BENEFITS AND CONSEQUENCES OF NO-TILLAGE AND COVER CROPS IN SEMI-ARID COTTON PRODUCTION

A Dissertation

by

JOSEPH ALAN BURKE

Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Julie A. Howe
Co-Chair of Committee,	Katie R. Lewis
Committee Members,	Jamie L. Foster
	Terry J. Gentry
	Thomas W. Boutton
Head of Department,	David D. Baltensperger

December 2022

Major Subject: Soil Science

ABSTRACT

The Texas High Plains (THP) is one of the most agriculturally productive regions of the world, however, the climatic conditions of the area can result in significant wind erosion exemplified by the Dust Bowl of the 1930s. Conservation management practices, such as no-tillage and cover cropping during traditional fallow periods have the potential to significantly reduce wind erodibility, but adoption has been slow because of producers' concerns regarding yield reductions following these practices. The purpose of my studies was to evaluate the two most common concerns with conservation adoption (water limitations and nitrogen (N) immobilization) and quantify the secondary ecosystem service (soil health) benefits from their adoption. The experiments were conducted at the Agricultural Complex for Advanced Research and Extension Systems in Lamesa, TX, in a long-term continuous cotton (*Gossypium hirsutum* L.) cropping system established in 1998. Treatments included 1) conventional tillage, winter fallow (CT); 2) no-tillage with rye (R-NT) (*Secale cereal* L.) cover crop; and 3) no-tillage with mixed species cover (M-NT). The mixed species cover consisted of 50% rye, 33% Austrian winter pea (*Pisum sativum* L.), 10% hairy vetch (*Vicia villosa* Roth), and 7% radish (*Raphanus sativus* L.), by seed weight. Results indicate that R-NT and M-NT significantly increased in-season water and did not reduce cotton yields compared to CT, which challenges the most commonly referenced reason for yield reduction on the THP. Herbage mass decomposition rates in the N immobilization study indicated that cover crop biomass production can potentially negatively impact N cycling potential, while supplemental N earlier in the season can increase cotton lint yield compared to existing Extension fertilizer application recommendations. Conservation management practices significantly increased biological indicators of soil health relative to CT and, in some instances, to native rangeland. Combined, these results demonstrate the additive benefits of conservation practices on the semi-arid THP. Further work addressing the economic and social dynamics of these conservation practices is still needed before widespread adoption should be expected.

DEDICATION

For my mom, Pam –

For putting me on this path in the first place;

For loving me despite me being me;

For encouraging me when I lacked courage;

For reminding me who I was when I forgot;

For sacrificing so I never had to;

And for gifting me a wicked sense of humor.

ACKNOWLEDGMENTS

To my chair, Dr. Lewis, this is where it all began. Thank you for adopting me into your lab when I had no home. It has been seven years since I walked into your Advanced Nutrient Management class, and I can honestly say I was changed for the good. I'm so thankful for how you and Clay (and now Kadence and Cade) welcomed me into your lives. You've supported me when I stumbled, pushed me to be greater than the sum of my parts, made me feel welcome in our world when I wasn't comfortable in my own skin, inspired me to build a legacy, and given me all the tools to grow. If I can manage to be a fraction of the scientists you are, then I will be very successful indeed. I'm excited about your future and to have been part of the effort to build a dynasty. Thank you, thank you, thank you.

To my co-chair, Dr. Howe, thank you for the philosophical discussion about every topic imaginable. I learned so much about the interconnected nature of soils and human health from you. I'll forever be thankful for the guidance I received from you across the desk, in the lab/field, or with a beer between us. Thank you.

To my committee members – thank you for helping me achieve over the last four years. Each of you has made a profound difference in my life. Dr. Foster, thank you for always being a sounding board, poor grammar catcher, a whiz with a heat sealer, and patient with me despite my best efforts to run head-first into a bad situation. Dr. Gentry, your stoicism is legendary and I'm very thankful there is always a twinkle of the eye to match your gaze. Thank you for your review of my work and your willingness to go along with whatever crazy project came to mind. Dr. Boutton, thank you for always reminding me to consider the world outside West Texas and how my work might impact others. You are a giant in science, and I am proud to have worked alongside you.

To all the faculty and staff at AgriLife Research in Lubbock – Gail, Dr. Dever, Dr. Dotray, Jim, Dr. Keeling, JoAnn, Dr. Moore, Cody, Robyn, Justin, Kathy, Maggie, and Dr. Wheeler, and in the Department of Soil and Crop Sciences in College Station – Taylor, Dr. Carson, Barbara, LeAnn, Dana, Ana, and Judy, thank you for all of your unique contributions and friendships. They and you mean the world to me.

To my lab mates in Lubbock – Amee, Tessa, Nicholas, Chris, Debrah, Ethan, Mark, Brandon, Erin, Julia, Lauren, Ray, and Ira; in College Station – Brady, Josh D., Annalee, Josh K., Ariana, Sarah M., Samantha, Isaiah, Carson, and Luke, thank you for all your friendship, support, advice, and talks. I would not be here today if it wasn’t for each of you. To all the ex-officio lab mates who became best friends – Heather, Sarah C., Brian, Holly, Aditi, and Marie, I love y’all and am so thankful for our time together.

To the best friends a guy could ask for – Katie and Paul, Jessica and Joshua, Chris, Kelsey D., Kelsey H. Nicole and Akshay, Emily and Chase, Sherah, Rachel and Michael, Anthony, Jill and Kyle, and Kat and Matt, thank you for always being there for me with a hug, bottle of wine to share, couch to crash on, and a kind ear. I love you all so much.

To my family – Mom, Randy, Matthew, Miranda, and Fawn, you’ve all been there for me since the beginning. You were the first to recognize something in me that I did not think I possessed and then inspired me to follow my dream without asking too often when I would graduate. Thank you for reminding me we aren’t a family of quitters, and that tomorrow is always a fresh start. I love you all so much.

To Kirk – the best boyfriend a man could ask for. This Ph.D. should probably be as much yours as it is mine after having to listen to me explain the work in excruciating detail over the last three years. Thank you for loving me through the stress, reminding me to sleep, and sending me food on occasion when I forgot to eat all day. You've opened my world to what can exist when we are authentically ourselves. You are my inspiration and I love you.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Dr. Katie Lewis (chair) of Texas A&M AgriLife Research at Lubbock, Dr. Julie Howe (co-chair) of the Department of Soil and Crop Sciences, Dr. Jamie Foster of Texas A&M AgriLife Research at Beeville, Dr. Terry Gentry of the Department of Soil and Crop Sciences, and Dr. Thomas Boutton of the Department of Ecology and Conservation Biology. This work was supported through collaborations with Dr. Paul DeLaune of Texas A&M AgriLife Research at Vernon and Dr. Wayne Keeling of Texas A&M AgriLife Research at Lubbock.

The Agricultural Complex for Advanced Research and Extension Systems in Lamesa, TX, USA is a collaborative site between Texas A&M AgriLife Research and Extension Center at Lubbock and the Lamesa Cotton Growers Association. We appreciate their ongoing support.

Funding Sources

Graduate study was supported by Texas A&M AgriLife Research through the Strategic Initiative in Water and Soil Health. This work was also made possible in part by the Texas State Support Committee of Cotton Incorporated under Grant Number 16-400-TX and Texas A&M AgriLife Research.

NOMENCLATURE

ACE	Autoclaved citrate extractable proteins
AcidP	Acid phosphatase
AlkP	Alkaline phosphatase
AG-CARES	Agricultural Complex for Advanced Research and Extension Systems
AMF	Arbuscular mycorrhizae fungi
ρ_b	Bulk density
BG	β-glucosaminidase
CC	Continuous cotton, conventional tillage
CCRC	Continuous cotton, rye cover
CT	Conventional tillage, winter fallow
C_{WUE}	Cotton water use efficiency
DAP	Days after planting
DAT	Days after termination
DM	Dry matter
Δ_{water}	Changes in profile soil water
EC	Electrical conductivity
ET	Evapotranspiration
FP	Farmer Practice
G^+	Gram-positive bacteria
G^-	Gram-negative bacteria
LSD	Least significant difference

M-NT	No-tillage, mixed species cover
NAG	β-glucosaminidase
NAT	Native rangeland
NO_3^--N	Nitrate-N
NRCS	Natural Resources Conservation Service
NUE	Nitrogen use efficiency
PCA	Principal Components Analysis
PIN	Supplemental N applied at pinhead square plus two weeks
PLFA	Phospholipid fatty acids
POxC	Potassium permanganate oxidizable carbon
POS	Supplemental N applied three weeks after cotton emergence
PRE	Supplemental N applied prior to planting cotton
PROC CORR	Correlation analysis
PROC GLIMMIX	Generalized linear mixed models
R-NT	No-tillage, rye cover
SHP	Southern High Plains
SOC	Soil organic carbon
Sulf	Arylsulfatase
THP	Texas High Plains
TN	Total N
VWC, θ	Volumetric water content

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

"Of the future of irrigation here in general, it may be said that there is opportunity for but the little indicated, at these widely scattered spots, but that this little will prove to be just that small amount needed for rendering practicable the utilization of the High Plains." – W.F. Hutson, 1898

Inexplicitly, life on the Texas High Plains (THP) is linked to water, either through precipitation or irrigation from the Ogallala Aquifer. The earliest settlers of the region diverted what little surface water they could find to increase crop and forage production and thus agriculture on the THP was born (Thoburn, 1931; Nostrand, 1996). By the late 1880s, the capacity to irrigate up to 400 ha was made possible through steam-powered irrigation pumps and shallow wells (Hutson, 1898). In one report, Hutson (1898) lavishly reported, "many of these wells are capable of furnishing a supply almost inexhaustible to ordinary means of pumping." Unfortunately, these conditions would not be as sustainable as Hutson predicted. Following World War II, irrigated land on the Texas Panhandle reached a high of 2.4 Mha in 1974 before declining to 1.6 Mha by 1989 and then increasing again to 1.9 Mha by 2000 (Colaizzi et al., 2009). On the Texas Southern High Plains (SHP), the irrigated area decreased 22% from 1998 to 2018 (USDA-NASS 1998, 2018). The decrease in irrigated lands on the THP is not only linked to decreasing water availability from the Ogallala Aquifer, but the environmental and climatic conditions on the THP. Hutson could not have known how dire the situation would become just three decades later when the rains stopped.

The Texas SHP encompasses approximately 54,300 km^2 of west Texas with Lubbock located on the eastern edge of the region (Fig. 1.1). The soils of this region formed from eolian sediments accumulated since the late Miocene epoch and range in texture from loams in the southwest to clays in the northwest (Gustavson and Holliday, 1999). A majority of the region consists of sandy loams and sandy clay loams. The two most prominent soil series are the Amarillo and Pullman series. Annual precipitation ranges from 310-560 mm (west to east) and the mean annual temperature ranges from 14-18°C (north to south) (Bomar, 1983). Th predominant crops in the region include cotton (*Gossypium hirsutum* L.), sorghum (*Sorghum bicolor* L.), wheat (*Triticum aestivum*), and peanuts (*Arachis hypogaea*) (USDA-NASS, 2019). At more marginal sites (i.e., >90% sand, highly erodible soils) range and pasture systems dominate (Li et al., 2017).

The combined effects of limited annual precipitation, elevated wind speed, and warm temperatures result in 200-500% greater evaporative demand than precipitation (Harris et al., 2014). To offset these losses from evaporation, crop producers on the SHP rely nearly 100% on groundwater as their irrigation source if water is available (Evett et al., 2020). The reliance on groundwater for irrigation in the SHP has resulted in a 15% decline in the saturated thickness of the Ogallala Aquifer in the region (McGuire, 2014). At current withdrawal rates, the SHP is expected to lose 35% of the irrigated cropland by 2030. Advances in irrigation technology like low energy precision application center pivots and drip irrigation have increased water use efficiency to >95% compared to furrow water systems (Lyle and Bordovsky, 1983). However, in some areas, irrigation well capacity has been depleted beyond the capacity to support irrigation at all (Bordovsky, 2019).

Compounding the concern of decreasing the saturated thickness of the Ogallala Aquifer is the unknown impact climate change will pose in the future. Future estimates suggest that air temperatures will slightly increase, and precipitation will decrease in the SHP (Tebaldi et al.., 2006). Predictions suggest that the SHP will experience mean annual temperature increases of 2-3°C and an annual average decline in precipitation of 30-127 mm by 2100 which will likely cause increases in irrigation water demand for the Ogallala Aquifer (Modala et al., 2017). Models utilizing three potential climate change scenarios indicated that evaporative demand would increase for the SHP resulting in up to 19.5% increases in irrigation requirement by 2090 (Awal and Fares, 2018). These losses in irrigation capacity may force some crop producers to convert to dryland cropping systems. Lascano et al. (2020) modeled potential cotton production in Amarillo and Pullman soil series given three (low, average, and high) precipitation scenarios. Their results indicated that in the Pullman (clay loam) series, cotton producers could expect profitable dryland yields in the average and high precipitation years. However, in the Amarillo (fine sandy loam) series, producers would not generate a profit regardless of rainfall. With so much unpredictability in the future of cropping systems on the SHP and limited information provided through modeled studies, it is important to generate a dataset in the environment with local growing standards to demonstrate best management practices for cotton producers in this region.

Figure 1.1 Soil textural map of the Texas High Plains (Reprinted from Baird, 2015).

The Agricultural Complex for Advanced Research and Extension Systems (AG-CARES) is located 100 km south of Lubbock near Lamesa, TX, USA (32° 46' 22", 101°

56' 18"). The site is a collaborative effort between the Texas A&M AgriLife Research and Extension Center at Lubbock and the Lamesa Cotton Growers. Overall, the goal of this site is to conduct research relevant to regional crop producers and demonstrate the best management practices that can allow these producers to be successful. The research trials described in Chapters 2-4 were conducted at AG-CARES. The mean average temperature and annual precipitation at AG-CARES is 16.3°C and 475 mm, respectively (Fig. 1.2). Soil at the site has been described as an Amarillo fine sandy loam, a benchmark series with significant distribution in the region (USDA-NRCS, 2016).

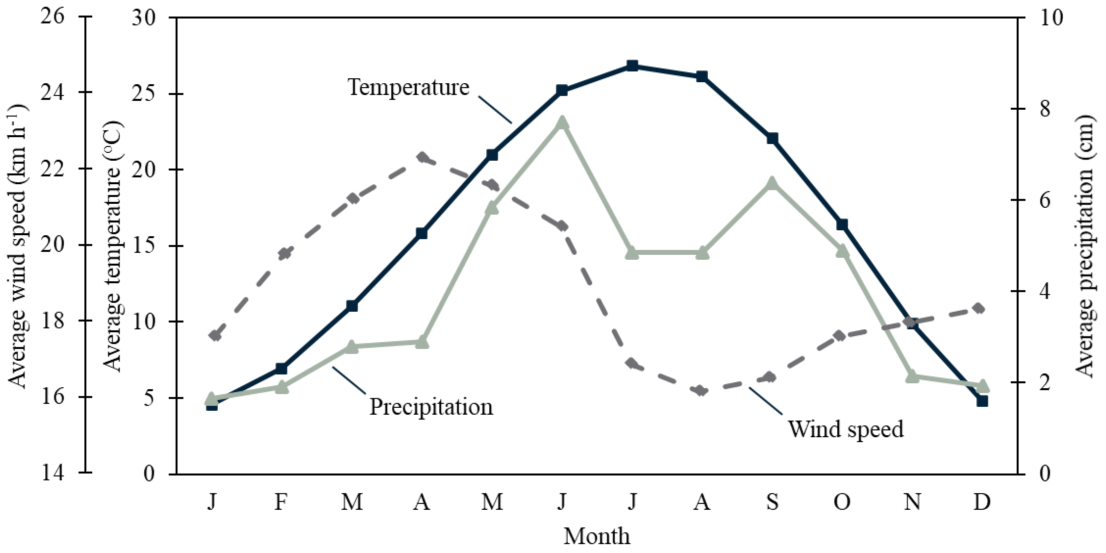

Figure 1.2 Monthly average wind speed, temperature, and precipitation at the Agricultural Complex for Advanced Research and Extension System, Lamesa, TX, USA.

In 1998, Drs. Wayne Keeling and Kevin Bronson established a trial to evaluate the impact of a recently released herbicide, Roundup® (glyphosate), on traditional and conservation (no-tillage, rye cover crop) cotton cropping systems (Lewis et al., 2018). The experiment was designed to compare two continuous cotton cropping systems: conventional tillage, winter fallow (traditional management practices for cotton) and no-tillage with a rye (*Secale cereal* L.) cover crop during the traditional fallow period. Through careful management and a team of dedicated scientists, this trial would become the only long-term conservation experiment for cotton production in west Texas. Over the years, this led to important discoveries in N management following cover crops (Bronson et al., 2001), soil C management (Lewis et al., 2018), soil water improvements with conservation agriculture (Burke et al., 2021; 2022), cotton lint yield response to conservation (Lewis et al., 2018), improvements in soil physical properties with conservation practices (DeLaune et al., 2019), and nutrient cycling dynamics of cover crops (Burke et al., 2019). Central to the discoveries made at AG-CARES was the desire of the researchers to improve agricultural production in the region by demonstrating best management practices that can empowering agriculturalists to achieve sustainability, both economically and environmentally.

These tenants are the foundation for this dissertation which builds upon years of regionally focused research to improve sustainable cotton production and translate best management practices directly to producers. However, despite all our knowledge, little is still known about the long-term synergistic impacts of no-tillage and cover cropping in semi-arid cotton production. The overall goal of this dissertation was to present the impacts in soil chemical, physical, and biological properties following the long-term adoption of conservation management in continuous cotton production. Specific objectives included:

1. Investigate the claim that cover crops reduce soil water leading to a decline in cotton lint yield compared to traditionally grown cotton.
2. Evaluate how N management practices impact cotton lint yield in traditional and conservation cotton cropping systems.
3. Quantify the long-term impacts of agronomic management on soil health parameters.

1.1. References

Awal, R.; Fares, A. Potential impact of climate change on irrigation water requirements for some major crops in the Norther High Plains of Texas. In *Bridging among disciplines by synthesizing soil and plant processes*, Wendroth, O.; Lascano, R.J.; Ma, L. (Ed). Madison, WI: ASA, CSSA, SSSA; **2018**, pp.145-170.

Biard, H. Assessing Pleistocene climate on the Southern High Plains through geochemical and physical characteristics of paleosols archived in the Blackwater Draw Formation. M.S. Thesis, **2015**, Department of Geology and Geophysics, Texas Tech University.

Bomar, G.W. Texas weather: Austin, TX, University of Texas Press, **1983**, pp. 265.

Bordovsky, J.P. Low-energy precision application (LEPA) irrigation: A forty-year review. *Trans. ASABE*, **2019**, *62*, 1343-1353.

Bronson, K.F.; Onken, A.B.; Keeling, J.W.; Booker, J.D.; Torbert, H.A. Nitrogen response in cotton as affected by tillage system and irrigation level. *Soil Sci. Soc. Am. J.*, **2001**, *65*, 1153-1163.

Burke, J.A.; Lewis, K.L.; DeLaune, P.B.; Cobos, C.J.; Keeling, J.W. Soil water dynamics and cotton production following cover crop use in a semi-arid ecoregion. *Agronomy*, **2022**, *12*, 1306.

Burke, J.A.; Lewis, K.L.; Ritchie, G.L.; Moore-Kucera, J.; DeLaune, P.B.; Keeling, J.W. Temporal variability of soil carbon and nitrogen in cotton production on the Texas High Plains. *Agron. J.*, **2019**, *111*, 2218-2225.

Burke, J.A.; Lewis, K.L.; Ritchie, G.L.; DeLaune, P.B.; Keeling, J.W.; Acosta-Martinez, V.; Moore, J.M.; McLendon, T. Net positive soil water content following cover crops with no tillage in irrigated semi-arid cotton production. *Soil Till. Res.*, **2021**, *208*, 104869.

Colaizzi, P.D.; Gowda, P.H.; Marek, T.H.; Porter, D.O. Irrigation in the Texas High Plains: A brief history and potential reductions in demand. *Irrig. Drain.*, **2009**, *58*, 257-274.

DeLaune, P.B.; Mubvumba, P. Winter cover crop production and water use in Southern Great Plains cotton. *Agron. J.*, **2020**, *112*, 1943-1951.

Evett, S.R.; Colaizzi, P.D.; Lamm, F.R.; O’Shaughnessy, S.A.; Heeren, D.M.; Trout, T.J.; Kranz, W.L.; Lin, X. Past, present, and future of irrigation on the U.S. Great Plains. *Trans. ASABE*, **2020**, *63*, 703-729.

Gustavson, T.C.; Holliday, V.T. Eolian sedimentation and soil development on a semiarid to subhumid grassland, Tertiary Ogallala and Quaternary Blackwater Draw Formations, Texas and New Mexico High Plains. *J. Sediment. Res.,* **1999**, *69*, 622-634.

Harris, I.; Jones, P.D.; Osborn, T.J.; Lister, D.H. Updated high-resolution grids of monthly climatic observations: The CRU TS3.10 dataset. *Intl. J. Climatol.*, **2014**, *34*, 623-642.

Hutson, W.F. Irrigation systems in Texas. **1898**, USGS Water Supply and Irrigation Paper No. 13, Washington, D.C., U.S. Geological Survey.

Lascano, R.J.; Leiker, G.R.; Goebel, T.S.; Mauget, S.A.; Gitz III, D.C. Water balance of two major soil types of the Texas High Plains: Implications for dryland crop production. *Open J. Soil Sci.*, **2020**, *10*, 274-297.

Lewis, K.L.; Burke, J.A.; Keeling, W.S.; McCallister, D.M.; DeLaune, P.B.; Keeling, J.W. Soil benefits and yield limitations of cover crop use in Texas High Plains cotton. *Agron. J.* **2018**, *110*, 1616-1623.

Li, C.; Fultz, L.M.; Moore-Kucera, J.; Acosta-Martinez, V.; Horita, J.; Strauss, R.; Zak, J.; Calderon, F.; Weindorf, D. Soil carbon sequestration potential in semi-arid grasslands in the Conservation Reserve Program. *Geoderma*, **2017**, *294*, 80-90.

Lyle, W.M.; Bordovsky, J.P. LEPA irrigation system evaluation. *Trans. ASABE*, **1983**, *26*, 776-781.

McGuire, V.L. Water-level changes and change in water storage in the High Plains Aquifer, predevelopment to 2013 and 2011-2013. USGS Scientific Investigations Report, **2014**, 2014-5218, Reston, VA, U.S. Geological Survey.

Modala, N.G.; Ale, S.; Goldberg, D.W.; Olivares, M.; Munster, C.L.; Rajan, N.; Feagin, R.A. Climate change projections for the Texas High Plains and Rolling Plains. *Theor. Appl. Climatol.*, **2017**, *129*, 263-280.

Nostrand, R.L. The Hispano homeland. University of Oklahoma Press, Norman, OK, **1996**.

Thoburn, J.B. Ancient irrigation ditches on the Plains. *Chronicles Oklahoma*, **1931**, *9*, 56-62.

Tebaldi, C.; Hayhoe, K.; Arblaster, J.M.; Meehl, G.A. Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change*, **2006**, *79*, 185-211.

USDA-NASS. Farm and ranch irrigation survey. In *1997 Census of Agriculture, Vol. 3, Special studies, Part 1* (AC97-SP-1). Washington, DC: USDA-NASS, **1998**.

USDA-NASS. Irrigation and water management survey. In *2018 Census of Agriculture, Vol. 3, Special studies, Part 1* (AC-17-SS-1). Washington, DC. USDA-NASS, **2019**.

USDA-NRCS. Amarillo Soil Series. Available online: https://soilseries.sc.egov.usda.gov/OSD_Docs/A/AMARILLO.html (accessed on 21 February 2022).

2. SOIL WATER DYNAMICS AND COTTON PRODUCTION FOLLOWING COVER CROP USE IN A SEMI-ARID ECOREGION[*]

Abstract

Conservation management practices such as no-tillage and cover crops can decrease soil's susceptibility to wind erosion, but adoption of these practices has been limited in the Texas High Plains (THP) where producers are concerned with cover crop water usage. The objective of this study was to evaluate the impact of no-tillage and cover crops on cotton (*Gossypium hirsutum* L.) lint yield and soil water content in deficit irrigated cropping system. Soil water was observed bi-weekly in long-term, continuous cotton systems established in 1998 that included (1) conventional tillage, winter fallow; (2) no-tillage with rye (*Secale cereale* L.) cover; and (3) no-tillage with mixed species cover located in Lamesa, TX, USA. Results include observations from 2018-2020 (years 21-23 of the study period). The adoption of conservation practices did not significantly reduce cotton lint yield compared to conventionally tilled, winter fallow cotton. Soil water was initially depleted with cover crops but was greater throughout the growing season following cover crop termination. Throughout the soil profile, water depletion and recharge were more dynamic with conservation practices compared to the conventionally tilled control. There were no differences in cotton water use efficiency between treatments. Results from this study indicate cover crop water usage is likely not

---

[*] Reprinted with permission from "Soil Water Dynamics and Cotton Production Following Cover Crop Use in a Semi-Arid Ecoregion" by Joseph Alan Burke, Katie Lynn Lewis, Paul Bradley DeLaune, Christopher Joseph Cobos, and Jack Wayne Keeling, 2022. *Agronomy*, 12, 1306, Copyright 2022 by Creative Commons Attribution (https://creativecommons.org/licenses/by/4.0/legalcode).

the cause of cotton lint yield decline observed from 2015 to 2017 in this deficit irrigated, semi-arid production system.

2.1. Introduction

During the Dust Bowl of the 1930s, approximately 5 Tg of topsoil was eroded from United States Great Plains which prompted the formation of the Soil Conservation Service and, ultimately, the Natural Resources Conservation Service (NRCS) to combat the loss of this vital resource (Zobeck et al., 2012). Since the Dust Bowl, agronomic conservation efforts such as reducing tillage and adopting crop rotations (Zobeck et al., 2012) coupled with governmental land-use policies such as the Conservation Reserve Program (Young et al., 2018) have reduced wind erosion by 80% on the Great Plains. However, historic droughts (Cano et al., 2018) coupled with climate change have produced several haboobs reminiscent of the 1930s on the Texas High Plains (THP) (Kelley et al., 2021) where conservation practices have limited adoption (Prokopy et al., 2019). Across the United States of America (USA), conservation tillage in cotton production accounts for only an estimated 40% of the acres compared to more than 65% of corn, soybean, and wheat acres (Claassen et al., 2018). On the Great Plains, only 30% of cotton acres utilize conservation tillage whereas 70% of southeastern cotton acres employ the practice. Producers' limited adoption of conservation management practices on the THP is poorly understood, but research suggests producers are concerned with yield reductions, water availability, and costs associated with adopting conservation management practices, especially in semi-arid regions (Prokopy et al., 2019). These concerns are compounded by the limited amount of cotton biomass produced during a growing season which necessitates the use of cover crops with reduced tillage (Claassen et al., 2018). In addition to understanding the barriers to adoption on the THP, it is important for researchers to evaluate the agricultural, economical, and ecological benefits and consequences of these conservation practices for producers to make the most informed management decisions.

On the THP, cotton (*Gossypium hirsutum* L.) is the most widely planted agricultural crop with 2.3 Mha planted in 2018, resulting in approximately $2.5 B in annual revenue for the state and nearly 25% of the USA exported cotton (USDA-ERS, 2018; USDA-NASS, 2018). The cotton productive capacity of the THP is largely dependent on underground irrigation from the Ogallala Aquifer (Evett et al., 2020) where irrigation helps to minimize intermittent moisture stress that can be problematic for cotton production in the region (Wanjura et al., 2002). In the THP, precipitation or irrigation during the maturation phase ensures cotton yield (Bordovsky et al., 2015) and shortages during flowering can result in significant yield reductions (Simao et al., 2013; Snowden et al., 2014). Pumping of the Ogallala and limited recharge has led the aquifer to a 50% decrease in irrigation capacity since the 1950s (Evett et al., 2020). Ensuring continued agricultural productivity on the THP will require the adoption of conservation management practices to secure our soil and minimize soil water loss.

Reduced tillage and cover crops are generally the most broadly adopted conservation management practices on the THP (Lewis et al., 2018). The adoption of these practices in the region has been shown to increase carbon storage (Lewis et al., 2018), soil aggregation (Fultz et al., 2013a,b), biological activity (Acosta-Martinez et al., 2017), nutrient cycling (Burke et al., 2019), and reduce a soils' susceptibility to wind and water erosion (Colazo et al., 2010). In a prior field assessment of the study presented in this manuscript in Lamesa, Texas (TX), USA, conservation management adoption in cotton cropping systems significantly increased soil water during key physiological growth stages (Burke et al., 2021b) but resulted in yield decreases compared to traditional practices (Lewis et al., 2018). Prior to cover crop termination, soil water was depleted more where active cover growth was occurring than the fallow control in all three years of the study (Burke et al., 2021b). However, after termination, soil water was generally greater throughout the profile following cover crops. Throughout active cotton growth increases in soil water were greater in the conservation system indicating greater water interception, infiltration, and percolation while decreases in soil water were more reduced following cover crops indicating that they minimized soil water loss from the soil surface and throughout the profile. The authors concluded that the increases in soil water with no-tillage and cover crops was likely the result of increased water storage capacity and decreased evapotranspiration from shading of the soil surface.

No-tillage and cover crops can improve soil physical properties and soil C storage which can increase water holding capacity (Blanco-Canqui et al., 2011). Despite the benefits, studies show that cover crops can utilize the limited soil water in semi-arid agroecoregions which can reduce the subsequent main crop yield in a variety of cropping systems (Dabney et al., 2001; Balkcom et al., 2007; Nielsen et al., 2016; Homan et al., 2018). The use of small grain cover crops resulted in reduced cotton lint yield of both dryland and irrigated cropping systems (Baughman et al., 2007; Lewis et al., 2018). In the Northern THP, soil water and cotton yields were increased by 16 and 50%, respectively, compared to traditionally grown cotton in a dryland system (Baumhardt et al., 2013). In the Texas Rolling Plains, no-tillage and cover crop use significantly increased cotton lint yields compared to traditional practices in a terminated wheat cover crop system (DeLaune et al., 2020).

The production of cover crop herbage mass can be limited on the THP due to minimal precipitation, low temperatures, and high wind speeds during the traditional fallow winter period (Keeling et al., 1989, 1996; Lewis et al., 2018; Burke et al., 2019; Burke et al., 2021b). As stated previously, the use of cover crops in this region can substantially reduce soil susceptibility to wind erosion (Colazo et al., 2010). Small grains perform this function better in the semi-arid THP because they require smaller amounts of moisture to get established and their growth physiology helps to slow wind across the soil surface reducing wind erosion (Keeling et al., 1989, 1996; Lewis et al., 2018). In dryland systems of west Texas, wheat (*Triticum aestivum* L.) and rye (*Secale cereale* L.) were more likely to establish and provide sufficient biomass to protect the soil surface when planted in the fall compared to 13 small grains and forage legumes that were evaluated (Keeling et al., 1989). The goal of this study was to evaluate the long-term effects of conservation management adoption on cotton lint yield and soil water dynamics. Based on previous research of conservation management practices in this semi-arid region, we hypothesize that cover crops and no-tillage will significantly reduce soil water prior to cover crop termination but increase soil water during active cotton growth.

2.2. Materials and Methods

2.2.1. Site description, experimental design, and cropping system management

The long-term field experiment was initiated in 1998 at the Agricultural Complex for Advanced Research and Extension Systems located near Lamesa, TX, USA (N 32°46’22”, W 101°56’18”; 919 m a.s.l.). Prior to the initiation of the study, the site had been used exclusively for conventionally tilled, continuous cotton production for at least 50 yr. Soil at the site was described according to USDA Soil Classification as an Amarillo fine sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs) with approximately 84, 10, and 6% g kg^{-1} sand, silt, and clay, respectively (USDA-NRCS, 2016). The Amarillo series is considered a benchmark soil with significant distribution (2.3 M ha) in the region. Additional soil characterization for the site is available in other reports (Lewis et al., 2018; Burke et al., 2019; DeLaune et al., 2019). This paper reports results from the 2018 through 2020 growing seasons (years 20-22 of the study).

In 1998, the conventional tillage and no-tillage with rye cover crop treatments were initiated as a randomized complete block design with three replications. The conventional tillage plots were 16 rows wide while the no-tillage with rye cover crop plots were 32 rows wide. In 2014, the no-till rye plots were split in half and a mixed species cover was implemented which included 50% rye, 33% Austrian winter pea

(*Pisum sativum* L.), 10% hairy vetch (*Vicia villosa* Roth), and 7% radish (*Raphanus sativus* L.), by weight. The single and mixed species cover crops were planted using a grain drill at a rate of 45 kg ha^{-1}. Cotton was planted annually as the main crop.

Treatments at the site included: 1) conventional tillage with a fallow period usually from November-May (CT); 2) no-tillage with rye cover (R-NT); and 3) no-tillage with mixed species cover (M-NT). Treatments were arranged as a randomized complete block design with three replications. Plots were 16-rows (1.02 m centers) wide and 76.2 m long. During active cotton growth, plots were irrigated using Low Energy Precision Application irrigation. Due to differences in annual precipitation and irrigation capacity, varying rates of irrigation were applied during each growing season to meet cotton water demands. Cover crops were not irrigated during the study. Any irrigation that occurred from October to April was applied after cover crop termination and prior to planting cotton (Table 2.1).

The cropping sequences are graphically summarized in Fig. 2.1. Cover crops were seeded using an 8-row grain drill on 19.1 cm row spacing on 17 November 2017, 4 December 2018, and 21 November 2019 following cotton harvest and were chemically terminated with glyphosate (potassium salt form) at a rate of 2.3 L ha^{-1} on 27 March 2018, 9 April 2019, and 27 March 2020. Prior to termination, cover crops were harvested from a 1-m^2 area and dried for 7-d at 60°C to determine herbage mass on a dry matter (DM) basis. Cotton was planted across all plots on 15 May 2018, 19 May 2019, and 18 May 2020. To aid harvest, the cotton was chemically defoliated in October of each year and mechanically harvested on 19 November 2018, 28 October 2019, and 31

October 2020. Annually, urea ammonium nitrate (32-0-0) was applied through fertigation in four equal applications for a total of 134.5 kg N ha^{-1}. A thorough discussion of the cropping systems is available in a previously published report (Lewis et al., 2018).

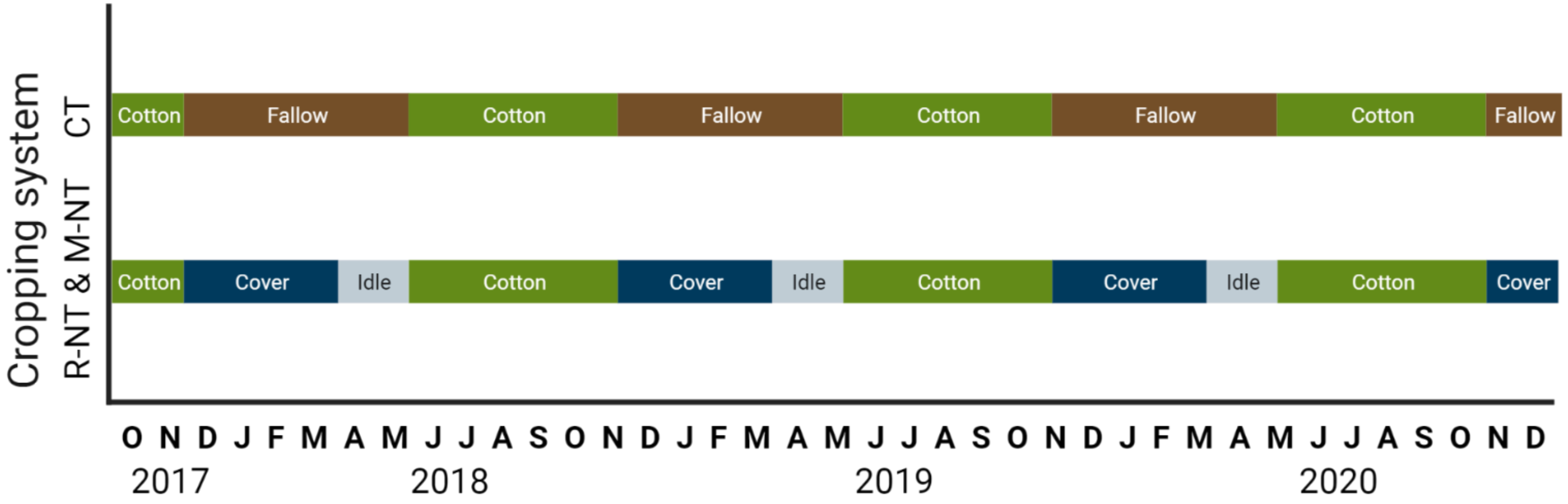

Figure 2.1 Continuous cotton cropping system sequences for conventional tillage, winter fallow (CT), no-tillage with rye cover (R-NT), and no-tillage with mixed species cover (M-NT) at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA from 1 October 2017 through 31 December 2020. Created with Biorender.com.

2.2.2. Sampling protocol and analysis

Soil samples were collected for general soil characterization on 6 April 2020 following cover crop termination on 27 March 2020 and prior to cotton planting on 18 May 2020 to a depth of 60 cm from each plot and analyzed for total N, nitrate-N, Mehlich III extractable macronutrients, pH, and electrical conductivity (EC). Soil samples were composites of three, 5.1-cm diameter cores per plot collected with a Giddings probe and separated into 0 to 15, 15 to 30, and 30 to 60 cm depth increments. Soil samples were dried at 60°C for 7 d and ground to pass a 2-mm sieve using a flair grinder. Total N (TN) was determined by combustion following fine grinding with a ring-and-puck grinder (McGeehan and Naylor, 1988). Residual soil inorganic nitrate-N (NO_3^--N) was determined using a colorimetric method involving cadmium reduction to nitrate following extraction with 2 M KCl using a 1:10 soil/extraction ratio (4 g soil:40 mL 2 M KCl) followed by analysis using flow injection spectrometry (FIAlab Instruments, Bellevue, WA, USA). Extractable soil nutrients including P, K, Ca, Mg, and S were extracted using a Mehlich III extractant and measured using inductively coupled plasma spectroscopy (Mehlich, 1984). Soil pH and EC were determined in a 1:2 soil to deionized water slurry utilizing a pH probe and conductivity electrode (Rhoades, 1982; Schofield and Taylor, 1955). An additional soil core was collected from each plot to determine the bulk density (ρ_b) at 0 to 15, 15 to 30, and 30 to 60 cm (Blake and Hartge, 1986).

A field-calibrated neutron probe (InstroTek Inc., Raleigh, NC, USA) was used to monitor soil water for volumetric water content (VWC, θ). Measurements were collected biweekly beginning in January 2018 and ran throughout the duration of the experiment unless we were unable to enter the field due to poor weather conditions (Pabuayon et al., 2019; Burke et al., 2021b). In March 2015, aluminum access tubes (8-cm diameter) were installed into each plot to a depth of 140 cm. Measurements were collected in 20-cm depth increments. The access tubes were constructed with a 60 cm removable top that allowed the top to be removed for agronomic field operations including plowing (CT), planting, and harvesting. The VWC for each measurement was multiplied by the 20-cm depth interval to determine soil water content (mm). In each growing season, soil water is presented as days after planting (DAP) cotton, therefore, negative DAP values represented days prior to planting cotton. Total soil water was calculated as the sum of water at each individual depth increment for the entire profile. The rate of change in soil water was calculated as the difference in profile soil water from one sampling date to the next, divided by the sampling interval, as:

$$\text{Changes in soil water (mm day}^{-1}\text{)} = [\theta_2 - \theta_1] / [t_2 - t_1]$$

where θ represents VWC (m^3 m^{-3}) and t represents sampling date (Burke et al., 2018). The same formula was used to determine changes of soil water at each depth. Cotton water use efficiency (C_{WUE}) was calculated by dividing cotton lint yield (kg lint ha^{-1}) by crop water use, where crop water use is defined as: (starting profile soil water (at planting) + in-season rainfall + in-season irrigation) – finishing profile soil water (at harvest) (Roth et al., 2013; Burke et al., 2021b). Runoff and deep drainage were assumed negligible because the field is level (0-1% slopes), had adequate water holding capacity in the subsoil (20.5 cm through 1 m depth), and did not receive substantial rainfall or irrigation during the study period based on methodologies common to the region (Roth et al., 2013; Pabuayon et al., 2019; DeLaune et al., 2020; Burke et al., 2021b).

2.2.3. Statistical approach and analysis

All statistical analyses were performed using SAS version 9.4 (SAS Institute, Inc., Raleigh, NC, USA). Data analysis was conducted using a generalized linear mixed model (PROC GLIMMIX) with cropping system treated as the fixed effect and replication as the random effect. The effect of year and year x treatment was determined, and due to a significant year effect, treatment means were evaluated within year. Year x treatment effect was not significant. Normality was determined using the Shapiro-Wilks test and all data was normally distributed. Means of treatment effects were compared within sample time using Fisher's least significant difference (LSD) at $P < 0.05$. Contour maps were made using SigmaPlot version 14.5 (Systat Software, Palo Alto, CA, USA).

2.3. Results and Discussion

2.3.1. Temperature, precipitation, and irrigation

Monthly mean temperature followed similar trends from 2018-2020 (Fig. 2.2) (National Centers for Environmental Information, National Oceanic and Atmospheric Administration). The average annual temperature at the research site was 16.7, 16.4, and 17.2°C in 2018, 2019, and 2020, respectively. The observed annual temperatures were 5, 4, and 8% greater than the 30 yr average. Increases in temperature were more likely observed in May and June of the study period compared to the long-term average.

Annual precipitation was 342, 300, and 195 mm in 2018, 2019, and 2020, respectively, which was 39, 58, and 144% lower than the 30-yr average precipitation. September and October 2019 experienced the greatest monthly precipitation with 97- and 105-mm, respectively. Variation in growing season precipitation resulted in variations in irrigation amounts, therefore 231.1, 274.3, and 289.6 mm irrigation was applied during the cotton growing seasons of 2018, 2019, and 2020, respectively, to meet crop water demand based on estimated evapotranspiration (ET) at the study site (Table 2.1). Irrigation amounts in each month were based on approximately 35% estimated ET replacement when irrigation capacity allowed it. The peak months for irrigation use in all years were July and August which coincides with peak cotton water demand (Grimes and Yamada, 1982). Reliance on irrigation from the Ogallala Aquifer to meet crop water demand is not sustainable under current withdrawal rates due to its limited recharge in the Texas High Plains (Cano et al., 2018).

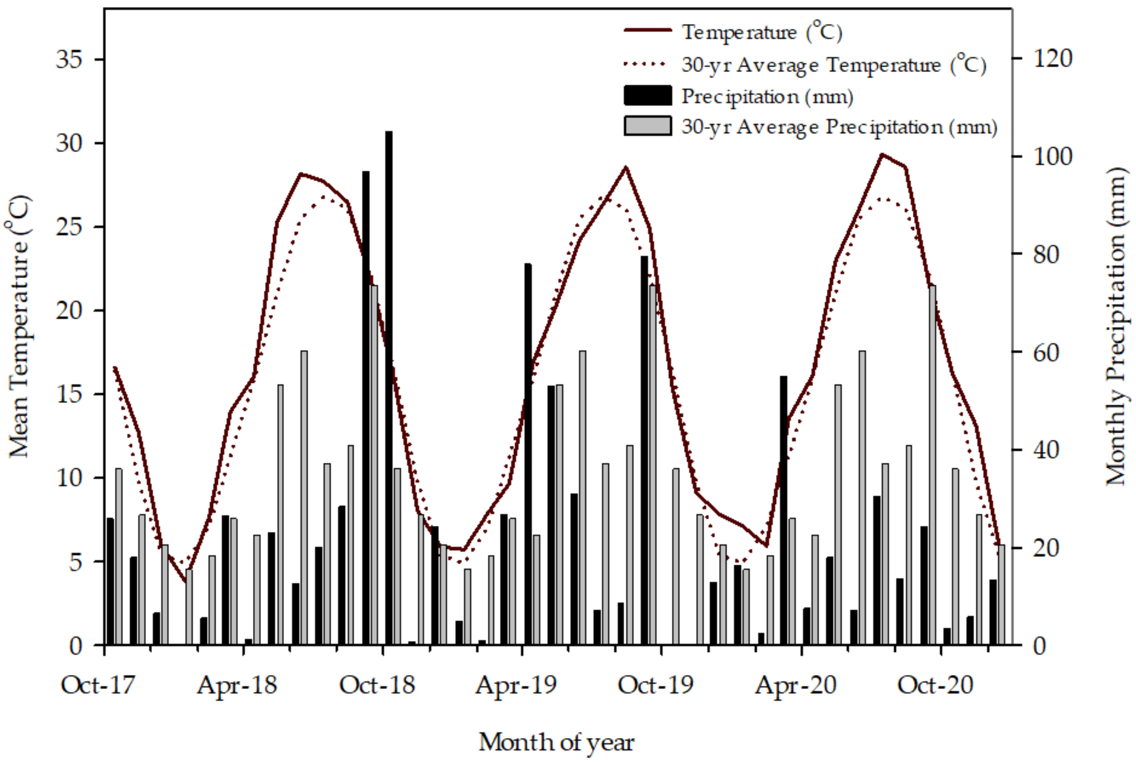

Figure 2.2 Mean monthly temperature and total monthly precipitation from rainfall and irrigation events and 30-year (1991-2020) climate averages at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA from 1 November 2017 through 30 November 2020 (National Oceanic and Atmospheric Administration – National Centers for Environmental Information, 2022).

Table 2.1 Pre-plant (October – April) and in-season (May – September) precipitation and irrigation for 2018, 2019, and 2020 at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA.

	Precipitation	Irrigation
Growing season	mm	
2017-2018		
October – April	78.0	38.1
May	22.9	33.0
June	12.5	0.0
July	19.8	71.1
August	28.2	71.1
September	96.8	17.8
Season (cumulative)	*258.2*	*231.1*
2018-2019		
October – April	249.9	45.7
May	52.8	33.0
June	30.7	17.8
July	6.9	88.9
August	8.4	71.1
September	79.3	17.8
Season (cumulative)	*428.0*	*274.3*
2019-2020		
October – April	93.2	57.2
May	17.8	26.7
June	7.1	34.3
July	27.9	95.3
August	13.5	76.2
September	13.5	0.0
Season (cumulative)	*173.0*	*289.6*

2.3.2. Soil characterization and cover crop herbage mass

Soil characteristics are presented in Table 2.2 and represent the effect of cropping system management after year 22 of the study period (established in 1998). Soil pH was reduced at the 0-15 cm depth with R-NT and M-NT treatments compared to CT. Reductions in soil pH at 0-15 cm was likely caused by increased C inputs and rhizodeposition of the cover crop systems compared to CT which stimulated microbial activity and decreased soil pH through microbial respiration (Ward et al., 2017). This phenomenon has been observed in other semi-arid cropping systems (Fultz et al., 2013; Lewis et al., 2018). The reduction in soil pH observed in this study can increase soil nutrient availability in semi-arid ecosystems (Thomas et al., 2007; Lopez-Fando and Pardo, 2009). No differences in soil pH between cropping systems were determined at 15-30 and 30-60 cm depths. Electrical conductivity was significantly impacted at all depths where EC was greatest with R-NT compared to CT and M-NT. In semi-arid, irrigated cropping systems, salt leaching can increase land degradation and reduce crop yields (Lopez-Fando and Pardo, 2009). Contrary to our study where R-NT increased EC at all depths, cover crops have been shown to reduce salt concentrations compared to fallow systems (Gabriel et al., 2012). We hypothesize that the increased biomass production with R-NT compared to M-NT from 2015 – 2020 (Fig. 2.3; Lewis et al., 2018) resulted in more numerous root channels for preferential water flow and that these channels allowed greater transport of soluble salts. This hypothesis is supported by significant increases in EC at the 30-60 cm depth compared to the 0-15 and 15-30 cm depth. Cropping systems had no impact on RB, total-N, K, Ca, Mg, and S at any depth. However, Ca and Mg significantly increased across treatments at the 30-60 cm depth. This is likely due to carbonate pedogenesis common to semi-arid regions (USDA-NRCS, 2016).

Table 2.2 Characterization of soil collected at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA in April 2020 at soil depths of 0 to 15, 15 to 30, and 30 to 60 cm from the conventional tillage winter fallow (CT), no-tillage rye cover crop (R-NT), and no-tillage mixed species cover (M-NT) treatments. Different letters within columns indicate differences between cropping systems within depth ($P < 0.05$).

Cropping system	**pH**	**EC**[1]	ρ_b[2]	**TN**[3]	**NO_3^--N**	**P**	**K**	**Ca**	**Mg**	**S**
	---	dS m^{-1}	g cm^{-3}				mg kg^{-1}			
	0-15 cm									
CT	7.7 a[4]	1.1 b	1.33	328	4.9 a	39 b	264	870	687	5
R-NT	7.2 b	1.7 a	1.58	483	0.6 b	54 a	340	884	658	13
M-NT	7.4 b	0.7 b	1.62	299	0.5 b	58 a	271	851	659	8
	15-30 cm									
CT	7.8	1.2 b	1.68	315	1.9 a	38	233	830	660	5
R-NT	7.6	2.2 a	1.69	354	0.2 b	25	250	813	693	28
M-NT	7.7	1.1 b	1.71	275	0.4 b	31	205	727	604	12
	30-60 cm									
CT	7.7	3.7 b	1.64	344	5.9	7	245	1244	974	49
R-NT	7.7	5.1 a	1.54	325	5.2	11	221	1258	1059	62
M-NT	7.4	2.8 c	1.51	374	5.3	16	237	1132	991	66

[1]Electrical conductivity; [2]Bulk density; [3]Total nitrogen; [4]Signficiant differences between cropping systems within depth ($P < 0.05$).

While there were no significant differences in ρ_b between treatments at any depths, RB in CT was generally smaller compared to R-NT and M-NT at the 0-15 cm depth. This was likely the result of surface plowing to a 15 cm depth in CT. Bulk density increased in the 15-30 cm depth and could indicate a potential restrictive layer which has been observed in the past (DeLaune et al., 2020). This increase in ρ_b would likely not restrict cotton or cover crop root growth but may influence infiltration and percolation of irrigation and precipitation (Howard and Gardner 1963; Blanco-Canqui et al., 2018; DeLaune et al., 2019). Earlier investigations of this cropping system showed little differences in bulk density, but R-NT decreased (in 2013) and then increased (in 2014) the penetration resistance based on soil moisture content at the two sampling events compared to the conventional control (DeLaune et al., 2019). It is uncommon in our region for producers to implement no-tillage without cover crops because the limited amount of biomass cotton produces would be insufficient to reduce wind erodibility. Since our study sought to replicate cropping systems common to the region (i.e. continuous cotton), it is impossible to separate the effects of cover cropping from no-tillage. The combined beneficial impacts of cover cropping and no-tillage have been shown to increase infiltration and water storage through greater soil organic carbon content (Blanco-Canqui and Ruis, 2018) and preferential flow paths (Meek et al., 1992; Mitchell et al., 1995).

The adoption of conservation management practices (i.e. R-NT and M-NT) had a significant effect on nutrient availability (Table 2.2). Soil NO_3^--N was significantly reduced by 88 and 84% at 0-15 and 15-30 cm, respectively, with R-NT and M-NT compared to CT. Reductions in soil NO_3^--N with the adoption of cover crops is likely caused by the uptake of NO_3^--N by the cover crop for growth and development (Bronson et al., 2001; Schipanski et al., 2014; White et al., 2020). In parts of the USA, cover crops are used to reduce NO_3^--N leaching, however, in semi-arid regions where leaching is limited and biomass decomposition is slowed, NO_3^--N uptake and immobilization may result in limited plant-available N at planting (Acharya et al., 2019). An evaluation of N demands of cotton following cover crops on the semi-arid THP demonstrated that an additional 38 kg N ha^{-1} would be required for adequate cotton production (Wagger, 1989). Regional evaluations of cover crop species showed that rye, wheat, Austrian winter pea, and hairy vetch were highly productive, but under dryland situations, the legumes produced limited biomass which could indicate that the legume species would generate limited biologically fixed N (Keeling et al., 1996). On the THP, an evaluation of seeding rates showed that there was no significant difference in rye or wheat production regardless of seeding rate (Richardson et al., 2011). Implications suggest that conservation systems can receive similar ecosystem service benefits of cover crops at lower seeding rates, saving producers money and water while reducing the potential for N immobilization (Pypers et al., 2007). In addition to seeding rate, cover crop termination timing plays an important role in N availability. While delayed termination timing increased biomass production, N release from biomass decomposition was delayed resulting in potential immobilization (Nuruzzaman et al., 2006). Producers should consider potential N limitations with cover crop adoption in semi-arid regions when determining cover crop seeding rate and termination timing in addition to N fertilization strategies following cover crop termination.

While leaching of NO_3^--N is likely uncommon in this cropping system due to prescriptive nutrient management, historic over-application of inorganic fertilizers resulted in significant increases in NO_3^--N leaching at depth in this cropping system

(Bronson et al., 2001). Like NO_3^--N, S showed significant increases at the 30-60 cm depth compared to the 0-15 and 15-30 cm depths. This is most likely the result of S leaching over time through over-application of S fertilizer (Bronson et al., 2001). In contrast to NO_3^--N, P was 44% greater in R-NT and M-NT compared to CT at the 0-15 cm depth. Cover crops have been shown to increase soil P availability through increased soil exploration with fibrous roots (Jorquera et al., 2008), reduction in soil pH (Bordovsky et al., 1994), P cycling enzyme activity (Nyakatawa et al., 2000), and microbial diversity (Boquet et al., 2004). The significant decrease in P concentrations at the 30-60 cm depth is likely the result of the limited activity of the aforementioned processes.

Cover crop herbage mass varied from 2,406 to 4,629 kg DM ha^{-1} during the duration of the study (Fig. 2.3). Rye herbage mass ranged from 2,528 to 4,629 kg DM ha^{-1} and M-NT herbage mass ranged from 2,406 to 4,560 kg DM ha^{-1}. The only significant differences in herbage mass production were observed in 2019 when M-NT produced greater herbage mass than R-NT. An earlier evaluation of the same cropping system from 2015 – 2017 resulted in significantly greater herbage mass with R-NT than M-NT in 2015 and 2017 and generally greater biomass in 2016 (Lewis et al., 2018). In 2018 and 2020, R-NT generally produced greater cover crop biomass compared to M-NT. Herbage mass was greater in 2020 compared to the other years in the study. In contrast to the THP, cover crop mixtures of wheat, Austrian winter pea, hairy vetch, and crimson clover (*Trifolium incarnatum* L.) produced more herbage mass compared to a single species (wheat) cover when averaged from 2013 – 2017 (DeLaune et al., 2019).

The authors attributed the herbage mass production to planting date and precipitation in March & early April. Like our study, their cover crops were seeded following cotton harvest in November which is later than the historical first killing freeze (early November) for the region. Generally, fall-planted legumes should be seeded 6-8 weeks prior to that date, and this likely limits the legume production in our system. While non-cereals account for 50% of our cover crop seed mixture by weight, they produce less than 1% of herbage mass at termination annually (data not shown). Interseeding cover crops directly into established cotton in mid-September is not possible within our cropping system because cotton harvest aids (applied in October) would be detrimental to the cover crop seedlings. Contrary to results from the Rolling Plains, cover crop herbage mass did not appear to be driven by precipitation in March and early April (DeLaune et al., 2019). Additional research is needed to understand the primary driver of herbage mass production in semi-arid ecoregions.

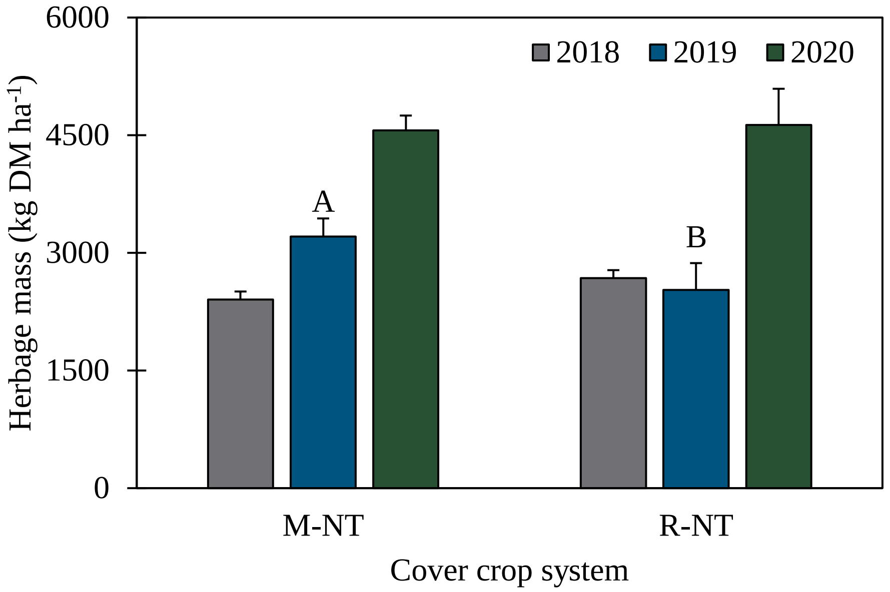

Figure 2.3 Rye (R-NT) and mixed species (M-NT) cover crop herbage mass (DM, dry matter) produced in 2018, 2019, and 2020 in Lamesa, TX, USA. Cover crop treatment means within year with the same letter are not different at $P < 0.05$. Differences were not determined in 2018 and 2020. Error bars represent standard error of the sample mean.

2.3.3. Cotton lint yield and water use efficiency

Cotton lint yield ranged from 540 to 853 kg lint ha^{-1} in 2018 to 2020 (Fig. 2.4). There were no significant differences in cotton lint yield between treatments in any year. Cotton lint ranged from 724 to 853 kg lint ha^{-1}, 683 to 765 kg lint ha^{-1}, and 540 to 706 kg lint ha^{-1} in 2018, 2019, and 2020, respectively. On average, cotton lint yields were greater in 2018 (810 kg lint ha^{-1}) followed by 2019 (728 kg lint ha^{-1}) and finally 2020 (600 kg lint ha^{-1}). In 2018, CT and R-NT generally produced greater cotton lint than M-NT, while in 2019 CT and M-NT generally produced greater cotton lint than R-NT. Averaged across the three years, cotton lint yield was generally greater in CT 765 kg lint ha^{-1}), followed by R-NT (691 kg lint ha^{-1}) and then M-NT (681 kg lint ha^{-1}).

Our results complicate an already complicated understanding of the effects of conservation management practices on cotton lint yield in semi-arid regions. Previous studies show both increases (Keeling et al., 1996; Hanks et al., 2007; Baumhardt et al,, 2013; Otte et al., 2019; DeLaune et al., 2020; Cao et al., 2021; Sinha et al., 2022) and decreases (Wagger, 1989; Lewis et al., 2018) in lint production following conservation management. Lint yields were generally reduced compared to production from 2015-2017 which received greater rainfall than the 2018-2020 study period; however, the annual variability in lint yield is common for the region (Lewis et al., 2018; Burke et al., 2021b). The reduction in yield observed in 2020 was likely caused by the greater amounts of herbage mass produced with the cover crops compared to 2018 and 2019. Increased herbage mass can result in N immobilization following termination (Alonso-Ayuso et al., 2020), and additional N fertilization may be required for the subsequent cash crop to minimize yield loss (Wagger, 1989). However, given increased N fertilizer input costs and limited availability from disrupted supply chains (Tennakoon et la., 2006), producers might be less inclined to apply supplemental N fertilizer. Therefore, alternatives to supplemental N fertilization may be required including maximizing cover crop termination timing to limit herbage mass production and maximize net N mineralization (Nuruzzaman et al., 2006; Krueger et al., 2011; Nielsen et al., 2015).

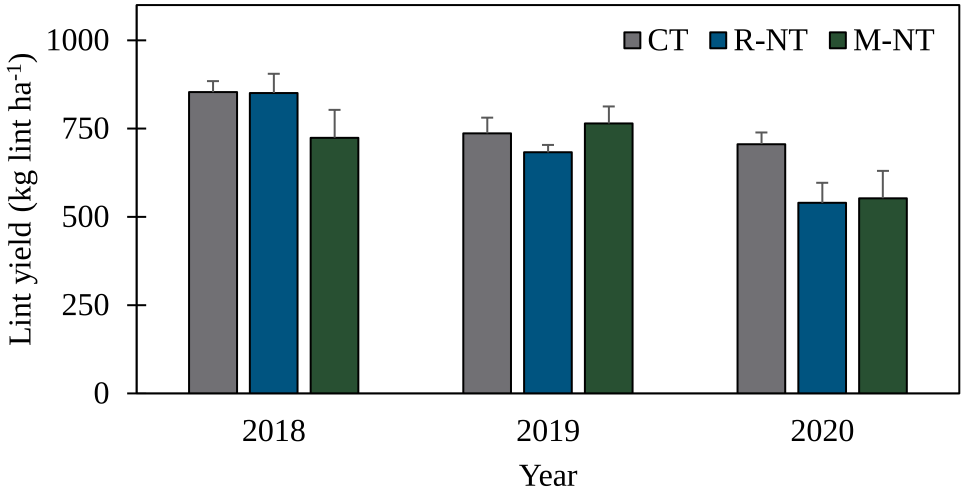

Figure 2.4 Cotton lint yield in the 2018, 2019, and 2020 growing seasons in Lamesa, TX, USA. Differences were not determined in any year at $P < 0.05$. Error bars represent standard error of the sample mean. Conventional tillage winter fallow, no-tillage rye cover, and no-tillage mixed species cover are represented CT, R-NT, and M-NT, respectively.

Cotton water use efficiency ranged from 0.96 to 3.04 kg lint ha^{-1} mm^{-1} from 2018 to 2020 (Table 2.3). Like cotton lint yield, no differences in C_{WUE} were observed during the study period. Cotton water use efficiency was greatest ($P < 0.001$) in 2018 (2.33 kg lint ha^{-1} mm^{-1}) when compared to 2020 (1.64 kg lint ha^{-1} mm^{-1}) and 2019 (1.59 kg lint ha^{-1} mm^{-1}). When averaged across years, C_{WUE} was generally greater in CT (1.99 kg lint ha^{-1} mm^{-1}) followed by R-NT (1800 kg lint ha^{-1} mm^{-1}) and M-NT (1.76 kg lint ha^{-1} mm^{-1}). Consistent with our results, previous evaluations showed no differences in cotton water use efficiency despite variability in cotton production from conservation practices (Unger and Vigil, 1998; Alfonso et al., 2020; Burke et al., 2021b). The lack of differences in water use efficiency between treatments supports our hypothesis that water is not the most limiting factor for cotton production in these systems (Lewis et al., 2018; Burke et al., 2021b).

Table 2.3 Water use efficiency for continuous cotton cropping systems at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA in 2018, 2019, and 2020. Differences were not determined in any year at *P* <0.05.

	Cotton water use efficiency		
	2018	2019	2020
Cropping system	kg lint ha^{-1} mm^{-1}		
Conventional tillage, winter fallow	2.41	1.63	1.92
No-tillage rye cover	2.47	1.48	1.45
No-tillage mixed species cover	2.10	1.66	1.54
P-value	*0.287*	*0.761*	*0.112*

2.3.4. Soil water dynamics

2.3.4.1. Profile soil water

Profile soil water followed similar trends in each year of the study where soil water was depleted with cover crops but increased following cover crop termination (Fig. 2.5a-c). In 2018, soil water was generally greater following cover crops (R-NT and M-NT) than CT throughout the growing season (Fig. 2.5a). Conversely, in 2019 and 2020 profile soil water was greater in CT compared to R-NT and M-NT prior to cover crop termination (Fig. 2.5b,c). Following cover crop termination and throughout the cotton growing season, profile soil water was greatest with R-NT and M-NT compared to CT. There was no difference in profile soil water between R-NT and M-NT at any sampling point during the study. There was little difference in profile soil water between any treatment in 2018. This is likely due to the limited amount of precipitation received from September 2017 (Lewis et al., 2018) – April 2018 (Table 1) which decreased the profile soil water for all treatments. The difference in soil water between CT and R-NT/M-NT was greater in the first 50 days after planting (DAP) in 2019 compared to 2018 and 2020. In 2020, the differences in soil water between CT and R-NT/M-NT were greatest from 50-100 DAP. The differences in profile soil water between treatments decreased from 100-150 DAP in each year of the study.

Previously, these systems demonstrated four distinct trends in soil water changes (Burke et al., 2021b), and our results support those findings, except in 2018 when there was greater soil water in the R-NT and M-NT systems compared to CT (Fig. 2.5a). Prior to planting cotton at 0 DAP there was a significant reduction in soil water with cover crops in 2019 and 2020 compared to CT. Cover crops have been reported to decrease soil water prior to termination in semi-arid regions (Wagner-Riddle, et al., 1997, Moebius-Clune et al., 2008). However, following cover crop termination, timely rainfall or irrigation can replenish depleted soil water in conservation systems to a greater degree than conventional practices through greater water capture and storage (Burke et al., 2021b). Increases in water capture and storage with cover crops is likely the result of a combination of reduced evaporation from shading of the soil surface (Mulumba and Lal, 2008), increased infiltration deeper into the soil profile via fine root channels (Dabney et al., 2001; So et al., 2009; DeLaune et al., 2019; DeLaune et al., 2020), and increased soil aggregation (Mirsky et al., 2011; Mitchel et al., 2015; Keene et al., 2017).

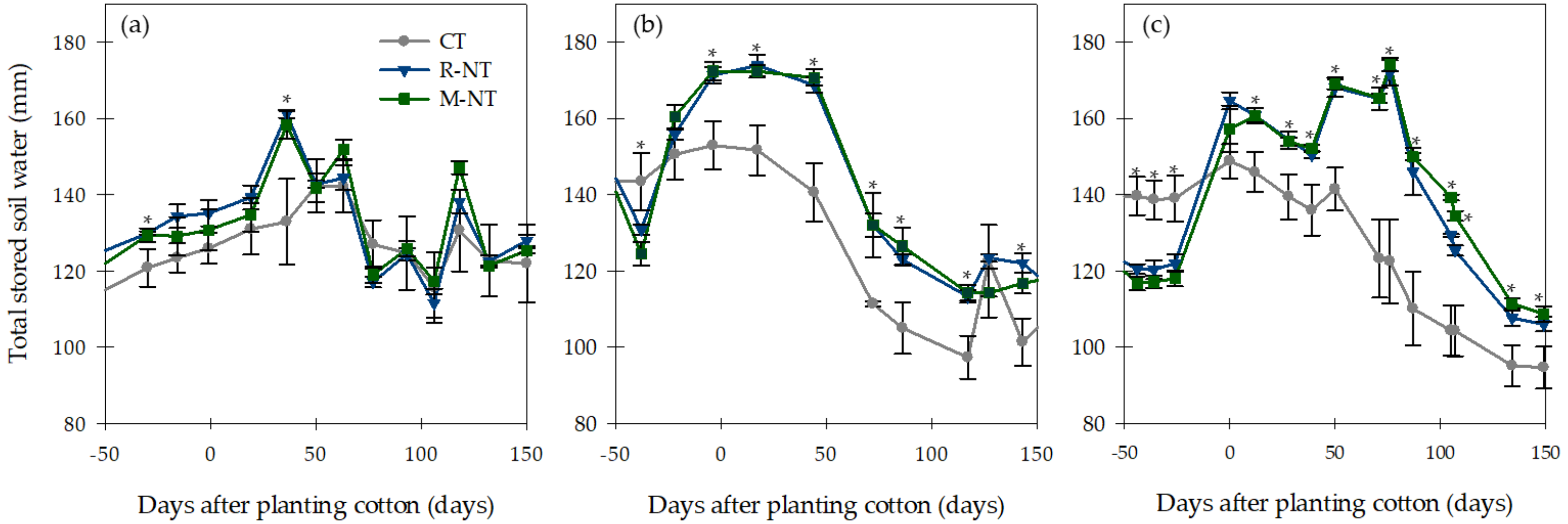

Figure 2.5 Total soil water (0- to 140-cm depth) in (a) 2018, (b) 2019, and (c) 2020 at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA. Negative values on the x-axis represent days prior to planting cotton. Bars represent standard error of the sample mean. Stars (*) represent significant differences between treatments at $P < 0.05$. Conventional tillage winter fallow, no-tillage rye cover, and no-tillage mixed species cover are represented CT, R-NT, and M-NT, respectively.

During active cotton growth (0-150 DAP), soil water was not different between treatments in 2018 (Fig. 2.5a) but was significantly greater in R-NT and M-NT compared to CT at most sampling points in 2019 and 2020 (Fig. 2.5b-c). In a former study at the same site from 2015-2017, differences in soil water between treatments were less pronounced than in this evaluation (Burke et al., 2021b). On average, there was greater precipitation during that evaluation than in the current study. Cover crops can increase water storage capacity through the mechanisms discussed previously. During periods of episodic drought that are common on the THP, cover crops may help to increase water storage and minimize loss resulting in increased drought mitigation potential (Baumhardt et al., 2013). Further investigations are needed to understand soil water dynamics following cover crop termination in semi-arid climates, especially where deficit irrigation is not possible.

Changes in profile soil water (Δ_{water}) were dynamic throughout the 2018-2020 study period (Fig. 2.6a-c). Overall, Δ_{water} ranged from -2.44 to 2.54 mm day^{-1} with the greatest decrease observed in M-NT (107 DAP, 2020) and the greatest increase in CT (127 DAP, 2019). In 2018, Δ_{water} ranged from -2.35 (77 DAP, M-NT) to 2.48 (118 DAP, M-NT) mm day^{-1} (Fig. 2.6a). In 2019, Δ_{water} ranged from -1.38 (72 DAP, M-NT) to 2.54 (127 DAP, CT) mm day^{-1} (Fig. 2.6b). In 2020, Δ_{water} ranged from -2.44 (107 DAP, M-NT) to 1.76 (76 DAP, M-NT) mm day^{-1} (Fig. 2.6c). Overall, the variability in Δ_{water} was greatest in the M-NT compared to CT and R-NT. Few differences in Δ_{water} were observed between treatments. In 2019 and 2020, increases in Δ_{water} were significantly greater for both R-NT and M-NT compared to CT immediately prior to 0 DAP. In 2018 and 2020, decreases in Δ_{water} were greatest with M-NT and R-NT between 71 and 77 DAP compared to CT.

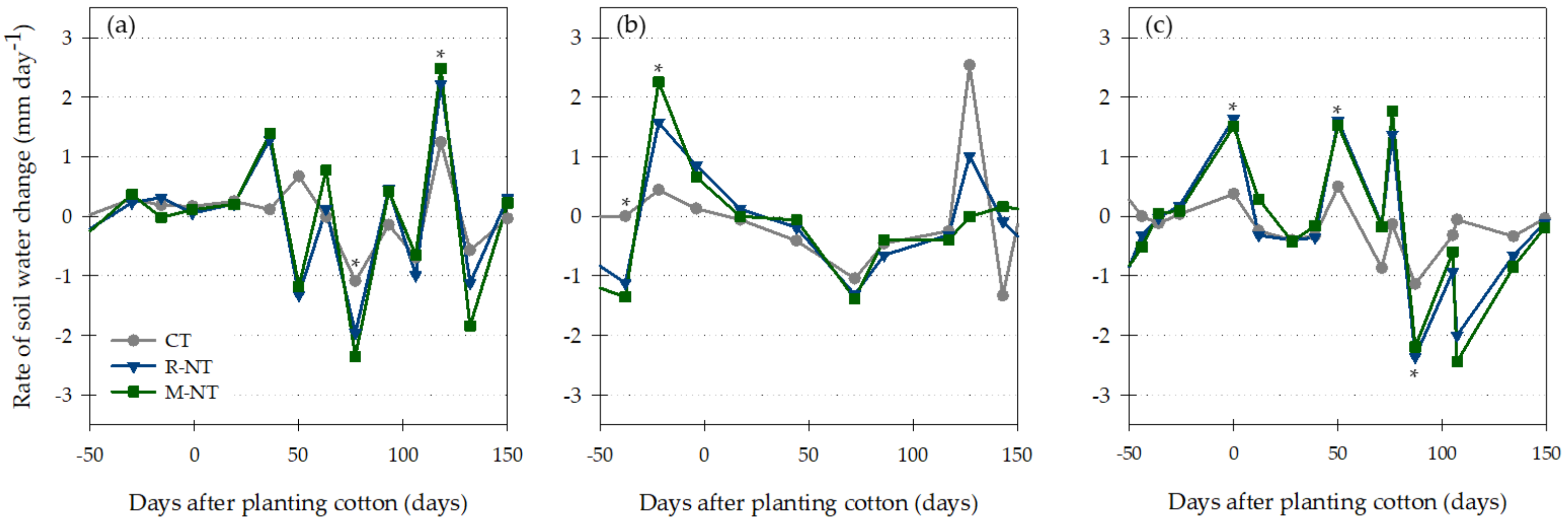

Figure 2.6 Changes in soil water in (a) 2018, (b) 2019, and (c) 2020 at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA. Negative values on the x-axis represent days prior to planting cotton. Stars (*) represent significant differences between treatments at $P < 0.05$. Conventional tillage winter fallow, no-tillage rye cover, and no-tillage mixed species cover are represented CT, R-NT, and M-NT, respectively.

2.3.4.2. Soil water at depth

Soil water at depth for the evaluated cropping systems from 2018 to 2020 is presented in Fig. 2.7. In 2018, soil water depletion at depth was greater in CT compared to R-NT and M-NT throughout most of the growing season except between ~75 to 150 DAP in the R-NT system where water was more depleted from 60 to 100 cm below the soil surface compared to CT and M-NT (Fig. 2.7a-c). There was greater soil water available from ~25 to 50 DAP throughout the profile in R-NT and M-NT compared to CT. Soil water dynamics were more pronounced in to the top 40 cm of the soil profile, especially in CT. Overall, soil water at depth was greater in 2018 compared to the other growing seasons. In 2019, soil water depletion at depth was greater in CT compared to R-NT and M-NT (Fig. 2.7 d-f). Soil water was reduced in R-NT and M-NT to ~50 and 70 cm below the surface, respectively prior to planting cotton at -50 to -30 DAP (Fig. 2.7 e,f). From -25 to 60 DAP there was significantly more soil water at depth in R-NT and M-NT compared to CT. Later in the growing season (75-125 DAP) soil water was more depleted at depth in CT compared to R-NT and M-NT. Soil water dynamics at depth followed similar trends in 2020 as they did in 2019 (Fig. 2.7 g-i). From -50 to -20 DAP, soil water was depleted at depth with R-NT and M-NT compared to CT. Following the decrease in soil water at depth, soil water was greater with R-NT and M-NT compared to CT from -10 to 90 DAP. Later in the growing season (100-150 DAP) soil water decreased at depth with all treatments but was greater in CT compared to R-NT and M-NT.

On the THP, potential evapotranspiration is generally greater than annual precipitation, thus minimizing water loss from the soil profile is essential to ensuring agricultural productivity, especially during water stress periods. Greater soil water during the growing season throughout the profile in 2018-2020 could potentially reduce the susceptibility to water stress (Fig. 2.7); however, the increased water did not result in a yield increase compared to CT indicating that water is not the greatest limiting factor. The use of cover crops can cause difficulties for cash crop production following cover crops, but the increase in ground cover, residue, and photosynthetic energy capture may benefit soil health through increased carbon capture and storage (Burke et al., 2021b). When winter precipitation is limited on the THP, proper termination timing can help to offset water cost associated with the cover crop (Bronson et al., 2001; White et al., 2020) and allow the systems to recover the maximum amount of water from spring precipitation events (Burke et al., 2021b). Additional research is needed within this system to determine if the greater soil water content throughout the profile during active cotton growth is plant available and the potential cause of yield decline with the conservation systems. We hypothesize the general yield decline observed intermittently in these systems in 2016, 2017 (Lewis et al., 2018), and 2020 is caused by N immobilization following cover crop termination (White et al., 2020).

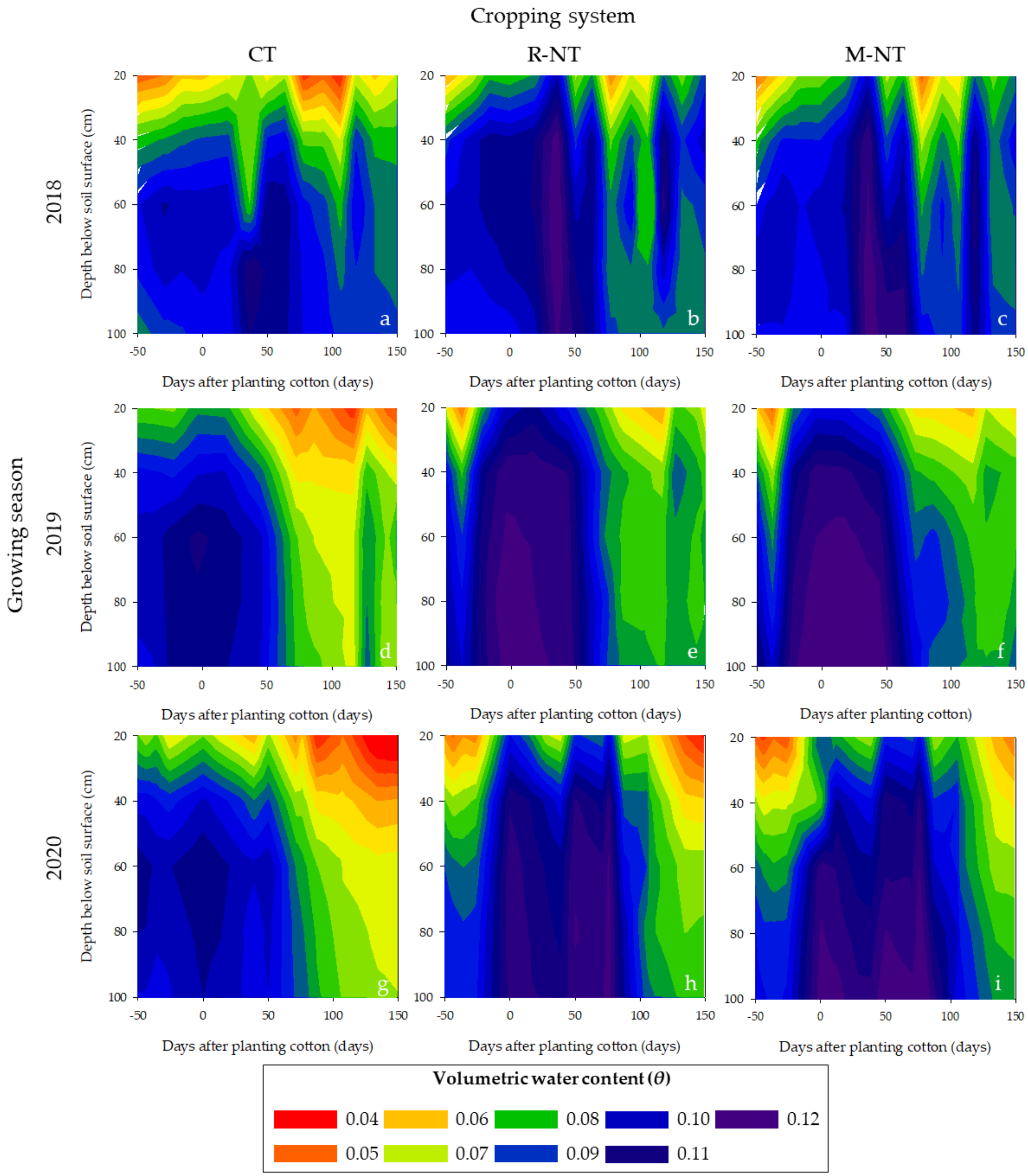
Cropping system
CT
R-NT
M-NT
Growing season
2018
2019
2020
Depth below soil surface (cm)
20
40
60
80
100
-50
0
50
100
150
Days after planting cotton (days)
Days after planting cotton)
a
b
c
d
e
f
g
h
i
Volumetric water content (θ)
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12

Figure 2.7 Volumetric water content (VWC) at depth for each cropping system (columns) based on days after planting cotton in each growing season (rows) in (a-c) 2018, (d-f) 2019, and (g-i) 2020 at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA for 0- to 100 cm below the soil surface. Negative values on the x-axis represent days prior to planting cotton. Conventional tillage winter fallow, no-tillage rye cover, and no-tillage mixed species cover are represented CT, R-NT, and M-NT, respectively.

Changes in soil water at depth followed similar patterns in 2018 and 2020 but were not similar in 2019 (Fig. 2.8). In 2018, there was a 23% greater increase in the change of soil water with R-NT and M-NT compared to CT between -30 and -20 DAP to a 50 cm depth (Fig. 2.8a-c). Patterns of positive and negative changes in soil water at depth were similar between all treatments in 2018 although the degree of change was greater in R-NT and M-NT than CT from 30 to 150 DAP. The greatest positive and negative changes in soil water occurred approximately 90 cm below the soil surface in the M-NT system at 77 (-0.52 mm day^{-1}) and 118 (+0.39 mm day^{-1}) DAP. From -50 to -10 DAP in 2019, positive increases in changes of soil water from 20 to 30 cm below the soil surface were similar for all the treatments averaging 127% increases in soil water prior to cotton planting. However, from -30 to -10 DAP, negative changes in soil water from 30 to 60 cm were 18% greater in R-NT and M-NT compared to CT. Deeper in the profile, positive changes in soil water were 21% greater at depth in R-NT and M-NT compared to CT at decreasing depth (90 to 20 cm below the soil surface) from -50 to 25 DAP. A similar trend occurred in CT (22% increase) from 50 to 125 DAP that was not observed to the same degree in R-NT and M-NT. In 2020, greater change in soil water at depth were observed overall in R-NT and M-NT compared to CT (Fig. 2.8g-i). From -30 to 0 DAP, 12% increases in soil water were observed throughout the profile of R-NT and M-NT than CT. The pattern continued at 45 to 50 (8%) and 90 to 105 (10%) DAP. At approximately 100 DAP, R-NT and M-NT had 16% negative changes in soil water from 75 to 100 cm and 90 to 100 cm for R-NT and M-NT, respectively. From 120 to 150 DAP, 32 and 24%decreases in soil water occurred in R-NT and M-NT from 20 to 65 and 20 to 90 cm below the soil surface, respectively, compared to CT.

Results from this study demonstrate that soil water increases were greater at depth with the conservation systems (R-NT and M-NT) compared to the CT system (Fig. 2.8). This suggests precipitation and irrigation interception and storage was greater following cover crops. While there were no significant differences in RB at any depth, the increase in RB at the 30-60 cm depth might indicate there is a potential plow pan within that depth (Table 2.2). Other evaluations at the site showed a significant increase in penetration resistance and RB at depth in CT compared to R-NT(DeLaune et al., 2019). The wetting barrier appeared to be at 75 and 45 cm in 2018 and 2020, respectively for the CT system, while there did not appear to be a wetting barrier in the R-NT and M-NT systems in any year (Fig. 2.8). Depletion of soil water throughout the profile in 2018 and 2020 were greater with the R-NT and M-NT systems compared to CT. Cotton rooting may have been more expansive through the profile in the conservation systems compared to CT because the roots utilized the preexisting root channels made by the cover crops (Meek et al., 1992; Schipanski et al., 2014) which allowed them to utilize additional soil water compared to the traditional cotton (Pabuayon et al., 2019).

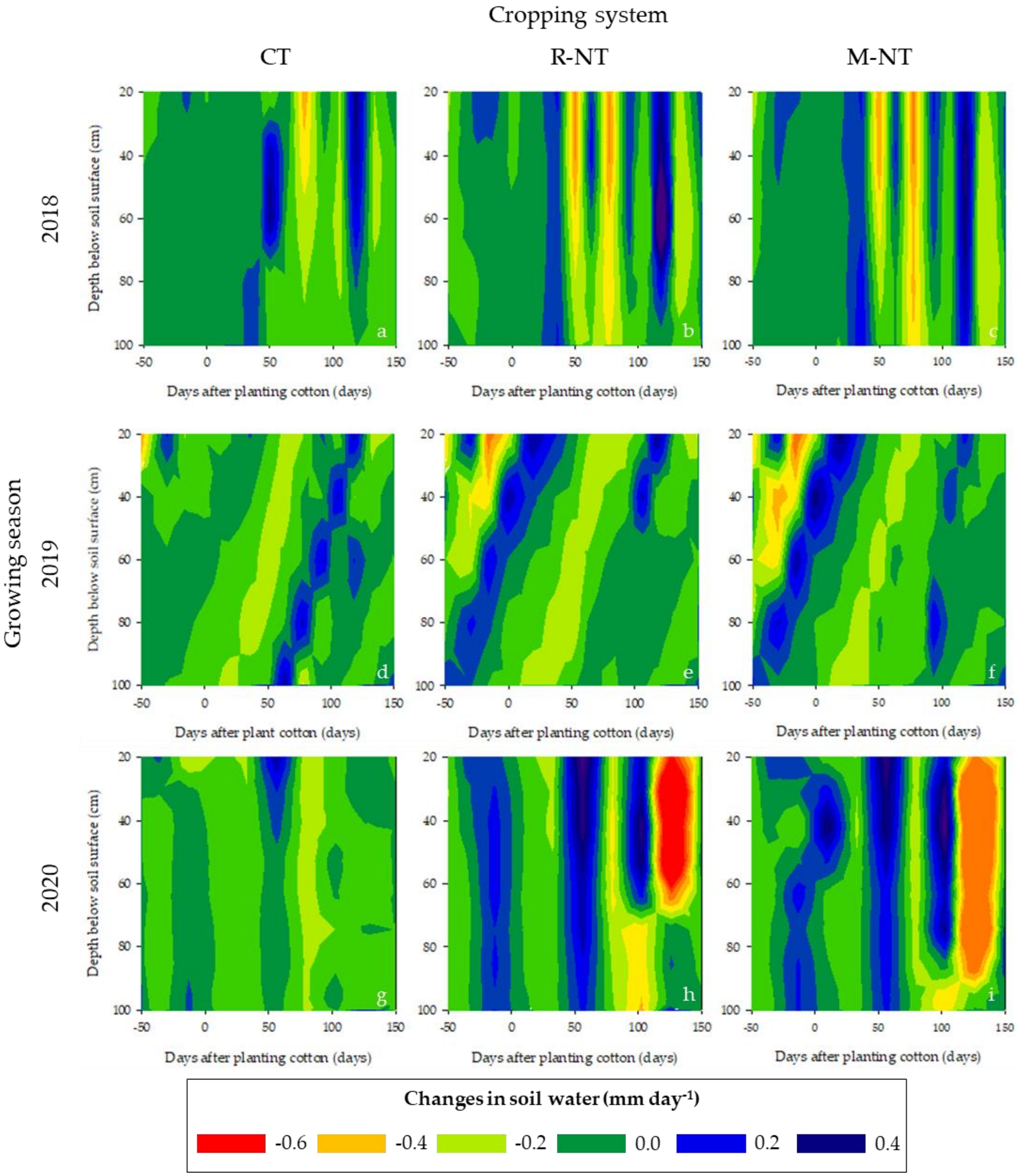

Figure 2.8 Changes in soil water depth for each cropping system (columns) based on days after planting cotton in (a-c) 2018, (d-f) 2019, and (g-i) 2020 at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA for 0- to

100 cm below the soil surface. Negative values on the x-axis represent days prior to planting cotton. Conventional tillage winter fallow, no-tillage rye cover, and no-tillage mixed species cover are represented CT, R-NT, and M-NT, respectively.

2.4. Conclusions

In semi-arid regions, water is often the primary limiting factor for agricultural production. This yield loss can be minimized with irrigation from surface and groundwater sources, however, in the THP where irrigation quality and quantity from the Ogallala Aquifer is declining, producers need alternatives to protect the valuable precipitation they receive. Compounding the problem in this region is wind erosion which can be limited with the use of cover crops and reduced tillage. This study evaluated water usage following cover crop termination and throughout the cotton growing season. Our results challenge the supposition that cover crops limit water availability during active cotton growth. While the cover crops do limit moisture immediately prior to cotton planting, they increase water interception and storage compared to traditional practices. Overall, there was not a significant reduction in cotton lint yield with the adoption of conservation management practices compared to traditional practices. These results are among the few studies demonstrating the benefit in water dynamics of cover crops in coarse-textured soils in semi-arid regions. The opportunity to utilize deficit irrigation to ensure cotton stand establishment is essential to minimize the risk associated with cover crop adoption in this area. The need for additional research on soil water dynamics following cover crops in dryland systems is essential to ensuring their successful adoption on the THP. With the very real potential for more limited water availability from the Ogallala Aquifer in the future, it is essential that any agronomic practices to reduce soil water loss be adopted for continued agricultural production in the region.

2.5. References

Acharya, R.N.; Ghimire, R.; Apar, G.C.; Blayney, D. Effect of cover crop on farm profitability and risk in the Southern High Plains. *Sustainability*, **2019**, *11*, 7119.

Acosta-Martinez, V.; Cotton, J. Lasting effects of soil health improvements with management changes in cotton-based cropping systems in a sandy soil. *Biol. Fertil. Soils*, **2017**, *53*, 533-546.

Alonso-Ayuso, M.; Gabriel, J.L.; Hontoria, C.; Ibanez, M.A.; Quemada, M. The cover crop termination choice to designing sustainable cropping systems. *Eur. J. Agron.*, **2020**, *114*, 126000.

Alfonso, C.; Barieri, P.A.; Hernandez, M.D.; Lewczuk, N.A.; Martinez, J.P.; Echarte, M.M.; Echarte, L. Water productivity in soybeans following a cover crop in a humid environment. *Agric. Water Manage.*, **2020**, *232*, 106045.

Balkcom, K.; Schomberg, H.; Reeves, W.; Clark, A.; Baumhardt, L.; Collins, H.; Delgado, J.; Duiker, S.; Kaspar, T.; Mitchell, J. Managing cover crops in conservation tillage systems. In *Managing Cover Crops Profitably*, 3rd ed.; Beltsville, A.C., Ed.; United Book Press, Inc. MD, 2007; pp. 44-61.

Baughman, T.; Keeling, W.; Boman, R. On-farm selected soil properties. *Comm. Soil Sci. Plant Anal.*, **2007**, *25*, 3087-3100.

Baumhardt, R.L.; Schwartz, R.; Howell, T.; Evett, S.R.; Colaizzi, P. Residue management effects on water use and yield of deficit irrigated cotton. *Agron. J.*, **2013**, *105*, 1026-1034.

Blanco-Canqui, H.; Mikha, M.M.; Pressley, D.R.; Claassen, M.M. Addition of cover crops enhances no-till potential for improving soil physical properties. *Soil Sci. Soc. Am. J.*, **2011**, *75*, 1471-1482.

Blanco-Canqui, H.; Ruis, S.J. No-tillage and soil physical environment. *Geoderma*, **2018**, *326*, 164-200.

Blanco-Canqui, H.; Weinhold, B.J.; Jin, V.L.; Schmer, M.R.; Kibet, L.C. Long-term tillage impact on soil hydraulic properties. *Soil Till. Res.*, **2017**, *170*, 38-42.

Blake, G.R.; Hartge, K.H. Bulk Density. In *Methods of soil analysis. Part 1. Physical and mineralogical methods*, 2nd ed.; Klute, A, Ed.; ASA & SSSA: Madison, WI, USA, 1986; pp. 363-375.

Boquet, D.J.; Hutchinson, R.L.; Breitenbeck, G.A. Long-term tillage, cover crop, and nitrogen rate effects on cotton: Yield and fiber properties. *Agron. J.*, **2004**, *96*, 1436-1442.

Bordovsky, J.P.; Lyle, W.M.; Keeling, J.W. Crop rotation and tillage effects on soil water and cotton yield. *Agron. J.*, **1994**, *86*, 1-6.

Bordovsky, J.P.; Mustain, J.T.; Ritchie, G.L.; Lewis, K.L. Cotton irrigation timing with variable seasonal irrigation capacities on the Texas South Plains. *Appl. Engineer. Agric.*, **2015**, *31*, 883-897.

Bronson, K.F.; Onken, A.B.; Keeling, J.W.; Booker, J.D.; Torbert, H.A. Nitrogen response in cotton as affected by tillage system and irrigation level. *Soil Sci. Soc. Am. J.*, **2001**, *65*, 1153-1163.

Burke, J.A.; Lewis, K.L.; Foster, J.L. Nitrogen dynamics following cover crops in Texas High Plains cotton. In Proceedings of the Beltwide Cotton Conferences, Virtual, 5-7 January 2021a.

Burke, J.A.; Lewis, K.L.; Ritchie, G.L.; Moore-Kucera, J.; DeLaune, P.B.; Keeling, J.W. Temporal variability of soil carbon and nitrogen in cotton production on the Texas High Plains. *Agron. J.*, **2019**, *111*, 2218-2225.

Burke, J.A.; Lewis, K.L.; Ritchie, G.L.; DeLaune, P.B.; Keeling, J.W.; Acosta-Martinez, V.; Moore, J.M.; McLendon, T. Net positive soil water content following cover crops with no tillage in irrigated semi-arid cotton production. *Soil Till. Res.*, **2021b**, *208*, 104869.

Colazo, J.C.; Buschiazzo, D.E. Soil dry aggregate stability and wind erodible fraction in a semiarid environment of Argentina. *Geoderma*, **2010**, *159*, 228-236.

Cano, A.; Nunez, A.; Acosta-Martinez, V.; Schipanski, M.; Ghimire, R.; Rice, C.; West, C. Current knowledge and future research directions to link soil health and water conservation in the Ogallala Aquifer region. *Geoderma*, **2018**, *328*, 109-118.

Cao, Y.; He, Z., Zhu, T.; Zhao, F. Organic-C quality as a key driver of microbial nitrogen immobilization in soil: A meta-analysis. *Geoderma*, **2021**, *383*, 114784.

Claassen, R.; Bowman, M.; McFadden, J.; Smith, D.; Wallander, S. Tillage intensity and conservation cropping in the United States. United States Department of Agriculture, Economic Res. Service, **2018**, EIB-197.

Dabney, S.M.; Delgado, J.A.; Reeves, D.W. Using winter cover crops to improve soil and water quality. *Commun. Soil Sci. Plant Anal.*, **2001**, *32*, 1221-1250.

DeLaune, P.B.; Mubvumba, P. Winter cover crop production and water use in Southern Great Plains cotton. *Agron. J.*, **2020**, *112*, 1943-1951.

DeLaune, P.B.; Mubvumba, P.; Ale, S.; Kimura, E. Impact of no-till, cover crop, and irrigation on cotton yield. *Agric. Water Manage.*, **2020**, *232*, 106038.

DeLaune, P.B.; Mubvumba, P.; Lewis, K.L.; Keeling, J.W. Rye cover crop impacts soil properties in a long-term cotton system. *Soil Sci. Soc. Am. J.*, **2019**, *83*, 1451-1458.

Evett, S.R.; Colaizzi, P.D., Lamm, F.R., O'Shaughnessy, S.A.; Heeren, D.M.; Trout, T.J.; Kranz, W.L. Lin, X. Past, present, and future of irrigation on the U.S. Great Plains. *T. ASABE*, **2020**, *63*, 703-729.

Gabriel, J.L.; Almendros, P.; Hontoria, C.; Quemada, M. The role of cover crops in irrigated systems: Soil salinity and salt leaching. *Agric. Ecosyst. Environ.*, **2012**, *158*, 200-207.

Grimes, D.W.; Yamada, H. Relation of cotton growth and yield to minimum leaf water potential. *Crop Sci.*, **1982**, *22*, 134-139.

Howard, T.; Gardner, H.R. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. *Soil Sci.*, **1963**, *96*, 153-156.

Fultz, L.M.; Moore-Kucera, J.; Zobeck, T.M.; Acosta-Martinez, V.; Allen, V.G. Aggregate carbon pools after 13 years of integrated crop-livestock management in semi-arid soils. *Soil Sci. Soc. Am. J.*, **2013a**, *77*, 1659-1666.

Fultz, L.M.; Moore-Kucera, J.; Zobeck, T.M.; Acosta-Martinez, V.; Webster, D.B.; Allen, V.G. Organic carbon dynamics and soil stability in five semiarid agroecosystems. *Agric. Ecosyst. Environ.*, **2013b**, *181*, 231-240.

Hanks, J.; Martin, S.W. Economic analysis of cotton conservation tillage practices in the Mississippi Delta. *J. Cotton Sci.*, **2007**, *11*, 75-78.

Holman, J.D.; Arnet, K.; Dille, J.; Maxwell, S.; Obour, A.; Roberts, T.; Roozeboom, K.; Schlegel, A. Can cover or forage crops replace fallow in the semiarid Central Great Plains. *Crop Sci.*, **2018**, *58*, 932-944.

Jorquera, M.A.; Hernandez, M.T.; Rengel, Z.; Marschner, P.; de la Luz, Mora, M. Isolation of culturable phosphobacteria with both phytate-mineralization and phosphate-stabilization activity from the rhizosphere of plants grown in a volcanic soil. *Biol. Fert. Soil*, **2008**, *44*, 1025.

Keeling, J.W.; Segarra, E.; Abernathy, J.R. Evaluation of conservation tillage cropping systems for cotton on the Texas Southern High Plains. *J. Prod. Agric*., **1989**, *4*, 566-571.

Keeling, J.W.; Matches, A.G.; Brown, C.P.; Karnezos, T.P. Comparison of interseeded legumes and small grains for cover crop establishment in cotton. *Agron. J.*, **1996**, *88*, 219-222.

Keene, C.L.; Curran, W.S.; Wallace, J.M.; Ryan, M.R.; Mirsky, S.B.; VanGessel, M.J.; Barbercheck, M.E. Cover crop termination timing is critical in organic rotational no-till systems. *Agron. J.*, **2017**, *109*, 272-282.

Kelley, M.C.; Ardon-Dryer, K. Analyzing two decades of dust events on the Southern Great Plains region of West Texas. *Atmos. Pollut. Res.,* **2021**, *12*, 101091.

Krueger, E.S.; Ochsner, T.E.; Porter, P.M.; Baker, J.M. Winter rye cover crop management influences on soil water, soil nitrate, and corn development. *Agron. J.*, **2011**, *103*, 316-323.

Lewis, K.L.; Burke, J.A.; Keeling, W.S.; McCallister, D.M.; DeLaune, P.B.; Keeling, J.W. Soil benefits and yield limitations of cover crop use in Texas High Plains cotton. *Agron. J*. **2018**, *110*, 1616-1623.

Lopez-Fando, C.; Pardo, M.T. Changes in soil chemical characteristics with different tillage practices in a semi-arid environment. *Soil Till. Res.*, **2009**, *104*, 278-284.

McGeehan, S.L.; Naylor, D.V. Automated instrumental analysis of carbon and nitrogen in plant and soil samples. *Commun. Soil Sci. Plant Anal.*, **1988**, *19*, 493-505.

Meek, B.D.; Rechel, E.R.; Carter, L.M.; DeTar, W.E.; Urie, A.L. Infiltration rate of a sandy loam soil: Effects of traffic, tillage, and plant roots. *Soil Sci. Soc. Am. J.*, **1992**, *56*, 908-913.

Mehlich, A. Mehlich-III soil test extractant: A modification of Mehlich-II extractant. *Commun. Soil Sci. Plant Anal.*, **1984**, *15*, 1409-1416.

Mitchell, J.P.; Shrestha, A.; Irmak, S. Trade-offs between winter cover crop production and soil water depletion in the San Joaquin Valley, California. *J. Soil Water Conserv.*, **2015**, *70*, 430-440.

Mirsky, S.B.; Curran, W.S.; Mortensen, D.A.; Ryan, M.R.; Shumway, D.L. Timing of cover crop management effects on weed suppression in no-till planted soybeans using a roller-crimper. *Weed Sci.*, **2011**, *66*, 55-61.

Mitchell, A.R.; Ellsworth, T.R.; Meek. B.D. Effect of root systems on preferential flow in swelling ground. *Commun. Soil Sci. Plant Anal.*, **1995**, *26*, 2655-2666.

Mitchell, J.P.; Shrestha, A.; Irmak, S. Trade-offs between winter cover crop production and soil water depletion in the San Joaquin Valley, California. *J. Soil Water Conserv.*, **2015**, *70*, 430-440.

Moebius-Clune, B.A.; van Es, H.M.; Idowu, O.J.; Schindelbeck, R.R.; Moebius-Clune, D.J.; Wolfe, D.W., Abawi, G.S.; Thies, J.E.; Gugino, B.K.; Lucey, R. Long-term effects of harvesting maize stover and tillage on soil quality. *Soil Sci. Soc. Am. J.*, **2008**, *72*, 960-969.

Mulumba, L.N.; Lal, R. Mulching effects on selected soil physical properties. *Soil Tillage Res.*, **2008**, *98*, 106-111.

Nielsen, D.C.; Lyon, D.J.; Hergert, G.W.; Higgins, R.K.; Holman, J.D. Cover crop biomass production and water use in the Central Great Plains. *Agron. J.*, **2015**, *107,* 2047-2058.

Nielsen, D.C.; Lyon, D.J.; Higgins, R.K.; Hergert, G.W.; Holman, J.D.; Vigil, M.F. Cover crop effect on subsequent wheat yield in the Central Great Plains. *Agron. J.*, **2016**, *108*, 243-256.

Nyakatawa, E.Z.; Reddy, K.C. Tillage, cover cropping, and poultry litter effects on cotton: I. Germination and seedling growth. *Agron. J.*, **2000**, *92*, 992-999.

Nuruzzaman, M.; Lambers, H.; Bolland, M.D.A.; Beneklaas, E.J. Distribution of carboxylates and acid phosphatase and depletion of different phosphorus fractions in the rhizosphere of a cereal and three grain legumes. *Plant Soil*, **2006**, *281*, 109-120.

Otte, B.; Mirsky, S.; Schomberg, H.; Davis, B.; Tully, K. Effect of cover crop termination timing on pools and fluxes of inorganic nitrogen in no-till corn. *Agron. J.*, **2019**, *111*, 2832-2842.

Pabuayon, I.L.; Singh, S.; Lewis, K.L.; Ritchie, G.L. Water extraction and productivity of cotton, sorghum, and sesame under deficit irrigation. *Crop Sci.*, **2019**, *59,* 1692-1700.

Prokopy, L.S.; Florees, K.; Arbuckle, J.G.; Church, S.P.; Eanes, F.R.; Gao, Y.; Gramig, B.M.; Ranjan, P.; Singh, A.S. Adoption of conservation practices in the United

States: Evidence from 35 years of quantitative literature. *J. Soil Water Conserv.*, **2019**, *74*, 520-534.

Pypers, P.; Huybrighs, M.; Diels, J.; Abaidoo, R.; Smolders, E.; Merckx, R. Does the enhanced P acquisition by maize following legumes in a rotation result from improve soil P availability? *Soil Biol. Biochem.*, **2007**, *10*, 2555-2566.

Richardson, A.E.; Lynch, J.P.; Ryan, P.R.; Delhaize, E.; Smith, F.A.; Smith, S.E.; Harvey, P.R.; Ryan, M.H.; Veneklaas, E.J.; Lambers, H.; Oberson, A.; Culvenor, R.A.; Simpson, R.J. Plant and microbial strategies to improve phosphorus efficiency of agriculture. *Plant Soil*, **2011**, *349*, 121-156.

Rhoades, J.D. Soluble salts. In *Methods of soil analysis. Part 2.* 2nd ed.; Page, A.L.; Miller, R.H.; Keeney, D.R., Ed.; ASA and SSSA Madison, WI, USA, 1982; pp. 167-178.

Roth, G.; Harris, G.; Gillies, M.; Montgomery, J.; Wigginton, D. Water-use efficiency and productivity trends in Australian irrigated cotton: A review. *Crop Pasture Sci.*, ***2013***, *64*, 1033-1048.

Schipanski, M.E.; Barbercheck, M.; Douglas, M.R.; Finney, D.M.; Haider, K.; Kaye, J.P.; Kemanian, A.R.; Mortensen, D.A.; Ryan, M.R.; Tooker, J.; White, C. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agric. Syst.* **2014**, *125*, 12-22.

Schofield, R.K.; Taylor, A.W. The measurement of soil pH. *Soil Sci. Soc. Am. Pro.* **1955**, *19*, 164-167.

Simao, F.; Ritchie, G.; Bednarz, C. Cotton physiological parameters affected by episodic irrigation interruption. *J. Agric. Sci. Tech.*, **2013**, *A 3*, 443-454.

Sinha, E.; Calvin, K.V.; Kyle, P.G.; Hejazi, M.I.; Waldhoff, S.T.; Huang, M.; Vishwakarma, S.; Zhang, X. Implication of imposing fertilizer limitations on energy, agriculture, and land systems. *J. Environ. Manage.*, **2022**, *305*, 114391.

So, H.B.; Grabski, A.; Desborough, P. The impact of 14 years of conventional and no till cultivation on the physical properties and crop yields of a loam soil at Grafton NSW, Australia. *Soil Tillage Res.*, **2009**, *104*, 180-184.

Snowden, M.; Ritchie, G.; Simao, F.; Bordovsky, J. Timing of episodic drought can be critical in cotton. *Agron. J.*, **2014**, *106*, 452-458.

Tennakoon, S.B.; Hulugalle, N.R. Impact of crop rotation and minimum tillage on water use efficiency of irrigated cotton in a Vertisol. *Irrig. Sci.,* **2006**, *25*, 45-52.

Thomas, G.A.; Dalal, R.C.; Standley, J. No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. *Soil Till. Res.*, **2007**, *94*, 295-304.

Unger, P.W.; Vigil, M.F. Cover crop effects on soil water relationships. *J. Soil Water Conserv.*, **1998**, *53*, 2000-2007.

USDA-ERS. Cotton and wool yearbook: 2018. Available online: https:// www.ers.usda.gov/data-products/cotton-wool-and-textile-data/ cotton-and-wool-yearbook/. (Accessed on 18 November 2021).

USDA-NASS. 2018 State Agriculture Overview: Texas. Available online: https://www.nass.usda.gov/ Quick_Stats/Ag_Overview/stateOverview.php?state=TEXAS. (accessed on 18 November 2021).

USDA-NRCS. Amarillo Soil Series. Available online: https://soilseries.sc.egov.usda.gov/OSD_Docs/A/AMARILLO.html (accessed on 21 February 2022).

Villalobos, F.J.; Fereres, E. Evaporation measurement beneath corn, cotton, and sunflower canopies. *Agron. J.*, **1990**, *82*, 1153-1159.

Wagger, M.G. Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. *Agron. J.*, **1989**, *81*, 236-241.

Wagner-Riddle, C.; Gillespie, T.J.; Hunt, L.A.; Swanton, C.J. Modeling a rye cover crop and subsequent soybean yield. *Agron. J.*, **1997**, *89*, 208-218.

Wanjura, D.F.; Upchurch, D.R.; Mahan, J.R.; Burke, J.J. Cotton yield and applied water relationships under drip irrigation. *Agric. Water Manage.*, **2002**, *55*, 217-237.

Ward, D.; Kirkman, K.; Hagenah, N.; Tsvuura, Z. Soil respiration declines with increasing nitrogen fertilization and is not related to productivity in long-term grassland experiments. *Soil Biol. Biochem.*, **2017**, *115*, 415-422.

White, C.D.R.; Lewis, K.L.; Keeling, J.W. Cover crop management in Texas High Plains cotton. In Proceedings of the Beltwide Cotton Conferences, Austin, TX, USA, 8-10 January 2020.

Young, C.E.; Osborn, C.T. Cost and benefits of the Conservation Reserve Program. *J. Soil Water Conserv.*, **1990**, *45*, 370-373.

Zobeck, T.M.; Van Pelt, R.S. Wind erosion. In *Soil management: Building a stable base for agriculture*; Hartfield, J.L., Sauer, T.J., Eds.; SSSA: Madison, WI, USA, 2012; pp. 209-227.

3. NITROGEN MANAGEMENT TO INCREASE COTTON PRODUCTION IN CONSERVATION CROPPING SYSTEMS

Abstract

The use of conservation management practices, like cover crops and no-tillage, is common in semi-arid cropping systems to reduce wind erosion. However, the use of these practices can also reduce cotton lint yield. The purpose of this study was to determine the impact of nitrogen (N) management in conservation cropping systems to increase cotton lint yield. Two experiments were conducted at the Agricultural Complex for Advanced Research and Extension Systems in Lamesa, TX, USA. The first experiment utilized litterbags in 2020 and 2021 to determine cover crop decomposition rates following termination. In 2020, approximately 75% of the cover crop biomass remained 128-d following termination while approximately 25% of the biomass remained 128-d after termination in 2021. The differences in decomposition rate between 2020 and 2021 are likely the result of significant differences in biomass production between the two years. The second experiment utilized four N fertilization timings to determine the impact of supplemental N fertilization on cotton yields following cover crop termination. An early-season application of N either preplant or post-emergence resulted in significantly greater cotton lint yields following cover crops in 2018 and 2019, but not 2020. Supplemental N did not increase cotton lint yield in the traditionally grown cotton. These results demonstrate that N management practices that account for potential N immobilization following cover crops can significantly increase

cotton lint yield and decrease the potential yield loss associated with conservation management practices in semi-arid regions.

3.1. Introduction

Conservation management practices such as no-tillage and cover cropping have grown in popularity along with interest in regenerative agricultural production. In semi-arid cotton growing regions like the Texas High Plains (THP), producers utilize cover crops and reduced tillage to protect the soil surface from wind erosion; however, these conservation management practices have been shown to decrease cotton lint yield compared to traditionally grown cotton (Lewis et al., 2018). Research in the region has demonstrated that cover crops limit early-season water availability but increase in-season water availability during active cotton growth (Burke et al., 2021; 2022), which indicates that water is likely not the yield decline culprit.

Previous studies have demonstrated the need for additional nitrogen (N) fertilization following cover crops to minimize the yield loss associated with N immobilization (Bronson et al., 2001; Nevins et al., 2020). In semi-arid west Texas, an additional 34 kg N ha^{-1} overcame the yield reductions following cover crops and resulted in significantly greater cotton lint yields compared to traditionally grown cotton (Bronson et al., 2001). Bronson et al. (2001) recommended this supplemental N application at the pinhead square cotton physiological stage. It is important to note that these results were ascertained utilizing pre-transgenic cotton varieties that are not commonly grown on the THP currently since the introduction of transgenic varieties in the early 2000s. Pabuayon et al. (2020) found that modern, transgenic cotton varieties utilize similar quantities of N as a historic variety, but it takes up a greater proportion of nutrients earlier in the growing season. The increase in early-season nutrient uptake could potentially result in late-season nutrient deficiencies if following the current Texas A&M AgriLife Extension nutrient application recommendations following cover crops on the THP.

The overall goal of this research is to better understand how the use of conservation cropping systems in semi-arid cotton production influences nutrient cycling potential and lint yield. Two experiments were conducted to explore that goal. The first experiment was designed to calculate the rate of cover crop decomposition and determine the impact of cover crop termination on soil nutrients and water dynamics. The second experiment was designed to evaluate how supplemental N fertilization can be used to minimize the yield loss associated with the adoption of reduced tillage and cover crops. The objective of these experiments was to determine (1) the decomposition rate and nutrient cycling potential of cover crop herbage mass following termination in semi-arid cotton cropping systems and (2) the role of N management to maintain cotton lint yield in conservation cropping systems. We hypothesized that cover crop decomposition rate will be dependent upon herbage mass production which will cause differing rates of N immobilization following cover crop termination.

3.2. Materials and Methods

3.2.1. Experiment One – Herbage mass, decomposition, and nutrient cycling

3.2.1.1. Site description and experimental design

The first experiment was conducted in long-term research plots at the Agricultural Complex for Advanced Research and Extension Systems (AG-CARES) located near Lamesa, TX (N 32°46’22”, W 101°56’18”; 919 m a.s.l.). The soil series has been described as an Amarillo fine sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs) (USDA-NRCS, 2016). Prior to the study initiation, conventionally tilled cotton had been grown continuously for at least 50 yr. In 1998, a study was initiated to evaluate the impact of the recently released glyphosate tolerant cotton in two continuous cotton cropping systems: 1) conventional tillage and winter fallow; and 2) no-tillage and rye (*Secale cereal* L.) cover crop. The treatments were arranged as a randomized complete block design with three replications. Plots were 76 m long and 16 rows wide (1.04 m centers) for the conventional treatment and 32 rows wide for the no-tillage, rye cover treatment.

In 2014, the no-tillage, rye cover crop plots were split into two 16-row plots to add a mixed species cover crop treatment. Treatments for the experiments presented here from 2020 to 2021 were three continuous cotton cropping systems arranged as a randomized complete block design with three replications and included: 1) conventional tillage and winter fallow (CT); 2) no-tillage and rye cover crop (R-NT); and 3) no-tillage and mixed species cover crop (M-NT). The cover crop mixture included 22.5 kg PLS ha^{-1} rye, 14.9 kg PLS ha^{-1} hairy vetch (*Vicia villosa* Roth), 4.5 kg PLS ha^{-1} Austrian winter pea (*Pisum sativum* L.), and 3.2 kg PLS ha^{-1} radish (*Raphanus sativus* L.). The cover crops were seeded following cotton harvest in each year of the study on 21 Nov 2019 and 4 Dec 2020 at a rate of 45 kg ha^{-1} using a no-till grain drill. Cover crops were terminated on 27 March 2020 and 9 April 2021 with glyphosate in the potassium salt form at a rate of 2.3 L ha^{-1}.

Cotton (DP 1646 B2XF, Bayer Crop Sciences, St. Louis, MO) was planted on 18 May 2020 and 12 May 2021 at a rate of 131,000 seeds ha^{-1}. On 26 June 2021, a series of thunderstorms produced a micro-downburst that was recorded at AG-CARES (National Weather Service, 2021). Wind speeds peaked at 193 kmph resulting in complete cotton crop failure. Cotton was replanted across all treatments on 6 July 2021. Due to the timing of the replant, cotton lint yield and quality were significantly reduced compared to average production (Keeling et al., 2021). Irrigation and fertilization were equal across all plots in all years. From May to Sept 2020, the plots received 290 mm irrigation and 173 mm precipitation. Additionally, they received 134.5 kg N ha^{-1} as urea ammonium nitrate (UAN, 32-0-0). Cotton was harvested on 31 Oct 2020 and 17 Nov 2021.

3.2.1.2. Sampling protocol and analysis

Prior to termination in each year, cover crop aboveground biomass was harvested randomly from a 1 m^2 area at ground level between tractor tire tracks. Collected biomass was dried at 60°C for 7-d and ground to 2 mm sieve in a Wiley mill (Model 4, Arthur H. Thomas Company, Philadelphia, PA). Herbage mass on a dry weight basis was calculated. Nitrogen uptake was determined by multiplying the N concentration by the herbage mass produced. Total C and N values were determined through combustion analysis (McGeehan and Naylor, 1988).

An additional 1 m^2 of biomass was collected from each of the two cover crop treatments for the decomposition study. The fresh harvested biomass from each of the three replications for both the rye and mixed species was homogenized prior to weighing and adding to litterbags. Previously constructed nylon 200 µm litterbags measuring 15 × 20 cm (Bar Diamond Inc., Parma, ID) were filled with 15.4 and 7.4 kg biomass ha^{-1} (fresh weight) for 2020 and 2021, respectively (Dubeux et al., 2006). The litterbags containing the herbage mass samples were installed the day following cover crop termination. In the field, litterbags were secured to the soil surface within the harvested biomass quadrants. This is done for two reasons: first, the treatments in this study have been chemically terminated and are therefore not actively growing, and second, placement outside of the harvested quadrants would represent double the amount of biomass inputs if the litterbags were placed there. A total of 108 litterbags were used in each cropping season (2 treatments × 3 plot replications × 3 within plot replications × 6 incubation times). Litterbags were collected at random from each plot 0, 4, 8, 16, 32, 64, and 128 d after cover crop termination (DAT). After collection, samples were transported to the lab, brushed to remove extraneous soil, weighed, and oven-dried at 60^{o}C for 72 h and weighed again. Biomass decomposition rate was fitted using a logarithmic decay curve.

Soil samples were collected for soil characterization following cover crop termination on 31 March 2021 to a depth of 60 cm. Composites of three, 5.1-cm diameter cores per plot were collected using a Giddings probe (Giddings Machine Co., Windsor, CO) and were divided into 0-15, 15-30, and 30-60 cm depth increments. The samples were dried at 60°C for 7 d and ground to pass a 2-mm sieve. Soil pH and electrical conductivity (EC) were determined from a 1:2 soil to deionized water slurry with a pH probe and conductivity electrode (Schofield and Taylor, 1955; Rhoades, 1982). Soil total N (TN) was determined through combustion (McGeehan and Naylor, 1988). Nitrate-N (NO_3^--N) was determined colorimetrically following cadmium reduction of soil samples extracted with 2 M KCl (1:10 soil/extractant ratio) and analyzed using flow injection spectrometry (FIAlab Instruments, Bellevue, WA, USA). Mehlich III extractable nutrients including P, K, Ca, Mg, and S were measured using inductively coupled plasma spectroscopy (Mehlich, 1984). An additional soil core was collected per plot to determine bulk density (ρ_b) at the same depth increments as the other soil samples.

3.2.1.3. Statistical approach and analysis

An analysis of variance was conducted for all parameters using a generalized linear mixed model (PROC GLIMMIX) using SAS version 9.4 (SAS Institute, Inc., Raleigh, NC, USA) with cropping system included as a fixed effect and replication as a random effect. Year and Year × Cropping System effects were determined, and due to a significant Year effect, means were evaluated within Year. Year × Cropping System effect was not significant. Means of treatment effects were compared within sample time using Fisher’s least significant difference (LSD) at $P < 0.05$.

3.2.2. Experiment Two – Supplemental N fertilization

3.2.2.1. Site description and cropping system management

The second experiment was initiated in 2018 to evaluate the impact of N fertilizer application timing on cotton lint yield following a rye cover crop terminated in March of each year (CCRC), and in a conventional tillage, winter fallow system (CC) at AG-CARES. The N treatments were replicated within each cropping system and included: 1) FP plus an additional 34 kg N ha^{-1} applied prior to planting cotton (PRE); 2) FP plus an additional 34 kg N ha^{-1} applied three weeks after cotton emergence (POS); and 3) FP plus an additional 34 kg N ha^{-1} applied at pinhead square plus two weeks (PIN) compared to a control that represented farmer's practices within the region (134.5 kg N ha^{-1}). Treatment 3 was based on Texas A&M AgriLife Extension soil fertility recommendations (Bronson et al., 2001). Treatments were arranged as a randomized complete block design within cropping system with three replications.

Cotton (DP 1522 B2XF) was planted on 16 May 2018 (replanted on 7 June 2018), 19 May 2019, and 21 May 2020 at 131,000 seeds ha^{-1}. The cotton was harvested on 26 Nov 2018, 31 Oct 2019, and 30 Oct 2020. The plots received 295, 274, and 282 mm of total irrigation in 2018, 2019, and 2020, respectively. Due to the extreme weather event described in experiment one this experiment was not conducted in 2021. Soil at the site has been described as an Amarillo fine sandy loam.

3.2.2.2. Sampling protocol and analysis

Prior to cotton planting in each year, three composited soil cores (5-cm diameter) were collected per plot to a depth of 60 cm using a Giddings probe. The soil samples were divided into 0-15, 15-30, and 30-60 cm depth increments and dried at 60°C for 7 d and ground to pass a 2-mm sieve. In addition to the general soil characterization analyses described in Experiment 1, the soil samples were also analyzed to determine micronutrient concentrations in the 0-15 cm depth and organic C (OC) and TN throughout the soil profile. Soil micronutrients including Fe, Zn, Mn, and Cu were extracted using diethylenetriaminepentaacetic acid (DTPA) and measured using inductively coupled plasma spectroscopy (Lindsay and Norvell, 1978). Soil OC and TN was determined using dry combustion (Storer, 1984; McGeehan and Naylor, 1988; Schulte and Hopkins, 1996). An additional soil core was collected per plot to determine bulk density at the same depth increments as the other soil samples. Cotton nitrogen use efficiency relative to the control (FP) was calculated as the difference of the lint yiueld from the control ling yield divided by the kg N ha^{-1}). Cotton lint yield was determined after mechanically stripping the cotton bolls from the plant after defoliation at harvest and then ginning the lint from the seed.

3.2.2.3. Statistical approach and analysis

Analysis of variance for all parameters was calculated using a randomized complete block design with three replications (PROC GLIMMIX, SAS 9.4, 2015).

Significant means of treatment effects were compared among treatments within year using Fisher's least significant difference (LSD) at $P < 0.05$ for all analyses.

3.3. Results and Discussion

3.3.1. Experiment 1 – Herbage mass, decomposition, and nutrient cycling

3.3.1.1. Soil characterization

There were no significant differences between treatments within depth for RB, K, and Mg (Table 3.1). Soil pH decreased with the inclusion of no-tillage and cover crops compared to CT at the 0-15 cm depth. This reduction in pH is likely the result of increased C inputs and rhizodeposition that stimulated microbial activity thus reducing the pH through the production of carbonic acid (Ward et al., 2017). There were no significant differences between treatments in EC at the 0-15 and 30-60 cm depth. However, there was a significant reduction in EC at 15-30 cm with the adoption of conservation management practices. Conservation practices, such as no-tillage and cover crops have been shown to decrease EC in semi-arid cropping systems through the uptake of salts into the cover crop biomass and creation of preferential flow paths that allow water to percolate deeper into the soil profile translocating salts (Gabriel et al., 2012). Sodium concentrations significantly decreased at the 0-15 cm depth with R-NT and M-NT compared to CT. This is likely due to the cover crop biomass reducing evapotranspiration from the soil surface (Mulumba and Lal, 2008; Burke et al., 2021).

Soil TN and P followed a similar trend where there was an increase in TN and P at the 30-60 cm depth with the use of cover crops and no-tillage. This was likely due to increased rooting density deeper in the profile with the cover crops that can result in increased microbial activity and diversity (Nyakatawa et al., 2000; Boquet et al., 2004; Jorquera et al., 2008). Unlike TN and P, NO_3^--N was significantly reduced following no-tillage and cover crops in the 0-15 and 15-30 cm depths. Nitrogen immobilization following cover crops is common in climates with reduced decomposition rates and is likely the cause of reduced NO_3^--N levels in this study (Acharya et al., 2019). Interestingly, there was a significant increase in NO_3^--N in the R-NT system compared to CT and M-NT at the 30-60 cm depth. Additional research is needed to better understand this phenomenon. There was generally greater S content in the 0-15 cm depth compared to the 30-60 cm depth across all cropping systems with greater S in CT compared to M-NT at 15-30 cm. This result contrasts with previous soil characterization studies of the site and needs further investigation before conclusions can be drawn (Lewis et al., 2018; Burke et al., 2022).

Table 3.1 Soil characterization of samples collected at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA in March 2021 at soil depths 0-15, 15-30, and 30-60 cm from the conventional tillage, winter fallow (CT), no-tillage rye cover crop (R-NT), and no-tillage mixed species cover (M-NT) treatments.

Management	B_D[1]	pH	EC[2]	OC[3]	TN[4]	NO_3-N	P	K	Ca	Mg	S	Na
Practice	g cm^{-3}	---	µmhos cm^{-1}	g kg^{-1}	mg kg^{-1}							
					0-15 cm							
CT	1.34	7.2 a[5]	295	3.0	242	21.4 a	79	327	1116	861	78	161 a
R-NT	1.42	6.8 b	213	3.6	313	2.3 b	88	351	966	691	45	93 b
M-NT	1.36	6.8 b	231	3.3	214	3.9 b	90	390	940	787	44	105 b
					15-30 cm							
CT	1.55	7.3	394 a	1.8	125	24.5 a	49	257	1069 a	849	81 a	159
R-NT	1.59	7.3	217 b	1.9	97	6.7 b	45	287	823 b	743	56 ab	115
M-NT	1.52	7.1	197 b	1.8	84	1.9 c	52	287	818 b	761	40 b	111
					30-60 cm							
CT	1.58	7.3	368	2.1 b	176 b	15.8 b	13 b	245	1285	1008	74	181
R-NT	1.57	7.2	372	3.5 a	344 a	28.3 a	20 a	268	1195	1032	80	199
M-NT	1.43	7.2	426	3.3 a	306 a	19.3 b	22 a	258	1155	1088	73	206

[1] Bulk density; [2] Electrical conductivity; [3] Organic carbon; [4] Total nitrogen; [5] Different letters within column and depth indicate significant differences ($P < 0.05$) between cropping systems.

3.3.1.2. Cover crop herbage mass production and decomposition

Cover crop herbage mass, N concentration, potentially available N, and C:N are presented in Table 3.2. There was no difference between any parameters in either year (*P* = 0.742). However, there was a significant decrease in cover crop herbage mass from 2020 to 2021 (*P* = 0.001). The observed decrease in biomass production was likely caused by decreased precipitation in the winter of 2020 coupled with below-average temperatures from January-March 2021. Previous results from the study site indicate that the 2021 biomass produced is the least amount recorded in the last six years (Lewis et al., 2018; Burke et al., 2022).

The decrease in biomass production also subsequently resulted in a significant decrease in the amount of potential N available to the subsequent cotton crop. The potential N available in the 2020 growing season from the cover crop herbage mass would be sufficient to meet average cotton lint goals for the region if 100% of the biomass could be mineralized during active cotton growth (Bronson et al., 2001).

Table 3.2 Cover crop herbage mass production, N concentration, potential N availability, and C:N for rye and mixed species cover crops grown at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA in 2020 and 2021. There were no significant differences for any measured parameter within any year ($P < 0.05$).

Year	Cover crop	Herbage mass	N	Potential N	C:N
		kg ha^{-1}	g kg^{-1}	kg ha^{-1}	----
2020	Rye	4630	3.1	142	13
	Mixed	4560	3.1	141	13
2021	Rye	1156	3.0	35	13
	Mixed	974	3.0	29	13

Herbage mass decomposition rates were different between to the two years the study was conducted (Figure 3.1). Decomposition rates were greater in 2021 compared to 2020. Biomass quality likely played an important role in the differences in decomposition rates between the two years (Talbot & Treseder, 2012). Based on the decomposition curves (Figure 3.1), approximately 75 and 28% herbage mass remained during peak cotton bloom, and subsequently, peak nutrient demand in 2020 and 2021, respectively. Despite differences in decomposition rate, the increased herbage produced in 2020 would have released 35 and 34 kg N ha^{-1} for R-NT and M-NT, respectively, compared to 25 and 21 kg N ha^{-1} released in 2021 for R-NT and M-NT, respectively. With complete cotton failure in 2021, it is impossible to compare these theoretical N release rates with crop uptake. Additional research is needed to better understand these dynamics in our semi-arid cropping systems. However, complete mineralization of cover crop herbage mass is unlikely to occur during a period where the subsequent cotton crop could directly benefit from the residue N (Wagger et al., 1998). A laboratory incubation utilizing fresh cover crop biomass harvest from the long-term tillage trial in Lamesa, TX, USA (Lewis et al., 2018) demonstrated that the cover crop input significantly stimulated the microbial communities which increased C mineralization 77% and primed existing soil organic matter in no-till systems with cover crops compared to the traditional tillage plots (White et al., 2016).

The primary ecosystem benefit of cover crops in west Texas is their ability to reduce soils susceptibility to wind erosion (Zobeck & Van Pelt, 2012). Utilizing the herbage mass and decomposition rate for 2020, it may be possible in our cropping systems to plant cover crops only in alternate years while still achieving the desired ecosystem benefit of cover crops for this region. While additional research would be needed to verify the observation made in 2020, it is theoretically possible that if sufficient biomass could be grown in ideal years, it might be enough to reduce erodibility over two growing seasons. The 2020 growing season was a record year for biomass production so additional research would be needed to ensure this is a possible solution for west Texas cotton producers.

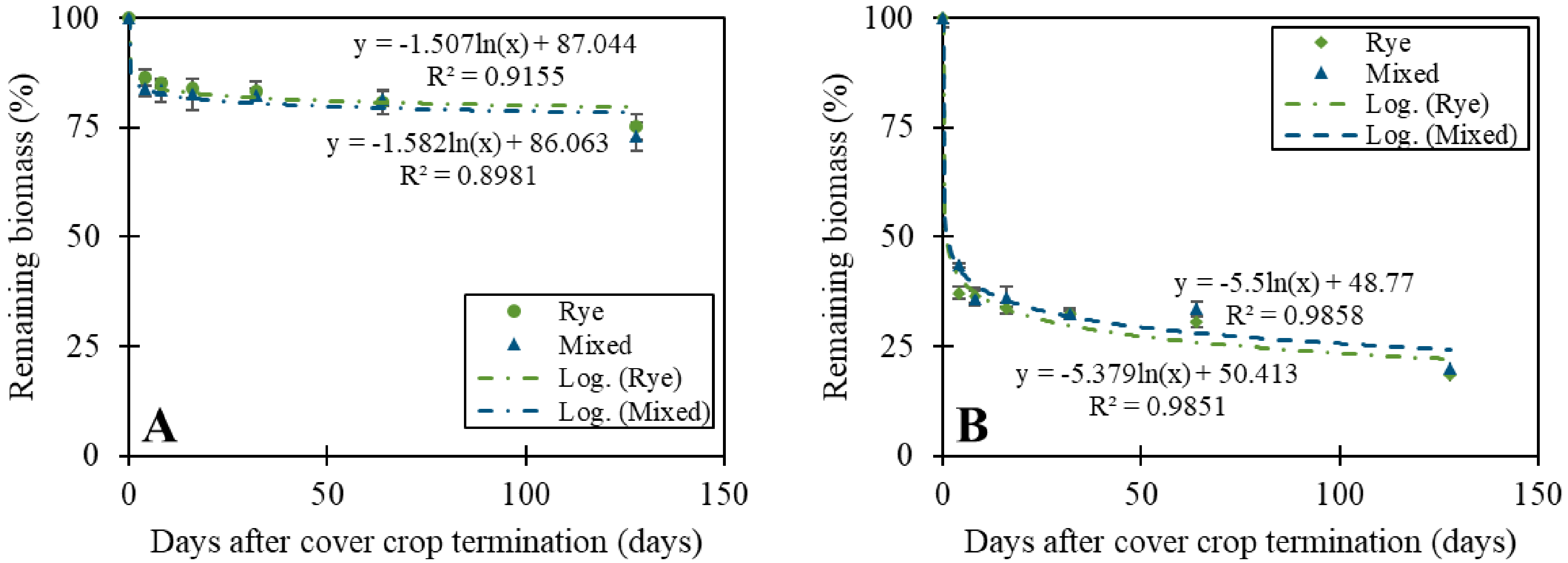

Figure 3.1 Herbage mass decomposition following cover crop termination at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA for A) 2020 and B) 2021. There was no difference ($P = 0.724$) between treatments in remaining biomass at any sampling point in either years ($P < 0.05$).

3.3.2. Experiment 2 – Supplemental N fertilization

3.3.2.1. Soil characterization

For Experiment 2, soil samples were collected in Mar 2018 for summary purposes. Generally, soil pH, NO_3^--N, P, and Na were similar between CC and CCRC. However, Ca, Mg, and S were greater in the CCRC than the CC system, especially at depth. The lack of numerical differences between the CC and CCRC cropping systems might be caused by the age of the systems (established 2014). In the long-term cropping system (established in 1998), greater differences between the traditional and conservation cotton cropping systems were observed (Lewis et al., 2018; Burke et al., 2022).

Table 3.3 Soil characterization of samples collected at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA in March 2018 at soil depths 0-15, 15-30, and 30-60 cm from the conventional tillage, winter fallow (CC) and conservation tillage, rye cover (CCRC) treatments.

Cropping system	pH	EC	NO_3^--N	P	K	Ca	Mg	S	Na
	-----	µmhos cm^{-1}				mg kg^{-1}			
					0-15 cm depth				
CC	7.5	180	7	40	197	583	571	14	39
CCRC	7.8	363	9	50	325	787	837	48	56
					15-30 cm depth				
CC	8.0	126	7	26	172	619	645	5	52
CCRC	7.8	270	8	19	242	1495	811	32	64
					30-60 cm depth				
CC	8.0	400	8	7	215	1284	862	54	102
CCRC	7.9	511	10	6	179	4178	906	76	101

3.3.2.2. Cotton lint yield

In 2018, cotton lint yield in the CC system was greatest with the PRE application of N followed by POS, and finally FP and PIN (Fig. 3.2). Cotton lint yields were 26 and 7% greater for the PRE and POS systems, respectively, while PIN was 5% less than the FP N fertilization systems. For CCRC, cotton lint yield was 43% greater with POS followed by PRE (22%) and then PIN (15%) compared to FP. The difference in N response may be due to two factors: nutritional demands of modern cotton varieties (Pabuayon et al., 2020) and overcoming N immobilization by microbes following cover crop termination (Nevins et al., 2020). The response of the added N in the CC system is likely driven by supplementing the nutritional demands of modern cotton varieties that require similar amounts of N to historical varieties but earlier in the growing season compared to those historical cultivars (Pabuayon et al., 2020). However, the yield response to added N in the CCRC system is likely driven by overcoming N immobilization following the cover crop (Nevins et al., 2020).

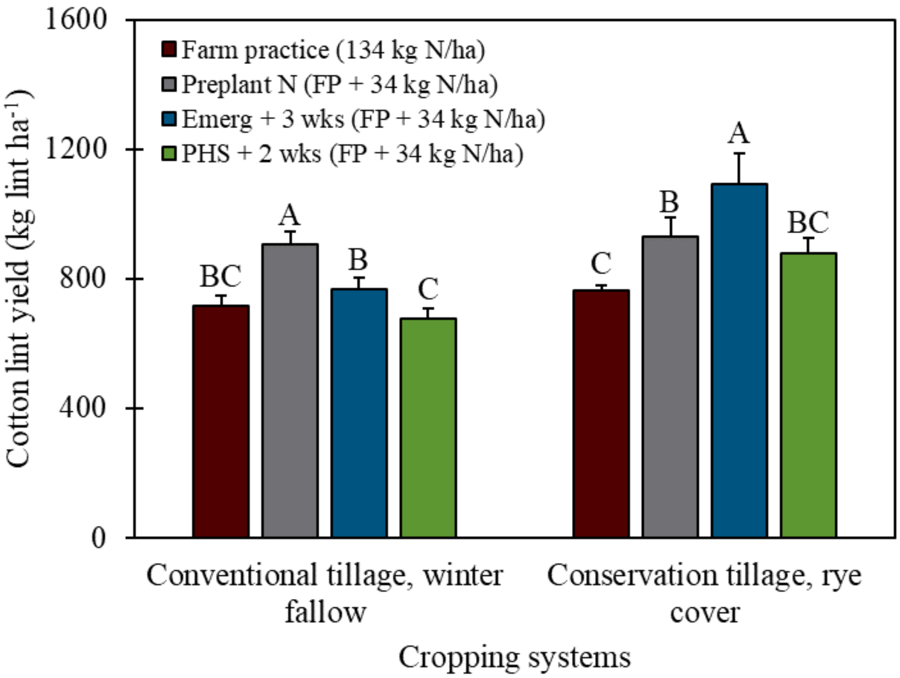

Figure 3.2 Cotton lint yield from harvest 2018 following different N application timings. Mean concentrations followed by the same letter within cropping system are not different at $P<0.05$ by Fisher's protected LSD. The vertical bars represent the standard error of the mean. Farmers Practices (134 kg N/ha), Additional 34 kg N/ha applied three weeks after emergence, and additional 34 kg N/ha applied at pinhead square plus 2 weeks are denoted as FP, Emerg + 3 wks, and PHS + 2 wks, respectively.

In CC, cotton lint yields were not different between the N fertilization strategies in 2019 (Fig. 3.3). There was a significant increase in cotton lint yield in CCRC in the PRE compared to the other N fertilization strategies. There was a 21% increase in lint yield in the PRE system compared to the FP. The 2019 growing season received greater precipitation compared to 2018 and 2020 which likely increased the overall yield potential ($P = 0.01$). In 2020, there was no significant difference between any of the N fertilization treatments in both the CC and CCRC cropping systems. Despite the lack of differences, there was a 6, 13, and 7% increase in cotton lint yield in the CCRC system using the PRE, POS, and PIN N fertilization systems, respectively.

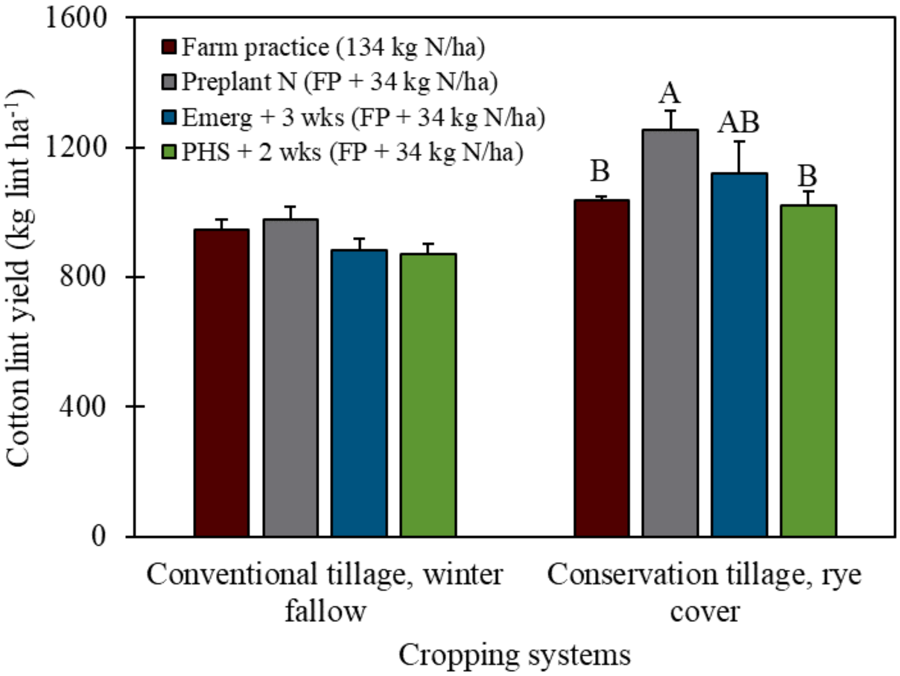

Figure 3.3 Cotton lint yield from harvest 2019 following different N application timings. Mean concentrations followed by the same letter within cropping system are not different at $P<0.05$ by Fisher's protected LSD. The vertical bars represent the standard error of the mean. Farmers Practices (134 kg N/ha), Additional 34 kg N/ha applied three weeks after emergence, and additional 34 kg N/ha applied at pinhead square plus 2 weeks are denoted as FP, Emerg + 3 wks, and PHS + 2 wks, respectively.

Overall, cotton lint yield in the CCRC system was 33, 30, and 18% greater with PRE, POS, and PIN N fertilization strategies, respectively, compared to the FP for the CC system and 20, 19, and 6% greater with PRE, POS, and PIN N fertilization strategies, respectively, compared to the FP for the CCRC system. This data challenges the current AgriLife Extension recommendation that supplemental N fertilization following a cover crop of 34 kg N ha^{-1} should be applied at pinhead square plus two weeks. Economic analysis of the return on investment additional N applications needs to be conducted.

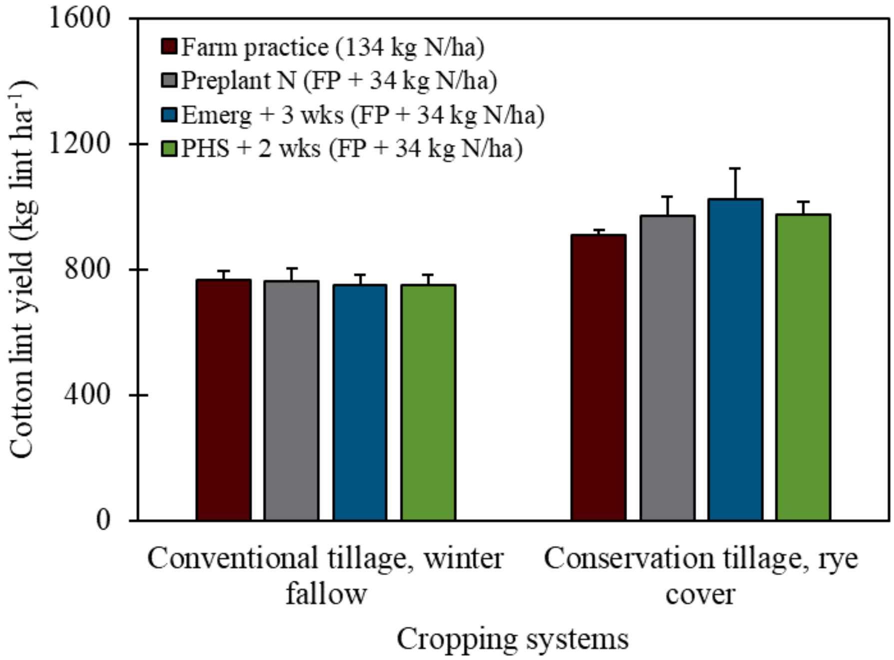

Figure 3.4 Cotton lint yield from harvest 2020 following different N application timings. There were no significant differences between treatments within cropping system. The vertical bars represent the standard error of the mean. Farmers Practices (134 kg N/ha), Additional 34 kg N/ha applied three weeks after emergence, and additional 34 kg N/ha applied at pinhead square plus 2 weeks are denoted as FP, Emerg + 3 wks, and PHS + 2 wks, respectively.

3.3.2.3. Nitrogen use efficiency

Table 3.4 2018 nitrogen use efficiency (NUE) of conventional tillage, winter fallow (CC) and conservation tillage, rye cover cropping systems at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA. Mean values with the same letter within year are not significantly different at $P < 0.05$. Additional 34 kg N ha^{-1} applied three weeks after emergence, and additional 34 kg N ha^{-1} applied at pinhead square plus 2 weeks are denoted as Emerg + 3 wks, and PHS + 2 wks, respectively.

Nitrogen Management	**Cont. Cotton (CC)**	**CC, Rye Cover**
	-----NUE, over check (kg lint kg N $^{-1}$)----	
Farm practice (135 kg N ha^{-1})	---	---
Preplant (+34 kg N ha^{-1})	5.52 a	4.85
Emerg + 3 wks (+34 kg N ha^{-1})	1.50 b	9.62
PHS + 2 wks (+34 kg N ha^{-1})	-1.17 c	3.40
P-value	0.001	0.076

In 2018, NUE was not increased with additional N in the CCRC system relative to the FP (Table 3.4). However, in the CC system, there was a significant increase in NUE in the PRE N fertilization system compared to POS and PIN systems. In 2019, there was no difference in NUE for the CC system (Table 3.5). Both the POS and PIN N fertilization systems resulted in decreases in NUE compared to the FP. For the CCRC system, NUE was significantly greater in the PRE N fertilization system compared to PIN which POS was significantly different from either the PRE or PIN systems. In 2020, there was no difference in NUE for either the CC or CCRC cropping systems relative to the check (Table 3.6). However, NUE was greater with the CCRC system compared to the CC system.

Table 3.5 2019 nitrogen use efficiency (NUE) of conventional tillage, winter fallow (CC) and conservation tillage, rye cover cropping systems at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA. Mean values with the same letter within year are not significantly different at $P < 0.05$. Additional 34 kg N ha^{-1} applied three weeks after emergence, and additional 34 kg N ha^{-1} applied at pinhead square plus 2 weeks are denoted as Emerg + 3 wks, and PHS + 2 wks, respectively.

Nitrogen Management	**Cont. Cotton (CC)**	**CC, Rye Cover**
	-----NUE, over check (kg lint kg N $^{-1}$)----	
Farm practice (135 kg N ha^{-1})	---	---
Preplant (+34 kg N ha^{-1})	0.89	6.47 a
Emerg + 3 wks (+34 kg N ha^{-1})	-1.85	2.57 ab
PHS + 2 wks (+34 kg N ha^{-1})	-2.30	-0.38 b
P-value	0.402	0.015

Table 3.6 2020 nitrogen use efficiency (NUE) of conventional tillage, winter fallow (CC) and conservation tillage, rye cover cropping systems at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA. Mean values with the same letter within year are not significantly different at $P < 0.05$. Additional 34 kg N ha^{-1} applied three weeks after emergence, and additional 34 kg N ha^{-1} applied at pinhead square plus 2 weeks are denoted as Emerg + 3 wks, and PHS + 2 wks, respectively.

Nitrogen Management	**Cont. Cotton (CC)**	**CC, Rye Cover**
	-----NUE, over check (kg lint kg N $^{-1}$)----	
Farm practice (135 kg N ha^{-1})	---	---
Preplant (+34 kg N ha^{-1})	-0.13	1.78
Emerg + 3 wks (+34 kg N ha^{-1})	0.03	3.44
PHS + 2 wks (+34 kg N ha^{-1})	-0.51	1.93
P-value	0.927	0.662

3.4. Conclusions

Conservation management practices reduce the susceptibility of soil to wind erosion, but farmers have concerns regarding their potential to reduce yields following the adoption of conservation practices on. However, variable herbage mass decomposition rates following cover crop termination complicate our understanding of these systems and potentially increase producers' hesitancy to adopt conservation management practices. These studies highlight the importance of supplemental N fertilization following cover crop termination and prior to planting cotton as a way to not only decrease yield loss potential but to yield greater lint than from traditional fertilizer applications. Texas cotton producers should consider implementing an additional application of N earlier in the growing season compared to existing Extension recommendations following a cover crop. Additional research is needed to better understand if these yield benefits can be replicated in dryland cropping systems.

3.5. References

Acharya, R.N.; Ghimire, R.; Apar, G.C.; Blayney, D. Effect of cover crop on farm profitability and risk in the Southern High Plains. *Sustainability*, **2019**, *11*, 7119.

Boquet, D.J.; Hutchinson, R.L.; Breitenbeck, G.A. Long-term tillage, cover crop, and nitrogen rate effects on cotton: Yield and fiber properties. *Agron. J.*, **2004**, *96*, 1436-1442.

Bronson, K.F.; Onken, A.B.; Keeling, J.W.; Booker, J.D.; Torbert, H.A. Nitrogen response in cotton as affected by tillage system and irrigation level. *Soil Sci. Soc. Am. J.*, **2001**, *65*, 1153-1163.

Burke, J.A.; Lewis, K.L.; Ritchie, G.L.; Moore-Kucera, J.; DeLaune, P.B.; Keeling, J.W. Temporal variability of soil carbon and nitrogen in cotton production on the Texas High Plains. *Agron. J.*, **2019**, *111*, 2218-2225.

Burke, J.A.; Lewis, K.L.; Ritchie, G.L.; DeLaune, P.B.; Keeling, J.W.; Acosta-Martinez, V.; Moore, J.M.; McLendon, T. Net positive soil water content following cover crops with no tillage in irrigated semi-arid cotton production. *Soil Till. Res.*, **2021**, *208*, 104869.

Burke, J.A.; Lewis, K.L.; DeLaune, P.B.; Cobos, C.J.; Keeling, J.W. Soil water dynamics and cotton production following cover crop use in a semi-arid ecoregion. *Agronomy*, **2022**, *12*, 1306.

Dubeux Jr., J.C.B.; Sollenberger, L.E.; Interrante, S.M.; Vendramini, J.M.B.; Stewart Jr., R.L. Litter decomposition and mineralization in bahiagrass pastures managed at different intensities. *Crop Sci.*, **2006**, *46*, 1305-1310.

Gabriel, J.L.; Almendros, P.; Hontoria, C.; Quemada, M. The role of cover crops in irrigated systems: Soil salinity and salt leaching. *Agric. Ecosyst. Environ.*, **2012**, *158*, 200-207.

Jorquera, M.A.; Hernandez, M.T.; Rengel, Z.; Marschner, P.; de la Luz, Mora, M. Isolation of culturable phosphobacteria with both phytate-mineralization and phosphate-stabilization activity from the rhizosphere of plants grown in a volcanic soil. *Biol. Fert. Soil*, **2008**, *44*, 1025.

Keeling, J.W.; Wheeler, T.; Lewis, K.L.; Dever, J.; Maeda, M.; Parajulee, M.; Monclova-Santana, C. 2021 AG-CARES Annual Report. Texas A&M AgriLife Research and Extension Technical Report 22-1. 2021, Available at https://lubbock.tamu.edu/files/2022/02/2021-AG-CARES-Report_final.pdf. Accessed 12 February 2022.

Lewis, K.L.; Burke, J.A.; Keeling, W.S.; McCallister, D.M.; DeLaune, P.B.; Keeling, J.W. Soil benefits and yield limitations of cover crop use in Texas High Plains cotton. *Agron. J.*, **2018**, *110*, 1616-1623.

Lindsay, W.L.; Norvell, W. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci. Soc. Am. J.*, **1978**, *42*, 421-428.

McGeehan, S.L.; Naylor, D.V. Automated instrumental analysis of carbon and nitrogen in plant and soil samples. *Commun. Soil Sci. Plant Anal.*, **1988**, *19*, 493-505.

Mehlich, A. Mehlich-III soil test extractant: A modification of Mehlich-II extractant. *Commun. Soil Sci. Plant Anal.*, **1984**, *15*, 1409-1416.

Mulumba, L.N.; Lal, R. Mulching effects on selected soil physical properties. *Soil Till. Res.*, **2008**, *98*, 106-111.

National Weather Service. June 26, 2021, damaging wind event. **2021**, Available at https://www.weather.gov/media/maf/events/2021/Severe_Wind.pdf. Accessed 18 October 2021.

Nevins, C.J.; Lacey, C.; Armstrong, S. The synchrony of cover crop decomposition, enzyme activity, and nitrogen availability in a corn agroecosystem in the Midwest United States. *Soil Till. Res.*, **2020**, *197*, 104518.

Nyakatawa, E.Z.; Reddy, K.C. Tillage, cover cropping, and poultry litter effects on cotton: I. Germination and seedling growth. *Agron. J.*, **2000**, *92*, 992-999.

Pabuayon, I.L.B.; Lewis, K.L.; Ritchie, G.L. Dry matter and nutrient partitioning changes for the past 30 years of cotton production. *Agron. J.*, **2020**, *112*, 4373-4385.

Rhoades, J.D. Soluble salts. In *Methods of soil analysis. Part 2.* 2nd ed.; Page, A.L.; Miller, R.H.; Keeney, D.R., Ed.; ASA and SSSA Madison, WI, USA, **1982**; pp. 167-178.

Schofield, R.K.; Taylor, A.W. The measurement of soil pH. *Soil Sci. Soc. Am. Pro.* **1955**, *19*, 164-167.

Schulte, E.E.; Hopkins, B.G. Estimation of soil organic matter by weight Loss-On-Ignition. In *Soil Organic matter: Analysis and Interpretation.* Magdoff, FR; Tabatabai; M.A.; Hanlon, Jr.; H.A., Ed.; Special publication No. 46. *Soil Sci. Soc. Amer.* Madison, WI, USA, **1996**; pp.21-32.

Stewart, C.E.; Halvorson, A.D.; Delgado, J.A. Long-term N fertilization and conservation tillage practices conserve surface but not profile SOC stocks under semi-arid irrigated corn. *Soil Till. Res.*, **2017**, *171*, 9-18.

Storer, D.A. A simple high volume ashing procedure for determining soil organic matter. *Commun. Soil Sci. Plant Anal.*, **1984**, *15*, 759-772.

Talbot, J.M.; Treseder, K.K. Interactions among lignin, cellulose, and nitrogen drive litter chemistry—decay relationships. *Ecology*, **2012**, *93*, 345-354.

Ward, D.; Kirkman, K.; Hagenah, N.; Tsvuura, Z. Soil respiration declines with increasing nitrogen fertilization and is not related to productivity in long-term grassland experiments. *Soil Biol. Biochem.*, **2017**, *115*, 415-422.

White, C.D.R.; Burke, J.A.; Lewis, K.L.; Acosta-Martinez, V.; Keeling, J.W.; DeLaune, P.B. Impact of agronomic practices on soil biological properties on the Texas High Plains. Proceedings of the Annual Agronomy Society of America, Crop Science Society of America, and Soil Science Society of America Meeting, **2016**, Phoenix, AZ, USA.

Zobeck, T.M.; Van Pelt, R.S. Wind erosion. In *Soil Management: Building a Stable Base for Agriculture*; Hartfield, J.L., Sauer, T.J., Eds.; SSSA: Madison, WI, USA, **2012**; pp. 209–227.

4. IMPACT OF CONSERVATION AGRICULTURE ON BIOLOGICAL INDICATORS OF SOIL HEALTH

Abstract

Understanding of soil health has substantially increased since the 1990s, however, soil health in semi-arid cropping systems is poorly understood, especially biological indicators of soil health. The goal of the research described in this chapter is to quantify biological indicators of soil health in a long-term cotton cropping system relative to native rangeland. Soil samples were collected at 0-5, 5-10, 10-35, 35-75, and 75-100 cm depth intervals from 28 May to 2 June 2018 from three continuous cotton cropping systems at the Agricultural Complex for Advanced Research and Extension Systems, Lamesa, TX, USA, and a native rangeland (NAT) located near Wellman, TX, USA. The three cropping systems were: 1) conventional tillage and winter fallow, CT; 2) no-tillage and rye cover, R-NT; and 3) no-tillage and mixed species cover, M-NT). Samples were analyzed for soil organic C (SOC), potassium permanganate oxidizable C (POxC), autoclaved citrate extractable proteins (ACE), potential enzyme activities (β-glucosidase, BG; β-glucosaminidase, NAG; acid and alkaline phosphatase, AcidP, AlkP; and arylsulfatase, Sulf), and microbial community structure utilizing phospholipid fatty acids. Results indicate that SOC, POxC, and ACE were significantly greater in R-NT and M-NT compared to NAT and CT at 0-5 and 5-10 cm depth. From 10 to 100 cm, SOC, POxC, and ACE were generally greater in NAT compared to the other systems. Soil microbial community biomass and diversity were greatest in the NAT while potential enzyme activities were greatest in the R-NT and M-NT systems. Carbon, N, and P cycling enzymes were most strongly positively correlated with gram-negative bacteria, arbuscular mycorrhizal fungi, and fungi while gram-positive bacteria and actinomycetes were most negatively correlated with those same enzymes. These results highlight that

intensively managed conservation cropping systems can improve soil health by stimulating microbial activity due to their nutrient cycling potential especially in semi-arid cropping systems.

4.1. Introduction

While traditional soil conservation efforts began on the Texas High Plains following the Dust Bowl to reduce wind erosion, producers are hesitant to adopt the modern soil health movement. Soil health has been described as the continued capacity of soil to perform a function that sustains humans. To achieve this goal, the Natural Resources Conservation Service (NRCS) has outlined four methods for promoting soil health: 1) manage more by disturbing less, 2) diversify with crop diversity, 3) keep living roots throughout the year, and 4) keep the soil covered as much as possible (NRCS, 2012). In traditional row crop agricultural production, the primary function of soil is to produce a crop. However, extreme weather events and the looming threat of climate change have prompted a shift in thinking to utilize historical conservation efforts in combination with the principles of soil health. When coupled with the principles of soil health, there are several management practices to support this goal, including reduced tillage and cover crops during traditional fallow periods. Despite significant investment from the NRCS, private conservation organizations, and Texas A&M AgriLife Research and Extension, the adoption of these practices remains low compared to other cotton-growing regions of the USA (Claassen et al., 2018). The adoption of these practices might be impeded by farmers' concerns regarding how these practices can potentially reduce their crop yield.

Two commonly referenced concerns with the adoption of cover crops is the utilization of limited precipitation by the cover crop over the subsequent cotton crop and the potential immobilization of N following termination of the cover crop. One potential mechanism to increase widespread adoption of conservation efforts is to highlight the secondary ecosystem service benefits of those practices. Of all the proposed soil health metrics, biological indicators of soil health have received considerable interest for their potential ability to rapidly measure and therefore identify increases in cropping system sustainability (Sanaullah et al., 2020; Lazicki et al., 2021; Nunes et al., 2021). A majority of soil health research has focused on carbon (C) management as it is a driver of soil biology and nutrient cycling (Follet at el., 1987; Nelson and Sommers, 1996). Subsequently, several soil health metrics have been proposed to relate their function to agricultural productivity (Haney et al., 2006; Nakajima et al., 2015; Moebius-Clune et al., 2016). However, these metrics need to be evaluated in semi-arid ecoregions such as the Texas High Plains, where biological C pools are relatively small (Blair et al., 2001; Bronson et al., 2004). The potential to increase soil C, and potentially biological indicators of soil health, is large in semi-arid cropping systems with low soil organic matter highlighting the potential for cropping systems to sequester large amounts of atmospheric carbon dioxide if the systems can be optimized (Lewis et al., 2018; Burke et al., 2019).

The purpose of this study was to perform the first, comprehensive assessment of soil health in semi-arid cotton cropping systems of west Texas and to understand the relationship between biological indicators of soil health. These results will complement the existing research evaluating nutrient cycling (Lewis et al., 2018; Burke et al., 2019), water dynamics (Burke et al., 2021, 2022), physical properties (DeLaune et al., 2019), and cotton production (Lewis et al., 2018; Burke et al., 2022).

4.2. Materials and Methods

4.2.1. Site description and experimental design

Two research sites were used for this study. The first was a native rangeland under blue grama (*Boutelous gracilis*), sideoats grama (*Bouteloua curtipendula*), buffalograss (*Bouteloua dactyloides*), little bluestem (*Schizachyrium scoparium*), prairieclover (*Dalea purpurea*), bundleflower (*Desmanthus leptolobus*), and mesquite (*Prosopis glandulosa*) (NAT) located near Wellman, TX (33^o 3' 37", -102^o 24' 24"), has not been plowed for at least 80 years although the site was likely never plowed because the land was not owned prior to those records (K. Attebury, personal communication, 31 May 2018). The second is a continuous cotton cropping system located at the Agricultural Complex for Advanced Research and Extension Systems (AG-CARES) near Lamesa, TX (32^o 46' 22", -101^o 56' 18"), contained three treatments with a randomized complete block design with three replications that included: 1) continuous cotton with fallow during winter (CT); 2) no-tillage with rye cover (R-NT); and 3) no-tillage with mixed species cover (M-NT). The mixed species cover included hairy vetch (*Vicia villosa* Roth), Austrian winter field pea (*Pisum sativum* L.), rye (*Secale cereal*), and radish (*Raphanus sativus* L.). Both cover crop treatments were planted using a grain drill at 45 kg ha^{-1} with the mixture comprised of 50% rye, 33% winter field pea, 10% hairy vetch, and 7% radish by weight. Cotton was planted annually as the cash crop. For additional information regarding the cropping system management practices refer to Lewis et al. (2018) and Burke et al. (2019).

4.2.2. Sampling protocol and soil analysis

Soil samples were collected to a 100-cm depth using a hydraulic soil probe (Giddings Machine Company, Windsor, CO, USA) on 31 May 2018 and 1 June 2018 for the NAT and AG-

CARES locations, respectively. Soil cores were subdivided into 0-5, 5-10, 10-35, 35-75, and 75-100 cm depths. The 0-5 and 5-10 cm depths were chosen to help characterize the microbial community structure and function while the 10-35, 35-75, and 75-100 cm depths were chosen because they correspond to the major soil horizons. The soil at both sites was classified as an Amarillo series, a benchmark soil of the Southern High Plains of Texas and is described as a fine sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs) with a pH of 7.5 (USDA-NRCS, 2016).

Soil organic carbon (SOC) was determined using instrumental combustion at the Texas A&M AgriLife Extension Soil Water and Forage Testing Lab in College Station, TX, USA (McGeehan and Naylor, 1988; Nelson and Sommers, 1996). Potassium permanganate oxidizable C (POxC) was determined by reaction with dilute permanganate according to Weil et al. (2003). Briefly, 2.5 g of air-dried soil was reacted with dilute potassium permanganate ($KMnO^4$) while shaking for 120 s on a reciprocating shaker (120 strokes min^{-1}). After shaking, the soil slurry was allowed to settle for 10 min in darkness and then 0.2 mL of the supernatant was transferred to a 50 mL centrifuge tube containing 20 mL of DI H_2O. The diluted supernatant was read on a spectrophotometer at 550 nm and POxC was calculated as:

$$\text{POxC (mg kg}^{-1}\text{)} = [0.02\text{ mol L}^{-1} - (a + bz)] \times$$
$$(9000\text{ mg C mol}^{-1}) \times (0.02\text{ L solution Wt}^{-1})$$

where 0.02 mol L^{-1} is the initial concentration of the $KMnO_4$ solution, a is the intercept of the standard curve, b is the slope of the standard curve, z is the absorbance of the unknown soil sample, 9000 mg is the amount of C oxidized by 1 mol of MnO_4 with Mn^{7+} reduced to Mn^{4+}, 0.02 L is the volume of the $KMnO_4$ solution reacted with soil, and Wt is the amount of soil in kilograms used in the reaction.

Four, colorimetric enzyme assays were conducted during this study: 1) β-glucosidase (EC 3.2.1.21, BG), which is responsible for hydrolyzing complex sugars (Eivazi and Tabatabai, 1988); 2) β-glucosaminidase (EC 3.2.1.30, NAG), which is responsible for the degradation of chitin (Parham and Deng, 2000); 3) acid (EC 3.1.3.2, AcidP) and alkaline phosphatase (EC 3.1.3.1, AlkP), which are responsible for the hydrolysis of phosphomonoesters into orthophosphates (Tabatabai and Bremner, 1969); and 4) arylsulfatase (EC 3.1.6.1, Sulf), which is responsible for the hydrolysis of ester-bonded S (Tabatabai and Bremner, 1970). The enzyme activities were determined using 0.5 g of air-dried soil with their appropriate substrate and incubated for 1 h at 37°C at their optimal pH as described by Tabatabai (1994) and Parham and Deng (2000). The enzyme activities were determined in triplicate using air-dried soil ground to pass a 2-mm sieve with one control where the substrate was added after the incubation and subtracted from the average sample value.

Microbially available organic N was determined through the autoclaved citrate extractable (ACE) protein method originally proposed by Wright and Upadhyaya (1998) with modifications by Hurisso et al. (2018). Briefly, 3 g of air-dried soil was weighed into 40-mL glass vials, and 24 mL of 20 mM sodium citrate solution (pH 7.0) was added. The vials containing the soil-sodium citrate solution were shaken on a reciprocating shaker (120 strokes min^{-1}) for 5 min and then autoclaved for 30 min at 121°C (103 kPa). The samples were then vortexed to resuspend the soil particles. A 2-mL aliquot was transferred to a microcentrifuge tube and centrifuged at 10,000 × g for 3 min. The supernatant (1 mL) was transferred to a new microcentrifuge tube for further processing that same day. In a 96-well chimney-bottom culture plate, 10 µL of the supernatant was added to each well along with 200 µL of Pierce BCA protein reagent (Sigma-Aldrich, Inc. St. Louis, MO, USA). The plate was sealed and incubated at 61.5°C on a heat block for 1 hr. After 1 hr, the seal was removed and the absorbances were measured at 562 nm on a spectrophotometer. A standard curve was prepared using bovine serum albumin for each plate.

Soil microbial community structure was determined with total phospholipid fatty acids (PLFAs) profiles by the Soil Health Assessment Center at the University of Missouri. An aliquot of fresh soil samples were packaged and store on ice after sample collection in the field. Within 24-h the samples were flash frozen with liquid N and lyophilized before shipment to the University of Missouri (Labconco, Kansas City, MO, USA)The PLFAs were calculated as microbial abundance using the sum of biomarkers from C14:0 to C20:0 with methanolysis of phospholipids analyzed by gas chromatography (Buyer and Sasser, 2012). The high-throughput nature of the extraction and analysis reduces the resolution of the peaks and certain isomers cannot be identified. The microbial communities identified through this analysis included: gram-negative bacteria (G^-), gram-positive bacteria (G^+), anaerobic bacteria, actinomycetes, fungi, arbuscular mycorrhizal fungi (AMF), and eukaryotes. Microbial communities were categorized using Sherlock Software version 6.0 (MIDI Corp, Newark, NJ, USA). While PLFA analysis was conducted on all depths, relative abundance was only determined on the 0-5 and 5-10 cm depths for the purposes of this evaluation.

4.2.3. Statistical design and calculations

Analysis of variance for all parameters was calculated using a randomized complete block design with three replications (PROC GLIMMIX, SAS 9.4, SAS Institute, Inc., Raleigh, NC, USA). Means of treatment effects were compared among treatments using Fisher’s least significant difference (LSD) at $\alpha = 0.05$ for all analyses. Spearman correlation coefficients were utilized to determine the relationship between all treatments at $P < 0.05$ using PROC CORR in SAS. Principal component analysis (PCA) was conducted using SigmaPlot 14.5 (Systat Software, Palo Alto, CA, USA).

4.3. Results and Discussion

4.3.1. Soil carbon and nitrogen fractions

There was a significant depth and system effect on SOC, PoxC, and ACE proteins (Figures 4.1, 4.2, 4.3). Soil organic C was significantly greater in the R-NT and M-NT systems compared to NAT and CT at the 0-5 and 5-10 cm depth (Fig. 4.1). Conversely, at 10-35 cm, SOC was significantly greatest in the NAT and CT systems compared to R-NT and M-NT. There was no significant difference between treatments in SOC at the 35-75 cm depth. At 75-100 cm, NAT was significantly greater than the CT, R-NT, and M-NT systems. In the CT system, SOC was relatively unchanged throughout the soil profile compared to the other treatments. There was no difference between the R-NT and M-NT systems at any depth. Through a 1 m depth, NAT has the greatest SOC storage compared to R-NT, M-NT, and CT.

Soil organic C stocks (0-100 cm depth) were greatest in the NAT, followed by R-NT, M-NT, and finally CT. Relative to the CT system which served as the control in this evaluation, NAT increased SOC stocks by approximately 13 Mg ha^{-1} compared to 5 and 6 Mg ha^{-1} for the M-NT and R-NT systems, respectively (Fig. 4.1 B). These results indicate a potential average C sequestration rate of approximately 0.25 to 0.30 Mg SOC ha^{-1} yr^{-1} with the conversion of CT to R-NT or M-NT over a 20 yr period.

Others have previously observed the benefits of conservation management practices, such as no-tillage and cover crops, to increase C sequestration (Fultz et al., 2013; Bowels et al., 2014;

Lewis et al., 2018; Burke et al., 2019; Sanjui et al., 2021); however, this process is not well understood in semi-arid climates where plant net primary productivity is reduced, and decomposition rates can be greater than more temperate regions (Liski et al., 2003). In a previous study conducted north of Lamesa in Lubbock, TX, McDonald et al. (2019) found that four years after the adoption of conservation management practices there was no significant difference in SOC between CT and a R-NT system. Li et al. (2017) demonstrated that following the conversion from cotton production to reseeded native rangeland it would take approximately 11 yr to significantly increase SOC. Additional research is needed to understand the timeline of SOC accumulation in our soils so producers can make the most impactful decision regarding their farms.

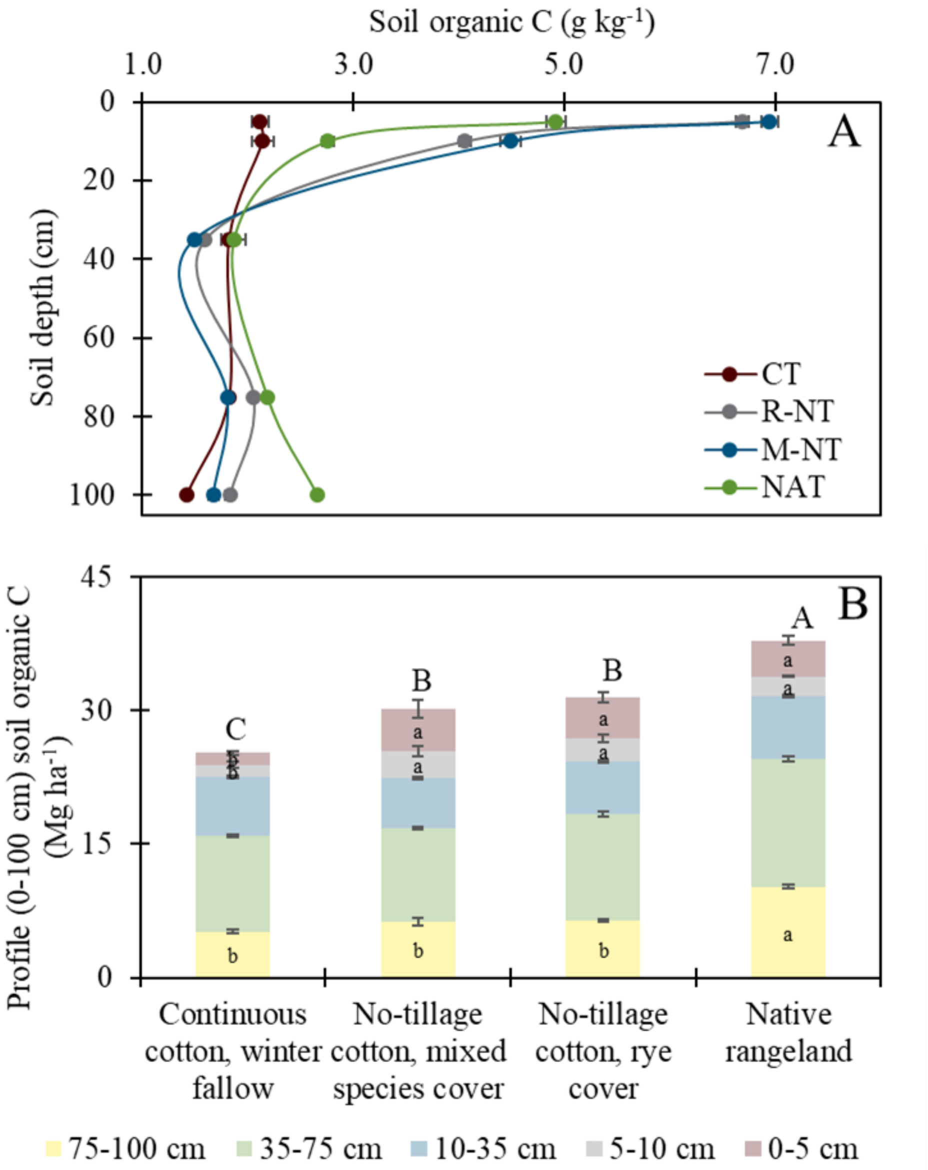

Figure 4.1 Soil organic carbon (SOC) concentrations (A) and profile SOC (B) at depth under different agricultural management practices. Error bars represent standard error of the sample mean. Asterisks represent significant differences between treatments within depth (*P* < 0.05). Conventional tillage, no-tillage rye cover, no-tillage mixed species cover, and native rangeland are denoted as CT, R-NT, M-NT, and NAT, respectively.

Potassium permanganate oxidizable C followed a similar trend as SOC (Fig. 4.2) and was significantly correlated (R^2=0.65, $P < 0.0001$). The R-NT and M-NT systems led to significant increases in POxC at the 0-5 and 5-10 cm depth compared to the NAT and CT systems. This trend reversed at the 10-35 cm depth with the NAT system having significantly greater POxC concentrations compared to the M-NT system. Since POxC represents a fraction of SOC that is considered to be the most mineralizable fraction for microbes (Weil et al., 2003), it is likely that increase in POxC observed in the R-NT and M-NT systems is caused by increased rhizodeposition and C inputs from the cover crops (Burke et al., 2019). These increases in fresh C inputs stimulate microbial activity which can help to cycle nutrients (Wagger et al., 1998) and improve soil physical characteristics (Fultz et al., 2013). Culman et al. (2012) have also shown that POxC is most sensitive to management changes compared to other C fractions which can make it a useful metric to track changes in soil organic matter.

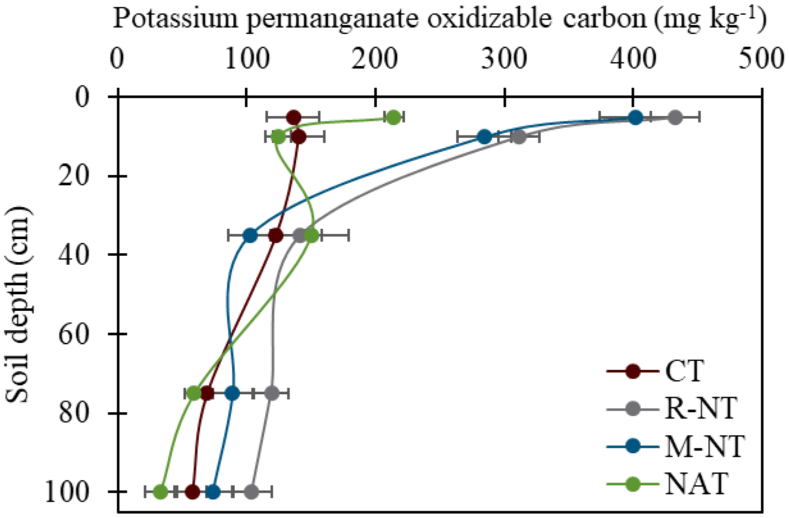

Figure 4.2 At depth potassium permanganate oxidizable carbon concentrations under different agricultural management practices. Error bars represent standard error of the sample mean. Asterisks represent significant differences between treatments within depth (*P* < 0.05). Conventional tillage, no-tillage rye cover, no-tillage mixed species cover, and native rangeland are denoted as CT, R-NT, M-NT, and NAT, respectively.

Soil proteins ranged from 96 to 453 mg kg^{-1} and were generally less than other semi-arid soils (Geisseler et al., 2019). Similar to both SOC and POxC, ACE proteins were significantly greatest in the R-NT and M-NT systems compared to CT and NAT at the 0-5 cm depth (P = 0.026). At the 5-10 cm depth, R-NT and M-NT were greater than CT but were not different from the NAT system ($P < 0.001$). There were no differences in ACE proteins between systems at the 10-35, 35-75, or 75-100 cm depths. In the CT system, ACE proteins did not change throughout the soil profile regardless of depth. Soil proteins have been linked to several soil health improvements including soil aggregation (Wright and Upadhyaya, 1996; Wright et al., 1999; Rillig et al., 2002; Fine et al., 2017), crop productivity (Wright et al., 1999) and land-use change (Halvorson and Gonzalez, 2006).

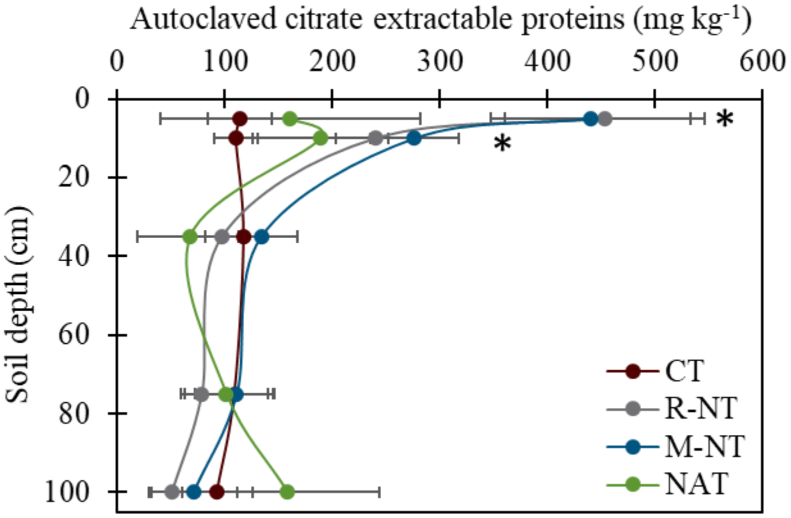

Figure 4.3 Autoclaved citrate extractable proteins at depth under different agricultural management practices. Error bars represent standard error of the sample mean. Asterisks represent significant differences between treatments within depth ($P < 0.05$). Conventional tillage, no-tillage rye cover, no-tillage mixed species cover, and native rangeland are denoted as CT, R-NT, M-NT, and NAT, respectively.

Our results demonstrate the potential impact of conservation management practices to increase SOC relative to CT and low input NAT systems near the soil surface. While these increases in the top 10 cm of the soil profile are substantial, these increases are not sustained deeper in the soil profile. The lack of increases in SOC at depth with the R-NT and M-NT systems relative to the CT and NAT systems is likely the result of limited cover crop root exploration in these semi-arid soils where winter precipitation is limited (Nevins et al., 2020; Burke et al., 2021; 2022).

4.3.2. Soil microbial community structure and function

Significant differences in the relative abundance of soil microbial community structure were observed in the G^+, AMF, and anaerobes with significant increases in these communities with NAT compared to CT, R-NT, and M-NT (Fig. 4.4). There were no significant differences in relative abundance between any of the cotton cropping systems. Gram-negative, G^+, and Actinomycetes represented the greatest relative abundance within each treatment, respectively. These results are similar to other studies (Murphy et al., 2011; Patkowska et al., 2016). Significant increases in anaerobes, AMF, and G^- bacteria are likely linked to differences in the plant communities between NAT and the cotton cropping systems which selects for more diverse microbial communities (Bu et al., 2020). The addition of no-tillage and cover crops in semi-arid cotton production has been shown to increase microbial biomass at a greater rate than rotation with an alternate crop like sorghum (*Sorghum bicolor* L.) alone (Acosta-Martinez et al., 2011). Microbial communities in sandy soils like the Amarillo series also recover more slowly from disturbances associated with drought and heat compared to loamy soils (Acosta-Martinez et al., 2014a). Since 2018 was a milder drought compared to the 2011 drought and in the early stages when soil samples were collected, it is possible that additional sampling in Fall 2018 or subsequent years might have resulted in similar differences as noted by Acosta-Martinez et al. (2014a). Currently (11 June 2022), west Texas is experiencing the 12th driest year in the past 128 years (National Weather Service, 2022). Samples should be collected now and annually for several years to track changes in soil microbial community composition and function following this drought event. Collecting this information from the long-term research plots at AG-CARES could yield valuable results helping us to understand how cropping systems react to drought and identify opportunities to make our cropping systems more resilient to drought and heat waves in the future.

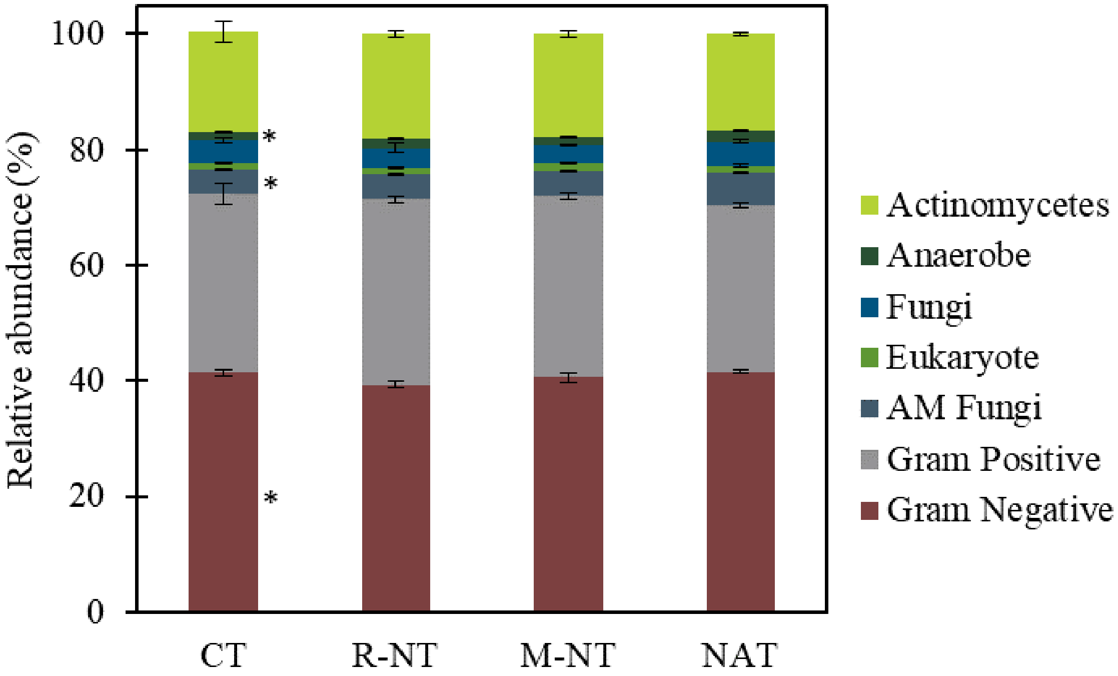

Figure 4.4 Functional composition of the soil microbial community in the 0-10 cm depth by management practice. Error bars represent standard error of the sample mean. The asterisks indicate significant differences at $P < 0.05$ between management practices. Conventional tillage, no-tillage rye cover, no-tillage mixed species cover, and native rangeland are denoted as CT, R-NT, M-NT, and NAT, respectively.

Potential soil enzyme activities were significantly greater in the R-NT, M-NT, and NAT systems compared to CT for BG, NAG, and AlkP (Fig. 4.5-4.7). There were no significant differences between treatments at depth for potential AcidP and Sulf enzyme activity (data not shown). Potential BG activity was significantly greater in R-NT compared to the other treatments (Fig. 4.5). In 2018, there was generally greater cover crop herbage mass in the rye system compared to the mixed species cover (Fig. 2.3). This likely stimulated microbial activity that increased the production of extracellular BG to break down that rye herbage mass (Sainju et al., 2015). The quantity and quality of C inputs in the soil can impact BG activity in the soil and likely explains the increase in BG activity in R-NT compared to M-NT or NAT (Patkowska et al., 2016 Sainju et al., 2021).

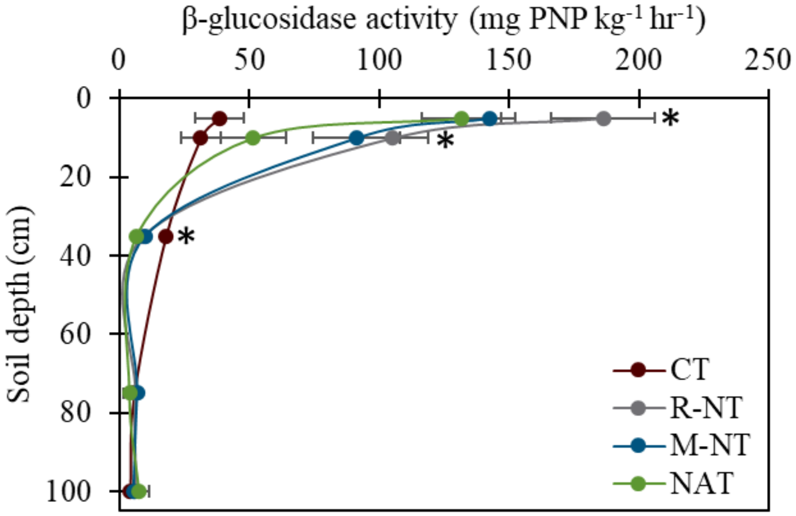

Figure 4.5 Potential β-glucosidase enzyme activity as affected by agricultural management practices at depth. Error bars represent standard error of the sample mean. Asterisks represent significant differences between treatments within depth. Conventional tillage, no-tillage rye cover, no-tillage mixed species cover, and native rangeland are denoted as CT, R-NT, M-NT, and NAT, respectively.

Potential NAG activity was significantly greatest at the 0-5 cm depth in the M-NT followed by the R-NT, NAT, and CT systems, respectively (Fig. 4.5). At the 5-10 cm depth, R-NT and M-NT were significantly greater than the NAT and CT systems, while at the 10-35 cm depth potential NAG activity was greatest in CT compared to the other systems. In semi-arid west Texas, potential NAG activity was reduced with the addition of a native seed grass mix and N-fixing alfalfa (*Medicago sativa*) compared to ‘WW-B.Dahl’ cultivar of Old World Bluestem [*Bothriochloa bladhii* (Retz) S.T. Blake] (Bhandari et al., 2018). The authors attributed the increase in potential NAG activity to overall increases in SOC, total N, and microbial biomass C and N. While there was significantly greater SOC with R-NT and M-NT compared to NAT and CT at 0-5 and 5-10 cm depths (Fig. 4.1), the cotton cropping systems had a variable effect on total N with significant increases in M-NT compared to CT in 2017 (Lewis et al., 2018) and no difference between treatments in 2020 (Table 2.2). However, other studies in the region have shown an increase in potential NAG activity with crop rotations compared to monoculture cotton production (Acosta-Martinez et al., 2011; 2014b). Additional research is needed to better understand the drivers of potential NAG activity in these semi-arid cotton production systems.

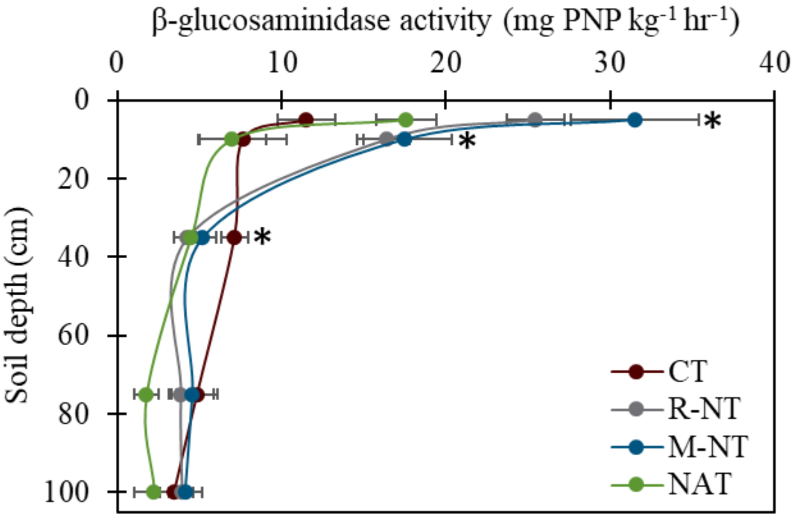

Figure 4.6 Potential β-glucosaminidase enzyme activity as affected by agricultural management practices at depth. Error bars represent standard error of the sample mean. Asterisks represent significant differences between treatments within depth. Conventional tillage, no-tillage rye cover, no-tillage mixed species cover, and native rangeland are denoted as CT, R-NT, M-NT, and NAT, respectively.

Differences in potential AlkP activity were observed in the 0-5, 5-10, 10-35, and 35-75 cm depths (Fig. 4.6). In the 0-5 cm depth, the NAT, R-NT, and M-NT systems were significantly greater than CT, while at the 5-10 cm depth NAT was significantly greater than the R-NT and M-NT systems which were greater than the CT system. However, at the 10-35 and 35-75 cm depth where NAT was significantly greater than each of the R-NT, M-NT, and CT systems. The mean monthly temperature in May 2018 was 3°C greater than the 30-yr average (Fig. 2.2) which likely resulted in shifts in the microbial community compared to average years. Acosta-Martinez et al. (2014b) showed that increased air temperature resulted in significant increases in potential enzyme activities, especially in native and crop rotations compared to traditionally grown cotton. They attributed these increases in potential enzyme activities to a stress response to the heat which could potentially impact soil health and biogeochemical cycling.

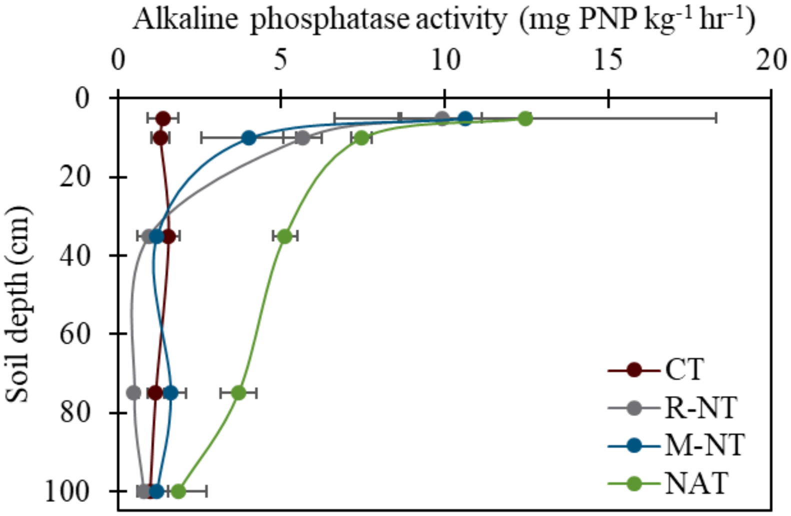

Figure 4.7 Potential alkaline phosphatase enzyme activity as affected by agricultural management practices at depth. Error bars represent standard error of the sample mean. Asterisks represent significant differences between treatments within depth. Conventional tillage, no-tillage rye cover, no-tillage mixed species cover, and native rangeland are denoted as CT, R-NT, M-NT, and NAT, respectively.

4.3.3. Relationship between biological indicators of soil health

Utilizing principal components analysis (PCA), approximately 56.7% of the variability in the data is explained with principal components (PC) one and two (Fig. 4.8). Principal component one centered around a majority of the biochemical indicators of soil health (SOC, POxC, ACE, BG, NAG, AlkP), while PC two was primarily driven by the microbial communities and the remaining biochemical indicators (Sulf and Acid-P). Other studies in the region have also shown that there is an inverse relationship between C, N, and P cycling enzymes and arylsulfatase, although those studies show a stronger positive relationship between C and N cycling enzymes and AcidP than we measured in our systems (Acosta-Martinez et al., 2014a). However, their analysis was limited to cotton cropping systems and did not include a

NAT reference, perhaps this difference can account for the antagonistic relationship between C and N cycling enzymes and AcidP because their systems showed greater significant differences in AMF and fungi than we observed between our treatments and AMF can increase P scavenging through their hyphae (Moore-Kucera and Dick, 2008).

Spearman correlation analysis was conducted to evaluate the relationships between the soil microbial community's relative abundance and the biological indicators of soil health (Table 4.1). The relative abundance for G^-, AMF, and fungi were positively correlated with all soil health indicators except Sulf. Gram+ bacteria and actinomycetes were negatively correlated with SOC, POxC, ACE, BG, NAG, and AlkP. Anaerobes were not significantly correlated with any soil health parameter. Eukaryotes were only correlated with BG and AcidP. Overall, these results are consistent with other studies that show strong relationships between microbial communities of interest and biological indicators of soil health (Acosta-Martinez et al., 2014a; Bu et al., 2020). Future microbial community compositional and functional studies in the long-term plots at AG-CARES should utilize more advanced microbial techniques (i.e., 16S DNA sequencing) to potential better understand the specific bacterial and fungal taxa correlations with biogeochemical cycling.

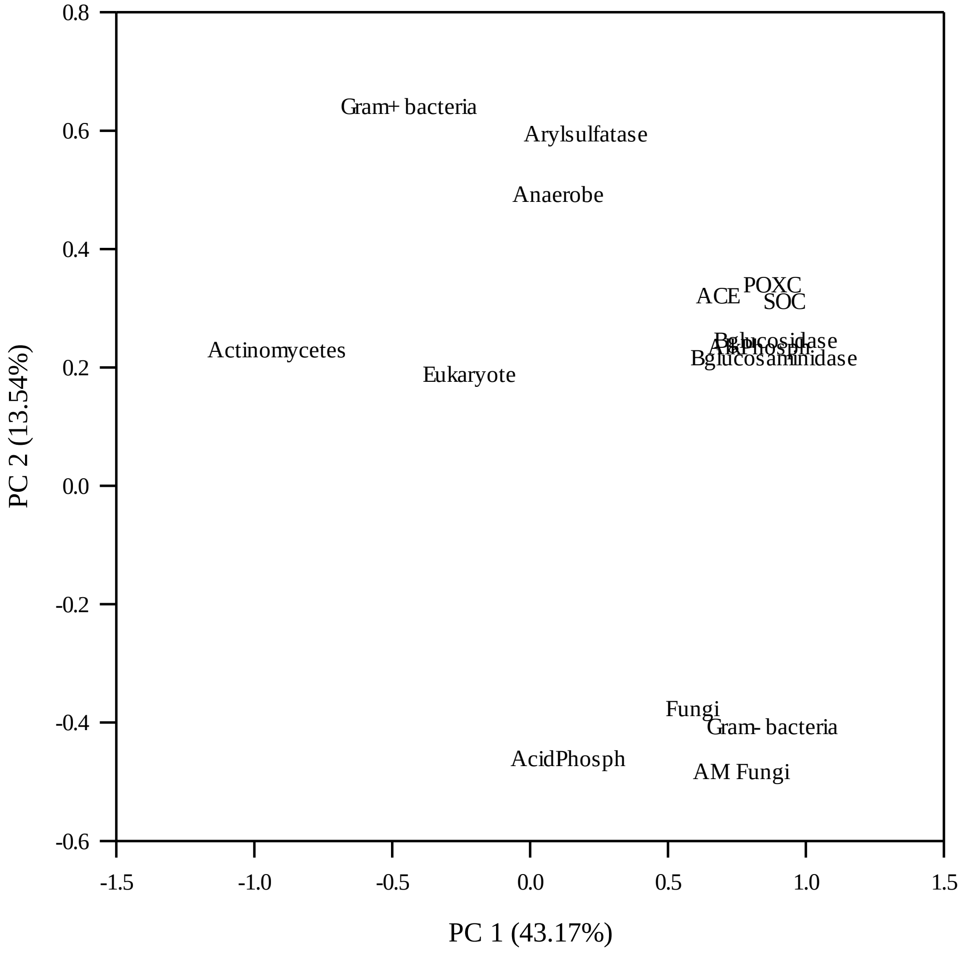

Figure 4.8 Principal component analysis of the biological indicators of soil health across agricultural management practices.

Table 4.1 Spearman correlation analysis between biological indicators of soil health and the relative abundance of the soil microbial community. Asterisks indicate significant difference at different levels (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$).

	Gram- bacteria	Gram+ bacteria	Actinomycetes	Anaerobes	AM Fungi	Fungi	Eukaryotes
Soil organic C	0.541***	-0.280**	-0.594***	0.019	0.537***	0.321**	-0.130
PoxC	0.621***	-0.383***	-0.665***	-0.038	0.527***	0.202*	-0.117
ACE proteins	0.397***	-0.248*	-0.430***	-0.070	0.413***	0.252*	-0.024
β-glucosidase	0.827***	-0.542***	0.832***	-0.132	0.760***	0.384***	-0.203*
β-glucosaminidase	0.688***	-0.422***	-0.676***	-0.100	0.619***	0.349***	-0.113
Acid phosphatase	0.184*	-0.147	-0.044	-0.096	0.147	0.039	-0.237*
Alkaline phosphatase	0.438***	-0.292*	-0.541***	0.021	0.525***	0.316**	-0.096
Arylsulfatase	0.076	-0.070	-0.169*	0.168	0.084	0.058	0.138

4.4. Conclusions

This study was one of the first detailed evaluations of soil health and the relationship between biological indicators of soil health in semi-arid cotton cropping systems. The use of conservation management practices, such as no-tillage and cover cropping, increased all biological indicators of soil health relative to traditionally grown cotton. Some biological indicators of soil health were significantly improved with the conservation practices compared to the native rangeland reference. These results highlight the importance of intensively managed cropping systems to improve the biogeochemical functioning of semi-arid ecoregions. Coupling the improvements in biological parameters of soil health with the increases in physical and chemical parameters can help to enhance agricultural productivity and minimize the potential impacts of climate change on the region. Assuming a C credit of \$68 Mg SOC^{-1} ha^{-1} yr^{-1}, cotton producers utilizing no-tillage and cover crops on sandy, semi-arid soil in our region could expect to receive approximately \$17 ha^{-1}. Only considering the potential C credit value is likely not enough incentive for cotton producers on the THP to adopt these conservation practices. Communicating the ecosystem service benefits, such as increased water storage (Burke et al., 2019, 2021), enhanced soil fertility, and reduced susceptibility to wind erosion (Fultz et al., 2013), of conservation practices can potentially increase the adoption potential of these conservation practices in semi-arid west Texas. However, the yield decline associated cover crop use is a limitation to their adoption, especially for the M-NT system which has significantly greater input costs compared to the CT system (Lewis et al., 2018). Additional work by economists and social scientists is needed locally to better understand the barriers to conservation management adoption by west Texas cotton producers. Linking these improvements in soil health to cotton lint production is essential to their continued adoption on the Texas High Plains, where adoption of conservation management practices has been limited. Continued soil health research in these long-term plots is essential to developing resilient cropping systems for the region.

4.5. References

Acosta-Martinez, V.; Lascano, R.; Calderon, F.; Booker, J.D.; Zobeck, T.M.; Upchurch, D.R. Dryland cropping systems influence the microbial biomass and enzyme activities in a semiarid sandy soil. *Biol. Fertil. Soils,* **2011**, *47*, 655-667.

Acosta-Martinez, V.; Cotton, J.; Gardner, T.; Moore-Kucera, J.; Zak, J.; Wester, D.; Cox, S. Predominant bacterial and fungal assemblages in agricultural soils during a record drought/heat wave and linages to enzyme activities of biogeochemical cycling. *Appl. Soil Ecol.*, **2014a**, *84*, 69-82.

Acosta-Martinez, V.; Moore-Kucera, J.; Cotton, J.; Gardner, T.; Wester, D. Soil enzyme activities during the 2011 Texas record drought/heat wave and implications to biogeochemical cycling and organic matter dynamics. *Appl. Soil Ecol.*, **2014b**, *75*, 43-51.

Bhandari, K.B.; West, C.P; Acosta-Martinez, V.; Cotton, J.; Cano, A. Soil health indicators as affected by diverse forage species and mixtures in semi-arid pastures. *Appl. Soil Ecol.*, **2018**, *132*, 179-186.

Blair, G.; Lefroy, R.; Whitbread, A.; Blair, N.; Conteh, A. The development of the $KMnO_4$ oxidation technique to determine labile carbon in soil and its use in a carbon management index. In *Assessment methods for soil carbon,* Lal, R.; Kimble, J.M.; Follett, R.F.; Stewart, B.A. Editors. CRC Press, Boca Raton, FL. **2001**, pp. 323-337.

Bowels, T.M.; Acosta-Martinez, V.; Calderon, F.; Jackson, L.E. Soil enzyme activities, microbial communities, and carbon and nitrogen availability in organic agroecosystems across an intensively-managed agricultural landscape. *Soil Biol. Biochem.*, **2014**, *68*, 252-262.

Bronson, K.F.; Zobeck, T.M.; Chua, T.T.; Acosta-Martinez, V.; van Pelt, R.S.; Booker, J.D. Carbon and nitrogen pools of Southern High Plains cropland and grassland soils. *Soil Sci. Soc. Am. J.,* **2004***, 68*, 1695-1704.

Bu, R.; Ren, T.; Lei, M.; Liu, B.; Li, X.; Cong, R.; Zhang, Y.; Lu, J. Tillage and straw-returning practices effect on soil dissolved organic matter, aggregate fraction and bacteria community under rice-rice-rapeseed rotation system. *Agric. Ecosyst. Environ.* , **2020**, *287*, 106681.

Burke, J.A.; Lewis, K.L.; DeLaune, P.B.; Cobos, C.J.; Keeling, J.W. Soil water dynamics and cotton production following cover crop use in a semi-arid ecoregion. *Agronomy*, **2022**, *12*, 1306.

Burke, J.A.; Lewis, K.L.; Ritchie, G.L.; Moore-Kucera, J.; DeLaune, P.B.; Keeling, J.W. Temporal variability of soil carbon and nitrogen in cotton production on the Texas High Plains. *Agron. J.*, **2019**, *111*, 2218-2225.

Buyer, J.S.; Sasser, M. High throughput phospholipid fatty acid analysis of soils. *Appl. Soil Ecol.*, **2012**, *61*, 127-130.

Claassen, R.; Bowman, M.; McFadden, J.; Smith, D.; Wallander, S. Tillage intensity and conservation cropping in the United States. United States Department of Agriculture, Economic Res. Service, **2018**, EIB-197.

Culman, S.W.; Snapp, S.S.; Freeman, M.A.; Schipanski, M.E.; Beniston, J.; Lal, R.; Drinkwater, L.E.; Franzluebbers, A.J.; Glover, J.D.; Grandy, A.S.; Lee, J.; Six, J.; Maul, J.E.; Mirsky, S.B.; Spargo, J.T.; Wander, M.W. Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. *Soil Sci. Soc. Am. J.*, **2012**, *76*, 494-504.

DeLaune, P.B.; Mubvumba, P.; Lewis, K.L.; Keeling, J.W. Rye cover crop impacts soil properties in a long-term cotton system. *Soil Sci. Soc. Am. J.*, **2019**, *83*, 1451-1458.

Eivazi, F.; Tabatabai, M.A. Glucosidases and galactosidases in soils. *Soil Biol. Biochem.*, **1988**, *20*, 601-606.

Fine, A.; Van Es, H.; Schindelbeck, R. Statistics, scoring functions, and regional analysis of a comprehensive soil health database. *Soil Sci. Soc. Am. J.*, **2017**, *81*, 589-601.

Follet, R.F. US agriculture’s relationship to soil carbon. *J. Soil Water Conserv.*, **2009**, *64*, 159A-165A.

Fultz, L.M.; Moore-Kucera, J.; Zobeck, T.M.; Acosta-Martinez, V.; Allen, V.G. Aggregate carbon pools after 13 years of integrated crop-livestock management in semi-arid soils. *Soil Sci. Soc. Am. J.*, **2013**, *77*, 1659-1666.

Geisseler, D.; Miller, K.; Leinfelder-Miles, M.; Wilson, R. Use of soil protein pools as indicators of soil nitrogen mineralization potential. *Soil Sci. Soc. Am. J.*, **2019**, *83*, 1236-1243.

Halvorson, J.J.; Gonzalez, J.M. Bradford reactive soil protein in Appalachian soils: Distribution and response to incubation, extraction reagent, and tannings. *Plant Soil*, **2006**, *286*, 339-356.

Hurisso, T.T.; Culman, S.W.; Zhao, K. Repeatability and Spatiotemporal Variability of Emerging Soil Health Indicators Relative to Routine Soil Nutrient Tests. *Soil Sci. Soc. Am. J.*, **2018**, *82*, 939-948.

Lazicki, P.; Rodrigues, J.L.M.; Geisseler, D. Sensitivity and variability of soil health indicators in a California cropping system. *Soil Sci. Soc. Am. J.*, **2021**, *85*, 1827-1842.

Lewis, K.L.; Burke, J.A.; Keeling, W.S.; McCallister, D.M.; DeLaune, P.B.; Keeling, J.W. Soil benefits and yield limitations of cover crop use in Texas High Plains cotton. *Agron. J.*, **2018**, *110*, 1616-1623.

Li, C.; Fultz, L.M.; Moore-Kucera, J.; Acosta-Martinez, V.; Horita, J.; Strauss, R.; Zak, J.; Calderon, F.; Weindorf, D. Soil carbon sequestration potential in semi-arid grasslands in the Conservation Reserve Program. *Geoderma*, **2017**, *294*, 80-90.

Liski, J.; Nissinen, A.; Erhard, M.; Taskinen, O. Climatic effects on litter decomposition from arctic tundra to tropical rainforest. *Glob. Change Biol.*, **2003**, *9*, 575-584.

McClure, A.; Steckel, L.; Raper, T.; Sykes, V., Montgomery, G.; Kelly, H.; Steward, S.; Lee, J. Cover crop quick facts. University of Tennessee Extension Publication, **2017**, W 417.

McDonald, M.D.; Lewis, K.L.; Ritchie, G.L., DeLaune, P.B.; Casey, K.D.; Slaughter, L.C. Carbon dioxide mitigation potential of conservation agriculture in a semi-arid agricultural region. *AIMS Agric. Food*, **2019**, *4*, 206-222.

McGeehan, S.; Naylor; D. Automated instrumental analysis of carbon and nitrogen in plant and soil samples. *Commun. Soil Sci. Plant Anal.*, **1988**, *19*, 493-505.

Moebius-Clune, B.N.; Moebius-Clune, D.J.; Gugino, B.K.; Idowu, O.J.; Schindelbeck, R.R.; Ristow, A.J.; van Es, H.W.; Thies, J.E.; Shayler, H.A.; McBride, M.B.; Wolfe, D.W.; Abawi, G.S. Comprehensive assessment of soil health: The Cornell framework manual, 3rd edition. Cornell University, Geneva, NY, **2016**.

Moore-Kucera, J.; Dick, R.P. PLFA profiling of microbial community structure and seasonal shifts in soils of a Douglas-fir chronosequence. *Microb. Ecol.*, **2008**, *55*, 500-511.

Murphy, D.V.; Cookson, W.R.; Brainbridge, M.; Marschner, P.; Jones, D.L.; Stockdale, D.A.; Abbot, L.K. Relationship between soil organic matter and the soil microbial biomass (size, functional diversity, and community structure) in crop and pasture systems in a semiarid environment. *Soil Res.*, **2011**, *49*, 582-594.

Nakajima, T.; Shrestha, R.K.; Lal, R. On-farm assessments of soil quality in Ohio and Michigan. *Soil Sci. Soc. Am. J.*, **2016**, *80*, 1020-1026.

National Weather Service. Drought Information Statement: Lubbock, TX Weather Forecast Office (LUB). Available from: https://www.drought.gov/drought-information-statements?wfo=LUB (Accessed 9 June 2022).

Natural Resource Conservation Service. 2012. Farming in the 21st century: A practical approach to improve soil health. Available at: https://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=stelprdb1245068&ext=pdf. (Accessed 17 February 2019).

Nelson, D.; Sommers, L. Total carbon, organic carbon, and organic matter. In: D.L. Sparks, Editor. *Methods of soil analysis, Part 3. Chemical methods*. Madison, WI: Soil Science Society of America, Inc., and American Society of Agronomy, Inc., Madison, WI. **1996**, pp. 961-1010.

Nevins, C.J.; Lacey, C.; Armstrong, S. The synchrony of cover crop decomposition, enzyme activity, and nitrogen availability in a corn agroecosystem in the Midwest United States. *Soil Till. Res.*, **2020**, *197*, 104518.

Nunes, M.R.; Veum, K.S.; Parker, P.A.; Holan, S.H.; Karlen, D.L.; Amsili, J.P.; van Es, H.M.; Wills, S.A.; Seybold, C.A.; Moorman, T.B. The soil health assessment protocol and evaluation applied to soil organic carbon. *Soil Sci. Soc. Am. J.*, **2021**, *85*, 1196-1213.

Parham, J.; Deng, S. Detection, quantification and characterization of B-glucosaminidase activity in soil. *Soil Biol. Biochem.,* **2000**, *32*, 1183-1190.

Patkowska, E.; Blazeqicz-Wozniak, M.; Konopinski, M.; Wach, D. The effect of cover crops on the fungal and bacterial communities in the soil under carrot cultivation. *Plant Soil Environ.*, **2016**, *62*, 237-242.

Rillig, M.C.; Wright, S.F.; Eviner, V. The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: Comparing effects of five plant species. *Plant Soil,* **2002**, *238*, 325-333.

Sainju, U.M.; Allen, B.L.; Caesar-TonThat, T.; Lenssen, A.W. Dryland soil carbon and nitrogen after thirty years of tillage and cropping sequence. *Agron. J.,* **2015**, *107*, 1822-1830.

Sainju, U.M.; Liptzin, D.; Dangi, S.; Ghimire, R. Soil health indicators and crop yield in response to long-term cropping sequence and nitrogen fertilization. *Appl. Soil Ecol.*, **2021**, *168*, 104182.

Sanaullah, M.; Usman, M.; Wakeel, A.; Cheema, S.A.; Ashraf, I.; Farooq, M. Terrestrial ecosystem functioning affected by agricultural management systems: A review. *Soil Till. Res.*, **2020**, *196*, 104464.

Tabatabai, M. Soil enzymes. **1994**, In *Methods of soil analysis, Part 2: Microbiological and biochemical properties*, Weaver, R., Angle, J., Bottomley, P., Editors. Soil Science Society of America, Madison, WI. pp. 775-833.

Tabatabai, M.A.; Bremner, J.M. Use of *p*-nitrophenyl phosphate for assay of soil phosphate activity. *Soil Biol. Biochem.*, **1969**, *1*, 301-307.

Tabatabai, M.A.; Bremner, J.M. Arylsulfatase activity in soils. *Soil Sci. Soc. Am. Proc*., **1970**, *34* 225-229.

Wagger, M.G.; Cabrera, M.L.; Ranells, N.N. Nitrogen and carbon cycling in relation to cover crop residue quality. *J. Soil Water Conserv.*, **1998,** *53*, 214-218.

Weil, R.R.; Islam, K.R.; Stine, M.A.; Gruver, J.B.; Samson-Liebig. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. *Am. J. Altern. Agric.*, **2003**, *18*, 3-17.

Wright, S.F.; Upadhaya, A. Extraction of abundant and unusual protein from soil and comparison with hyphal protein of arbuscular mycorrhizal fungi. *Soil Sci. Soc. Am. J.*, **1996**, *161*, 575-586.

Wright, S.F.; Starr, J.R.; Paltineanu, I.C. Changes in aggregate stability and concentration of glomalin during tillage management transition. *Soil Sci. Soc. Am. J.*, **1998**, *63*, 1825-1829.

5. CONCLUSIONS

Agricultural production on the semi-arid Texas High Plains has been marked by resilient and dogged adaptation to climatic extremes, technological innovations, and social upheaval in the relatively short history of human settlement in the region. However, the combined economic, environmental, and social challenges mounting for modern producers are stressing the resolve of the normally robust west Texans. We set out to understand how intensively managed traditionally grown continuous cotton cropping systems responded to the inclusion of no-tillage and cover crops. Our results indicate that conservation management practices improve water interception and storage capacity, reduce evapotranspiration potential, increase soil carbon fractions, and stimulate microbial nutrient cycling when implemented into continuous cotton cropping systems. Unfortunately, conservation management practices can also reduce cotton yield if cover crop herbage mass becomes excessive. Cotton yield loss following cover crops can be minimized by increasing early-season N fertilizer applications to stimulate microbes and limit N immobilization to the subsequent cotton crop, challenging a 20-year Extension recommendation. It is important to note that these benefits are possible because we possess the capacity to deficit irrigate our research site during periods of episodic drought. It is very unlikely that similar improvements in physical, chemical, and biological parameters would be possible in dryland cropping systems. The potential risk associated with adoption of conservation management practices in dryland cotton production should be carefully considered before attempting such practices. While we have shown significant improvements in ecosystem services, more research is needed to understand the economic impacts of these conservation practices on-farm. Continued collaborative efforts between researchers and agricultural producers to address these critical issues will ensure the region is viable for generations to come.

6. APPENDIX A

Table 6.1 Soil microbial community in the 0-10 cm depth by management practice. Different letters within depth represent significant differences between cropping systems at $P < 0.05$. Conventional tillage, no-tillage rye cover, no-tillage mixed species cover, and native rangeland are denoted as CT, R-NT, M-NT, and NAT, respectively.

	Microbial community						
	Gram negative	Gram postive	Actinomycetes	Anaerobes	AM fungi	Fungi	Eukaryotes
	pmol g soil^{-1}						
Cropping system	0-5 cm						
CT	6079 c	4132 b	2402 b	225 c	569 c	539 c	153 b
R-NT	11974 b	9212 b	4881 a	475 b	1223 b	1178 b	431 a
M-NT	12605 b	9028 b	4690 a	484 b	1300 b	891 bc	407 a
NAT	16589 a	9554 a	4615 a	705 a	2226 a	1992 a	523 a
	<0.001	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.003*	*0.003*
	5-10 cm						
CT	5378 b	4322 b	2279 b	199 b	560 b	519	160
R-NT	7268 ab	6245 a	3745 a	297 a	806 a	582	218
M-NT	7849 ab	6446 a	3876 a	310 a	867 a	577	280
NAT	6954 a	5845 a	3865 a	314 a	979 a	541	151
	0.010	*0.002*	*0.001*	*0.002*	*0.001*	*0.963*	*0.066*