (Eriksson et al., 1990; Godden et al., 1992), and are generally more efficient at degrading grass lignin compared to wood lignin (Buswell and Odier, 1987).

The relative higher numbers for GPB compared to GNB can be explained by differences in cell wall architecture. Gram positive bacteria have thicker cell walls compared to GNB and can better survive harsher drier environments than GNB (Silhavy et al., 2010). Gram positive bacteria have thus been observed in outer areas of soil macroaggregates, while GNB are found in greater abundance inside aggregates (Frasier et al., 2016; Hattori, 1988). Gram positive filamentous bacteria, actinomycetes, are known for degrading resistant compounds like lignin (Buswell and Odier, 1987).

Generally, lower GNB was observed compared to GPB (Table 5.5) during this investigation. This finding is contrary to other findings where the rhizosphere has been reported to harbor more GNB than GPB (Paul and Clark, 1996). However, in a study in Wyoming, Ghimire et al. (2014) found increases in GPB over GNB and attributed it to C source diversity and reduced soil disturbance. Gram (-) bacteria are copiotrophs that utilize labile C sources more efficiently, while GPB are oligotrophic and exploit more recalcitrant C sources (Fierer et al., 2007). Our cover crop mix was dominated by recalcitrant grass species, which may explain why GPB dominated GNB in the microbial community.

Finney et al. (2017) using an 8 cover crop species mix (sunn hemp, soybean, red clover, hairy vetch, forage radish, oat, canola and cereal rye) increased GPB compared to a NT no cover crop treatment. Results of other studies also agreed with these findings (Buyer et al., 2010; Maul et al., 2014).

The cover crop mix being primarily composed of grasses added residue that was higher in lignin, theoretically favoring relatively more fungi (Bossuyt et al., 2001; Kramer et al., 2012). Legumes in the cover crops mix succumbed due to low precipitation and erratic rainfall distribution witnessed during the study period.

No-till treatments increased total soil TFB compared to CT (Table 5.7), which concurred with other research findings (Klavdivko, 2001; Frey et al., 1999; Beare et al., 1997). However, some studies have also reported either no effect or decreases in fungal biomass under no-till (Spedding et al., 2004; Helgason et al., 2009). The fungal proliferation observed was also possibly due to increased diversity of residue from cover crops (Ranjard and Richaume, 2001). The lowest TFB observed under Conv. Till. may be related to tillage directly damaging fungal tissue and drastically reducing abundance (Balesdent et al., 2000; Six et al., 2002). Low water extractable organic C levels (Table 5.14) that were recorded during the same period correlated with the lowest TFB values that were observed under Conv. Till. Mathew et al. (2012) positively correlated fungal biomarkers with SOC.

The relative increase in FBR that was observed in this study was attributed to no till and cover crop practices (Table 5.12). Manure and cover crops have been reported to have a huge influence on soil microbial communities (Fraser, 1988; Powlson, 1987). The study site's soil texture, clay loam, may also have played a role in the results that were observed in this investigation, as the silt and clay may have stimulated amino sugar stabilization resulting in long-term C storage (Glaser et al., 2006; Zhang et al., 1998). Guggenberger et al. (1999) reported no increase in fungal biomass in some sites due to the lowest clay and silt contents at those sites. However, to the contrary, Strickland and Rousk (2009) reported no significant differences in FBRs in a study similar to ours.

Other studies have shown grass species cover crops, oat (*Avena sativa)*, cereal rye (*Secale cereale* L.) and winter wheat (*Triticum aestivum* L.) increasing AMB in soils (Kabir and Koide, 2000; Kabir and Koide, 2002; Lehman et al., 2012; White and Weil, 2010).

Significant increases in mycorrhizal biomass under no-till have also been reported for other cropping systems like cotton and maize (*Zea mays* L.)-wheat rotation (Acosta-Martínez et al., 2010; Drijber et al., 2000; Wang et al., 2012). Hyphal networks of AMF are physically disrupted by tillage, which may also decrease soil moisture (Helgason et al., 2009; Simmons and Coleman, 2008). Tillage destroys mycorrhizal hyphae in soil, reducing P accumulation by AMB (Evans & Miller, 1990; McGonigle and Miller, 1996). Mycorrhizal fungi establish plant root-fungal interactions important for water and nutrient uptake. Arbuscular mycorrhizal fungi have also been linked to SOC physical protection through increased macroaggregation (Six et al., 2006). Arbuscular mycorrhizal fungi also produce the glycoprotein, glomalin, that helps bind soil particles into aggregates, thereby improving soil physical properties. Arbuscular mycorrhizal fungi play a pivotal role in soil aggregation and stability (Rillig and Mummey 2006; Tisdal and Oades 1982), binding soil particles more strongly together than those in the surrounding matrix (Kemper and Rosenau 1986).

Saprophytes are heterotrophic microorganisms whose sources of energy and C are primarily dead and decaying organic materials. Cover crops residues and root biomass from radish and turnip intercrops may have enhanced SB. Turnips and radishes add root C which is generally more stable than residue C (Kong and Six, 2010; Kong et al., 2011).

Protozoa consume bacteria (Wood, 1989) and are involved in organic matter decomposition and nutrient cycling in the rhizosphere (Foissner, 1999). Relatively higher protozoa biomass indicates a soil ecosystem that enhances nutrient cycling through predation on bacteria. Protozoa populations are also a good indicator of soil quality since they feed on other organisms and react swiftly to any changes in management systems (Foissner, 1999). Protozoa

and nematodes discriminately feed on bacteria and fungi, shifting soil microbiota community and residue decomposition rates (Ingham, 1998).

The research site had been under no-till since 2001 prior to treatment imposition in 2013 at the inception of this study. The consistently lower FBR in the Conv. Till treatment, especially in autumn 2015 post cover crops samples, indicated a tillage induced shift in the relative abundance of fungi and bacteria in the soil ecosystem. The higher FBR in no till cover, grazed and intercropped systems compared to Conv. Till is a clear indication of the impact of tillage on soil microbiota. Soil tillage mechanically destroys soil macroaggregates, and in the process exposes protected organic matter to oxidation (Beare et al., 1994) and rapid mineralization (Alvear et al., 2005). Sparling (1997) noted that for a soil undergoing degradation, microbial C will decline more rapidly compared to organic matter. Hungria et al. (2009) concurred asserting that under CT microorganisms were more C limited. Soil tillage has also been reported to negatively affect soil microbial activity (Hussain et al., 1999; Sagar et al., 2001).

Several studies (Minoshima et al., 2007; Spedding et al., 2004, Runion et al., 2004; Feng et al., 2003; Drijber et al., 2000) reported a proportional increase in abundance of both bacteria and fungi under no-till. Surface residue quality also affects soil fungal and bacterial community composition (Nicolardot et al., 2007). The low-quality residue from the cover crops mix generally resulted in cover crops treatments having increased fungi vs. bacteria biomass, as also shown in other studies (Bossuyt et al., 2001; Kramer et al., 2012). However, some research findings are in contrast, with no fungal dominance being witnessed under no till (Spedding et al., 2004). Helgason et al. (2009) actually reported no till favoring bacterial activity.

Fungal residues have been reported to decompose slower than bacterial residues (Martin and Haider, 1979), and thus F:B ratio can potentially be used as a relative measure for soil C

storage and as an indicator for sustainable soil ecosystems (Bardgett and McAlister, 1999; Bailey et al., 2002). Fungi are initial and early colonizers that are involved in macromolecule lignin and cellulose breakdown into smaller units that benefits bacteria and some fungi that cannot directly utilize cellulose. Minimum soil disturbance as observed under no-till favors fungal hyphal network growth and proliferation as substantiated by higher fungal biomass under no-till treatments compared to conventional till (Wardle, 1995).

The drop in Solvita 1-day CO_2–C observed due to tillage can be related to negative impact on soil microbiota. Other studies have also reported tillage as having adverse effects on soil microbial activity (Hussain et al., 1999; Sagar et al., 2001). Research reported by Holland and Coleman (1987) showed NT soil produced about three times more CO_2–C than conventionally tilled surface soils. Mixing plant residues with soil through plowing alters metabolic quotient, with no-till being more efficient in sequestering C (Ocio and Brookes, 1990). Although this study did not show any significant impact on soil organic phosphorus due to CT, NT, cover crops, intercropping or grazing at this time. Cover crops species, like oats and rye, with mycorrhizal associations, can increase arbuscular mycorrhizal colonization in soils, thereby facilitating P uptake by following crops (Karasawa et al., 2002; Kabir and Koide, 2002). However, cover cropping has not been associated with organic P accumulation but only mineralization and turnover of microbial P (Oberson et al., 1996; Daroub et al., 2001; Kuo et al., 2005).

Tillage had a profound impact on biological, chemical and physical characteristics of the soil ecosystem for a site that has been under no-till since 2001. These effects were more pronounced in autumn 2015 following a tillage event prior to wheat seeding. Conventional tillage resulted in significantly lower mycorrhizal fungi (Table 5.8), GPB (Table 5.6) and GNB

(Table 5.5), saprophytes (Table 5.9), and protozoa (Table 5.10) than all other treatments. The Conv. Tillage treatment also trended lowest in total soil microbial biomass, TBB (Table 5.3), TFB (Table 5.7), PB (Table 5.10), Solvita 1-day CO_2-C (Table 5.13), WEOC (Table 5.14), WEON (Table 5.15) and ammonium-N (Table 4.4 and 4.5) during this investigation. Declines in microbial biomass have been linked to soil degradation (Doran and Parkin, 1994; Sparling, 1997). Each tillage event can accelerate a temporary microbial flush that results in higher CO_2-C losses and reduced diversity of soil microbiota. Other research (Govaerts et al., 2008; Helgason et al., 2009) has reported greater bacteria and fungi under no-till compared to conventional till as with our findings. No-till and cover crops have been reported to increase SOC (Motta et al., 2001; Ding et al., 2002) and microbial biomass C (Granatstein et al., 2002; Franzluebbers et al., 1994). Soil tillage can disrupt soil structure, hastening SOC mineralization, while no-till can increase arbuscular mycorrhizae which can increase soil aggregation, findings from our study that are consistent with other studies (Alvear et al., 2005).

Greater cropping intensity appeared to improve soil quality compared to leaving the land fallow. Drijber et al. (2000) demonstrated how soils planted to wheat following a legume crop had higher microbial biomass compared to that of a wheat fallow rotation. Practices that promote less soil disturbance, like no-till, promote soil macroaggregation that protects microbiota habitat, with residues providing substrates (Borga et al., 1994; Bossio et al., 1998; Zelles et al., 1992). The bacterial biomass increase observed in our study was likely related to labile C from freshly added cover crops. No till cover crops also increased WEON and SOC (Tables 5.15 and 2.9), thereby enhancing soil microbial growth and proliferation observed during the same periods (Table 5.3). Conversely, tillage reduced WEON and SOC during this study (Tables 5.15 and 2.9).

WEOC is generally a readily available C source for soil microbes (Haney et al., 2008). Blanco-Canqui et al. (2015) asserted the need for continuous use of cover crops in semi-arid regions for sustained soil benefit. Brennan and Acosta-Martinez (2017) showed that increased frequency of cover cropping increased microbial C in soil. The impact of cover crops on SOC may take years to be observable, while decreases in SOC with tillage can rapidly occur (Dalal and Mayer, 1986; Balesdent et al., 1990; Cambardella and Elliott, 1993; Franzluebbers et al., 1995; Soon et al., 2001). Soil cultivation destroys soil organic matter protection of C through aggregate degradation, enhancing organic C oxidation (Beare et al. 1994).

Conclusion

The introduction of NT cover crops and intercropping to continuous wheat systems had a beneficial effect on soil microbial community structure and nutrient cycling. Phospholipid Fatty Acid (PLFA) profiling in soils post NT cover crop and intercropping increased biomass for total living microbial mass, total bacteria, total fungi, gram (+) bacteria, gram (-) bacteria, arbuscular mycorrhiza, saprophytes, protozoa, and undifferentiated microbes compared to CT. Conventional tillage had a profound and swift impact on the soil ecosystem. Conventional tillage physically disrupts soil structure exposing organic matter and hastening mineralization by increasing rates of decomposition. Conventional tillage affected soil moisture and temperature. Tillage when temperatures are high under moderate soil moisture conditions stimulates microbial activity with more nutrient release to the soil ecosystem. The subsequent soil drying negatively impacted soil microbiota activity and proliferation.

No-till, cover crops and intercropping tended to bring about ecosystem stability. The NT soil ecosystem exhibited greater nutritional balance and less environmental stress. No-till

enhanced soil aggregation. Cover crops and intercropping with radishes and turnips increased above ground residues and below ground root biomass and root C. The surface residue reduced surface evaporation, creating conducive conditions for slower mineralization and sustained release of nutrients from organic matter, resulting in a higher net mineralization compared to conventional tillage. Slower mineralization effectively mineralizes more with reduced potential losses to the environment.

The fungi:bacteria ratio increased in cover crops and intercropped treatments over CT. The residue, which had relatively high C:N ratio, increased fungal over bacterial biomass. Solvita 1-day CO_2-C was in agreement with PLFA profiles and with SOC (R^2=0.84), SON (R^2=0.69) and NH_4^+–N (R^2=0.94), and was a manifestation of the positive impact NT, cover crops and intercropping on soil microbiota and consequently soil quality under monoculture wheat systems. The effects of grazing on the above were minimal and inconclusive.

No till cover crops brought microbial diversity and proliferation to monoculture wheat systems. Introduction of cover crops to agroecosystems enhanced soil quality by creating conditions that promote diversity, nutrient cycling, and multiplying of soil biota instrumental in soil aggregation. Cover crops technology leveraged resilience of agroecosystems for sustainable production that is environmental friendly, with a potential of curtailing radiative CO_2 losses to the atmosphere and sinking C into the soil ecosystem.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Reintroduction of cover crops into twenty-first century agriculture has drawn worldwide attention and is in part due to an ever-growing population that has propelled science into considering sustainable ecosystem services and functions. The USDA-NRCS Soil Health initiative was launched in 2012, providing a framework and guiding principles for improving soil health and quality. These principles advocate for keeping soil covered, using minimum soil disturbance, increasing crop diversity, and utilizing proper grazing management. The prevalent continuous wheat production system of the Southern Great Plains was identified as potentially benefiting from cover crops technology. The objective of this research was to determine changes in soil biogeochemistry, soil physical properties and moisture dynamics of continuous wheat systems as impacted by cover crops, grazing and mixed intercropping in the Texas Rolling Plains.

Cover crops included during the fallow period in this study inevitably used soil moisture in comparison to treatments with no cover crops. Moisture depletion by cover crops was more discernable at study inception, partly due to the recurrent drought, and eased with subsequent seasons. Precipitation following cover crops tended to even out stored soil water for all treatments whether with or without cover crops. In the final year of cover cropping, CT without a cover crop had the least stored soil water at both the beginning and end of the growing season, while treatments with cover crops exhibited numerically greater stored moisture. Cover crops increased soil moisture recharge and soil water holding capacity.

Cover crops mitigated potential soil NO_3^-–N losses, likely through microbial immobilization. All no cover crops treatments showed higher soil NO_3^-–N, with Conv. Till

having the highest in comparison to cover crops treatments. Conventional tillage apparently stimulated mineralization and subsequent nitrification, increasing the risk for possible NO_3^- leaching. Continued use of cover crops with high C:N ratio caused apparent N immobilization and deficiency which negatively impacted wheat yields in the final year of investigation. Research on inorganic fertilizer management for semi-arid regions where establishment of legumes is a problem under dryland conditions is needed to help mitigate N immobilization by cover crop residue. Soil organic N and C as determined by the Haney test were higher in NT cover crops treatments compared to CT. No treatment effects were observed for P and S. Haney soil K was lowest under Conv. Till. No till cover crops treatments increased total plant C and SOC, although the latter effect was short lived. No significant effects on nutrient cycling were observed due to grazing and/or intercropping with turnips and radishes.

The soil microbial impact of cover crops in continuous wheat was evaluated using Phospholipid Fatty Acid (PLFA) profiling to characterize soil microbial community and structure and nutrient cycling relationships. PLFA quantifies living microbiota which is actively involved in nutrient cycling. The introduction of cover crops into the fallow period of continuous wheat systems changed the soil microbial community and structure. No till cover crops and intercropping treatments increased the biomass for total living microbial biomass, total bacteria, total fungi, gram (+) bacteria, gram (-) bacteria, arbuscular mycorrhiza, saprophytes, protozoa, and undifferentiated microbes compared to conventional tillage. The no-till with cover crops combination apparently created a more favorable environment for soil biota proliferation and diversity. Cover crops produced above and below ground biomass, providing substrates for soil microorganisms. No-till enhanced soil aggregation, surface mulching and reduced evaporation and temperature of surface soil. Correlation analyses of Solvita 1-day CO_2-C with SOC, SON

and NH_4^+–N showed strong relationships with R^2 of 0.84, 0.69 and 0.93, respectively. No till with cover crops increased soil biota and nutrient cycling. Grazing and intercropping impacts were not observed for most studied parameters.

Changes in soil physical properties after three years of treatment were noted in this study. Conventional tillage resulted in fewer large macroaggregates in surface soil, lower aggregate mean weight diameter, and higher soil bulk density. Under rainfall simulation, Conv. Till had the shortest time to runoff initiation and the highest concentrations of total solids, total P and NH_4^+–N in runoff. Conversely, soils under NT with cover crops showed higher aggregation and infiltration rates and lower nutrient runoff loads. No-till cover crops treatments improved soil physical properties which were manifested in the soil water dynamics witnessed during the course of the study.

Although cover crops use soil moisture, soil water profiles were similar to those of no cover crop treatments after cover termination and the first significant rainfall event. Cover crops added biomass, provided surface mulching, and increased soil microbiota, nutrient cycling, soil macroaggregation, aggregate stability, infiltration rates and water holding capacity. Cover crops reduced surface runoff and runoff nutrient loads. Strategic adoption of cover crops into continuous wheat systems should include a full cost/benefit analysis, optimization of time of cover crop planting and termination, and close monitoring of rainfall forecasts in order to improve success.

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APPENDIX

Soil Potassium

2013/2014 season

Generally, Mehlich extractable soil potassium (K) did not show any significant variations due to treatment effects from 2013 to 2016. The first year of cover crops, 2013 did not show any differences in soil K (Table 4.15) for both post cover crops and post wheat periods.

Table A.1: Extractable soil potassium in post cover and post wheat samples in 2013/14

Treatments	Fall 2013 soil K by depth (mg kg^{-1})				Spring 2014 soil K by depth (mg kg^{-1})			
Depth (cm):	**0-15**	**15-60**			**0-15**	**15-30**	**30-60**	
Conv. Till	241a	196a			222a	187a	140b	
NT.No.Cover	263a	199a			248a	192a	164ab	
NT.No.Cover.Int	257a	182ab			215a	187a	160ab	
NT.Cover.Graze	225a	153c			234a	177a	151ab	
NT.Cover.No.Graze	254a	157bc			219a	185a	167ab	
NT.Cover.Graze. Int	252a	160bc			236a	197a	177a	
NT.Cover.No.Graze.Int	239a	169bc			236a	208a	164ab	

† Means within a column followed by the same letter are not different by LSD (0.05).

2014/2015 season

The same trends were observed the second year running of cover crops. There were no useful significant differences due to treatment effects in Mehlich extracted soil K for 2014/2015 growing season (Table 4.16).

Table A.2: Extractable soil potassium in post cover and post wheat samples in 2014/15

Treatments	Fall 2014 soil K by depth (mg kg^{-1})				Spring 2015 soil K by depth (mg kg^{-1})			
Depth (cm):	**0-15**	**15-30**	**30-60**		**0-5**	**5-15**	**15-30**	**30-60**
Conv. Till	226abc	201ab	178ab		230a	212a	194a	218a
NT.No.Cover	207bc	185b	180ab		269a	196a	198a	195ab
NT.No.Cover.Int	239ab	222a	201a		212a	185a	204a	180ab
NT.Cover.Graze	197c	198ab	172ab		250a	217a	242a	174b
NT.Cover.No.Graze	226abc	200ab	174ab		256a	189a	190a	218a
NT.Cover.Graze. Int	218bc	175b	158b		258a	199a	192a	207ab
NT.Cover.No.Graze.Int	252a	224a	206a		268a	223a	239a	198ab

† Means within a column followed by the same letter are not different by LSD (0.05).

Soil Sulfur

The soil surface soil S concentrations were not affected by treatment during the entire period under investigation, 2013 to 2016. The differences that were recorded in subsurface horizons did not follow any distinct pattern.

2013/2014 season

The 2013/14 growing season soil Sulfur analyses did not show any significant differences following both cover crops and wheat periods (Table 4.17).

Table A.3: Extractable soil sulfur in post cover and post wheat samples in 2013/14

Treatment	Fall 2013 soil S by depth (mg kg^{-1})			Spring 2014 soil S by depth (mg kg^{-1})		
Depth (cm):	**0-15 cm**	**15-60 cm**		**0-15 cm**	**15-30 cm**	**30-60 cm**
Conv. Till	6.5a†	9.5a		5.3b	6.3a	4.5a
NT.No.Cover	6.5a	32.5a		7.3ab	40.0a	71.0a
NT.No.Cover.Int	5.8a	69.0a		6.0b	11.0a	138.0a
NT.Cover.Graze	5.5a	86.8a		8.5ab	31.3a	157.0a
NT.Cover.No.Graze	5.0a	82.8a		53.8a	8.0a	87.8a
NT.Cover.Graze. Int	5.5a	10.8a		6.3b	3.3a	8.0a
NT.Cover.No.Graze.Int	5.0a	37.0a		7.0ab	10.0a	97.8a

† Means within a column followed by the same letter are not different by LSD (0.05).

2014/2015 season

The 2014/2015 growing season did not show any treatment effect differences of importance either both following cover crops and winter wheat (Table 4.18).

Table A.4: Extractable soil sulfur in post cover and post wheat samples in 2014/15

Treatments	Fall 2014 soil S by depth (mg kg^{-1})				Spring 2015 soil S by depth (mg kg^{-1})			
Depth (cm):	0-15	15-30	30-60		0-5	5-15	15-30	30-60
Conv. Till	13.5ab†	13.8a	70.8ab		6.9a	5.9a	27.8a	9.7a
NT.No.Cover	9.8ab	17.8a	34.8a		9.0a	5.7a	12.7a	6.1a
NT.No.Cover.Int	12.3ab	17.0a	9.5ab		9.3a	6.1a	7.3a	8.3a
NT.Cover.Graze	10.3ab	10.3a	30.8b		10.4a	6.6a	9.4a	12.9a
NT.Cover.No.Graze	9.0b	8.8a	27.3b		8.9a	5.8a	8.6a	11.2a
NT.Cover.Graze. Int	14.0a	29.0a	10.7ab		7.0a	5.9a	7.5a	7.4a
NT.Cover.No.Graze.Int	13.0ab	10.5a	1.4b		9.2a	22.9a	7.2a	8.9a

† Means within a column followed by the same letter are not different by LSD (0.05).