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Soil Moisture Dynamics in Cover Cropping Systems: From Local to Global Scales

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SOIL MOISTURE DYNAMICS IN COVER CROPPING SYSTEMS: FROM LOCAL TO GLOBAL SCALES

A Thesis

by

MANISH GAUTAM

Submitted in Partial Fulfillment of the
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SOIL MOISTURE DYNAMICS IN COVER CROPPING SYSTEMS: FROM LOCAL TO GLOBAL SCALES

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July 2023

ABSTRACT

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Cover cropping systems, which have gained recognition for their ability to enhance soil health and promote sustainability are also associated with potential risks related with declining soil moisture and pose a dilemma for farmers considering the adoption of cover crops in water deficit semi-arid settings worldwide. To address this pressing issue, we conducted a participatory cover cropping trial in the Lower Rio Grande Valley (LRGV) region, encompassing four different farms and supplemented this experiment with a meta-analysis to answer our soil moisture and climate parameters and quantify the impact of cover crops on soil moisture levels. The findings revealed that cover crops absorb soil moisture during the cover cropping season, particularly in farms with clay soil. However, no significant impact on soil moisture was observed during cash cropping seasons in all the farms under study. The negative effect of cover crops on soil moisture was counterbalanced by precipitation events across all farms. Additionally, we observed that the root biomass and root distribution of cover crops play a significant role in governing soil moisture dynamics along the vertical soil moisture profile. However, further extensive examination is required to fully understand these dynamics. Our meta-analysis indicated that the impact of cover crops on soil moisture varies depending on the soil depth and the aridity of the region. In humid and sub-humid regions, cover crop-induced soil moisture losses were most pronounced in the uppermost soil layer, up to ~35 cm. In contrast, in arid and semi-arid climatic regions, the losses extended to depths of ~ 60 to 75 cm. These findings suggest that cover crop-induced soil moisture losses may be confined to specific depths, creating an opportunity for cash crops to access moisture at greater depths. Future research should focus on exploring climate-specific cover crop species suitable for different soil types and cultivation practices, particularly concerning the vertical soil moisture profile. Considering the significant influence of rainfall, it is essential for future studies to quantify the amount of rainfall required to offset the negative impact of cover crops. Additionally, the study of other physiological parameters such as evapotranspiration, ground cover, and shading effects can provide a comprehensive understanding of soil moisture dynamics under the cover cropping system at local and global scales.

DEDICATION

I could not have gotten here without the effort and support of my family. To my parents, Bhim Nath Gautam, and Laxmi Timalsina Gautam, thank you for believing in me and encouraging me always—I always carry their blessings and teachings with me through all ups and downs and promise that I shall do my best to make my both of you proud. To my brothers and sisters, Suman Gautam, Anushree Singh and Anuj Singh, who shared their life with me, making my childhood beautiful and helped me become who I am today. I would also like to remember Tara Timalsina Singh and Ravi Singh who loved and guided me as second parents. To my grandmother, Tika Maya Timalsina, who gave me unparalleled love and care, your blessings are a boon to me throughout my life.

To my constant happiness, Jyoti Sedhai, thank you so much for your unconditional love and support and being a part of my life. To all the friends whom I shared sorrow and happiness with, thank you for your support and inspiration and filling my life with emotions.

Thank you for all your love.

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CHAPTER I

INTRODUCTION

Moisture stress and soil water in semiarid ecosystems

In arid and semi-arid regions, plants are exposed to high water stress conditions because of larger evapotranspiration which can lead to soil moisture deficits (Rind et al., 1990). Therefore, water availability is the major limiting factor for plant productivity in both arid and semi-arid regions particularly when the potential transpiration exceeds the actual transpiration. Potential transpiration refers to the transpiration when the root zone water content is high and stomatal resistances are minimal whereas actual transpiration refers to the transpiration when root zone water may be limiting (Fischer & Turner, 1978). Because of high evapotranspiration and soil moisture deficits in the long summer days, the growth and development of crops are severely affected and the farmers are compelled to terminate their crops without much yield (Fischer & Turner, 1978). The effect of such water stress and frequent drought condition in such dry regions is escalated due to precipitation being often exceeded by evapotranspiration (Schwabe et al., 2013).

The path traveled by water and energy from the soil, through plants, and into the atmosphere in response to water potential gradients is referred to as Soil-Plant-Atmosphere Continuum (SPAC) (Norman & Anderson, 2005; Rekwar et al., 2022). The transfer of water in the SPAC is driven by the energy gradient generated by the water potential difference resulting from high potential in the soil, to a gradually lower potential in plant and the atmosphere.

Physically, as the plant begins to lose water through evaporation from the leaves, it will initiate a subsequent decrease in water potential within its tissues, which corresponds to a reduction in water potential in the cells of that tissue (Shackel et al., 1997). Furthermore, water from the xylem replaces water lost from the surface of mesophyll cells, and plants extract additional water molecules from the roots to the leaf via the cohesion-tension characteristics of water in the xylem (Reichardt & Timm, 2012; Steudle, 2001). The cohesion-tension theory of water transport in plants is regarded primarily responsible for water transport in plants and play a vital role in soil-plant-atmosphere continuum (Angeles et al., 2004; Shackel et al., 1997; Steudle, 2001; Tyree, 1997).

In these dry areas, plants exhibit several adaptations for drought resistances which includes both drought avoidance and drought tolerance strategies under highly water stressed conditions (Sanchez et al., 2002; Tomlinson et al., 2013). As plants lose water from their tissues, the water potential in the associated tissue is reduced. As plant water stress increases in severity, cells suffers from turgor loss which consequently affects the growth and development of the plants (Shackel et al., 1997). Drought avoidance is a mechanism for avoiding lower water status in tissues during drought by maintaining cell turgor and cell volume either through active water uptake, or via reduction of water loss while drought tolerance is a mechanism by which plants maintain metabolism even at low water potential (Sanchez et al., 2002).

Under water-limited conditions, several morphological and physiological adaptations in plants have been reported as drought resistance strategies such as increase in leaf density (leaf weight per unit area) with aridity, simple entire leaves with Kranz anatomy and C_4 photosynthesis in summer annuals, production of smaller denser leaves in herbaceous plants, and higher root to shoot ratio in dry regions (Fischer & Turner, 1978); osmotic adjustments and antioxidant capacity, reduced transpiration, increased water uptake by an extensive root system (Sanchez et al., 2002); deeper rooting system (Benjamin & Nielsen, 2006); small vessels and high stem density that reduce xylem cavitation (xylem embolism) (Tomlinson et al., 2013).

It is evident that the success and survival of many agricultural crops and reforested ecosystems in arid and semi-arid regions depends on the continued availability of water which requires an effective water conservation system and proper access to irrigation (Halli et al., 2021; Leib et al., 2006; Tabatabaei et al., 2020). Soil water is a serious limitation for plant growth in semi-arid land ecosystem and severe soil water deficit could result in degradation of plants and even desertification (Huang et al., 2021). For example, (Yang et al., 2023) reported a reduction in the grain maize yield from 16.99 tha-1 to 13.82 tha-1 under sufficient water levels (80%) and severe water stress levels (50%) respectively. Similarly, the onset of drought and decline in soil moisture reserves have critical impacts on the agricultural crops during various stages of their growth and development (Narasimhan & Srinivasan, 2005). Therefore, there is an urgency to evaluate the soil-water-plant-atmosphere dynamics and its interaction with natural and managed vegetation in agricultural sectors and restorative ecosystems (Huang et al., 2021).

Cover cropping semi-arid agroecosystems: Is it water-wise?

Cover cropping is a sustainable agricultural management practice beneficial for soil and water conservation, recycling of nutrients, weed and pest suppression and improved soil health (Rai, 2021; Snapp et al., 2005). It is well known that one of the major functions of cover crops is to enhance the nutrient cycle, especially in the short term, by reducing nitrate leaching and by acting as a green manure which facilitate biological nitrogen fixation in the soil (Constantin et al., 2010; Krstić et al., 2018). A secondary role of cover crop is to increase soil organic carbon and organic nitrogen (Fageria et al., 2005; Jian et al., 2020), and in turn, soil fertility (Camarotto et al., 2018). Cover crops also increase the soil labile organic carbon pools which are vital for increasing soil productivity (Zhou et al., 2012). Cover crops might also assist in the mitigation of greenhouse gases but the effect of cover crops on the emissions of carbon-dioxide (CO_2) and nitrous-oxide (NO_2) is highly dependent on the management practices associated with cover cropping such as irrigation, and residue retention (Kaye & Quemada, 2017; Muhammad et al., 2019; Nguyen & Kravchenko, 2021; Wegner et al., 2018). Furthermore, cover crops are also known to have allelopathy properties with the potential to control weeds in organic vegetable farms in semiarid sub- tropical Texas (P. Soti & Racelis, 2020). Therefore, cover cropping has been regarded as imperative for improving soil health management and promotion of restoration of natural and managed ecosystem (Wallander et al., 2021).

However, depending on the water budget, i.e., amount of rainfall, drainage and evapotranspiration by cover crops, cover crops may also negatively affect crop production by subtracting water and immobilizing nutrients (Krstić et al., 2018; Sharma et al., 2017; Wortman et al., 2012). While cover crops are more likely to reduce the soil surface evaporation due to presence of residue, reduction of wind speed at the soil surface, and reduction of the solar radiation reaching the soil surface by the crop canopy (Sharma et al., 2017), the major concern for farmers in arid and semi-arid regions remains: Do cover crops use the soil moisture which might affect the subsequent cash crops in the next season (Williams et al., 2000)?

Incidentally, several studies report mixed effects of cover crops on soil moisture conservation in arid and semi-arid regions (Wang et al., 2019; Whish et al., 2009). Cover crop-induced moisture deficits have been reported by several studies and have been found to reduce the subsequent cash crop yields (Kaspar & Singer, 2015; Kasper et al., 2022). Soil moisture differences between cover cropping and conventional agriculture at the soil surface (10 cm depth) was 0.03 $m^{-3}m^{-3}$, with conventional agriculture being higher than cover cropping. However, at the 55 cm soil depth, moisture levels were similar between the two treatments and throughout the monitoring period (Camarotto et al., 2018). Krstić et al., (2018) reported significantly highest water loss and lower soil water storage under cover crop treatments as compared to control. Camarotto et al., (2018) reported negligible impact of cover crop cultivation in soil moisture despite drought conditions while Pinto et al., (2017) emphasized the effect of cover crop cultivation duration and growth on soil moisture. Despite all these, interests in cover cropping have increased in recent years and studies suggest that there is a rise in both the number of U.S. farmers incorporating the practice and the number of acres covered under cover crops (Kasper et al., 2019, 2022).

Are Cover Crops viable for the Lower Rio Grande Valley?

The Lower Rio Grande Valley (LRGV) of southern Texas is in the United States-Mexico borderland and lies at the confluence of the temperate and tropical conditions which gives rise to vegetation that are unique and rich in diversity (Leslie Jr., 2016). The climate is characterized by semiarid conditions with very hot and dry summers and mild winters, and highly erratic rainfall which occur typically during spring (March-May) or early fall (September-October) and generally drier periods during the rest of the year (Leslie Jr., 2016). Texas alone occupies 14.05% of the total acres of farm area in the United States and thus is ranked first in the country in terms of both the number and the area of the farms (USDA NASS, 2021). The Rio Grande Valley is one of the most important agricultural areas in Texas with its warm, semi-arid climate and close proximity to the Rio Grande River (Savannah, 2017). Most of the crops grown in this region include citrus, onions, winter wheat, corn, cotton, oats, sorghum, soybeans, sunflower, sugarcane, and watermelons (Savannah, 2017; USDA NASS, 2021). The LRGV is composed of different soil types ranging from sandy loam to clay loam. At the same time, farms in the regions are highly dependent on rainfall for moisture and have extremely low levels of organic matter and are increasingly infertile. With most land conversion happening within the last 100 years, preserving, and enhancing existing soil health for the long-term sustainability of agriculture in this region is becoming increasingly important to the farmers in Rio Grande Valley (RGV). However, water resources remain subject to large variation in the face of climate change and increasing drought intensity in the region. Despite being an agricultural hotspot, 66% of the cropland in LRGV is unirrigated and water deficit still remains a primary concern of most of the farmers in this region (Kasper et al., 2022).

In arid and semi-arid regions like RGV, where water is the primary limiting factor, by all indications, it is necessary to assess the suitability of cover crops and identify whether they can be beneficial for agriculture and reforestation management practices (Soti et al., 2019). Therefore, it is essential to estimate the impacts of cover crops on soil moisture and associated benefits across different soil depths and soil textures under cover cropping system in Lower Rio Grande Valley. To this end, a large cover cropping trial has been initiated across different farms in the Rio Grande Valley region to address the questions about cover crop impacts on soil moisture, soil health, and the influence of cover crops on insect biodiversity. This thesis seeks to quantify and assess the cover crops-led moisture variation across a range of soil types (different farm locations) and explore the cover crop-soil moisture relationship in dryland farming systems of Lower Rio Grande Valley region, a semi-arid water limited region of South Texas.

CHAPTER II

EXPERIMENTAL ASSESSMENT OF COUPLED ROOT AND SOIL MOISTURE DYNAMICS IN COVER CROPPING SYSTEMS OF SEMI-ARID SOUTH TEXAS

Abstract

Cover cropping, an agricultural practice in which non-cash crops are planted and terminated before reaching maturity, may reduce weed and pest outbreaks, promote soil microbiomes, enhance soil fertility, and sequester carbon to support climate-neutral agriculture. However, it has been noted to negatively impact soil moisture, particularly in semi-arid and arid climates, giving pause to farmers reluctant to adopt cover cropping as standard practice. We sought to identify under what conditions cover crops significantly reduce soil moisture, specifically the interaction between cover crop root biomass/distribution and factors associated with on-farm practice and site conditions. To this end, we executed a cover crop experiment across four different farms by installing soil moisture sensors at multiple depths 7,15, and 25 cm, and 10,30, and 60 cm in years 1 and 2, respectively) and supplemented these observations with targeted root biomass and moisture sampling up to 40 cm depth. My analysis revealed that cover crops had negative impacts on soil moisture in farms with clay loam soil types, restricted to the cover cropping season, while there was no impact in sandy loam soil types throughout the year. However, the amount of rainfall received after cover cropping season was found to offset the cover crop-induced moisture deficit for the following cash cropping season. The degree of cover crop-induced moisture losses declined along the soil depth profile, which we found to be related to the decline of rooting density along the same profile (shallowest soil layer i.e., 0-10 cm had significantly higher cover crop root biomass). However, there was no significant correlation between the relative change in soil moisture with both root biomass (gm/m^3) and root length density (cm/m^3). These results highlight the importance of cover crop rooting depth and consideration of past and expected rainfall on decision-making related to timing of cover crop termination as key determinants of whether cover crops will reduce soil moisture in semi-arid farms both locally and globally.

Introduction

Cover cropping, widely adopted as a sustainable cropping system, is an agricultural practice of planting non-cash crops (cover crops), terminating them pre-maturely and incorporating them into the soil to return the biomass back into the soil. According to USDA NASS, (2019), within United States of America, around 15.4 million acres of cover crops have been reported by farmers in 2017 which is 50-percent increment as compared to 2012 (Wallander et al., 2021). The increasing attraction to cover crops is likely due to the long terms benefits of cover to enhance several ecosystem services such as soil fertility, soil water availability, control weed and pest outbreaks, enhance soil biological activity, sequester carbon, and improve nutrient cycling (Savannah, 2017; Sharma et al., 2017; P. G. Soti et al., 2016; Wang et al., 2019; Zhou et al., 2012). However, farmers are largely concerned about the potential cover crop-induced soil moisture loses, especially in arid and semi-arid climatic regions, where evapotranspiration exceeds precipitation under high temperatures, and has a compounding effect on water stress through its effects on vapor pressure density (VPD) (Grossiord et al., 2020). A suite of studies suggested that cover crop-induced soil moisture losses do not have detrimental impacts on the following crops (Wang et al., 2019; Whish et al., 2009) while some reported that cover crops may lead to significant soil moisture deficit causing serious harm to the subsequent cash crops (Kasper et al., 2022; Nielsen et al., 2015).

In arid and semi-arid climatic regions, farmers with limited access to irrigation are extremely reluctant to adopt cover cropping due to concerns that cover crop-induced soil moisture deficit will cause significant harm to their cash crop yield (Kasper et al., 2022). Cover crops, when grown to full maturity can yield higher biomass and may ensure large benefits to soil health but interestingly, it might also result in cover crops competing for soil moisture and nutrients with subsequent cash crops (Qin et al., 2021). Reese et al., (2014) found that higher cover crop production led to lower corn yield in the subsequent cash cropping season in a semi-arid region implying that duration of crop and its maturity indeed affect the soil moisture utilization by the cover crops. Moreover, Krstić et al., (2018) reported that cover crops reduced soil water storage in dry year of 2012 and the effect was most pronounced during cover crop growing season. With this, he also suggested that cover crop-induced moisture deficit is due to evapotranspiration, leaching and plant water uptake whereas, in control treatment, the only means of water loss was through evapotranspiration and leaching.

In a recent study in the Rio Grande Valley of south Texas, a semi-arid water limited region, Kasper et al., (2022) found highly variable year-to-year variation in cover crop impacts on soil moisture and subsequent cash crop yields. In the first year, cover crop-induced extreme soil moisture deficits resulted in cash crop failure; in the later years, however, under sufficient precipitation, the cover crops did not have much negative impact on soil moisture and lower yield drops in sorghum. These results suggest that both the timing and quantity of precipitation matter greatly and warrants the need to consider such climatic factors and management aspects of farming when studying the impact of cover crops on soil moisture (Kasper et al., 2022).

More broadly, the plant water uptake of cover crops is dependent on myriad of factors including soil physical and biological properties, cover crop species, time of termination, residue management, irrigation availability, soil texture and the amount of precipitation (Alonso-Ayuso et al., 2014; Burgess et al., 2014; Currie & Klocke, 2005; Gabriel et al., 2014; Khan & McVay, 2019; Miller et al., 2011; Nielsen et al., 2015; Sultani et al., 2007; Whish et al., 2009; M. M. Williams et al., 2000). Given multiple confounding variables, it can be challenging to accurately assess the impact of cover crops and identify the factors driving the cover crop influence on soil moisture, especially in participatory research settings where farmers oversee the management decisions. These challenges can be mitigated by studying the effects of cover crops on soil moisture across multiple seasons and sites, and quantifying confounding abiotic and biotic variables. There should be a statistical/experimental design reference out there that discusses this trade-off generally within ecological research. Either one does an experiment with everything tightly controlled, or when that's not possible one attempts to at least measure the variables which were not controlled so they can be considered as additional predictor variables within mixed models.

To this end, we instrumented four different farms implementing a cover crop experiment with soil moisture sensors at multiple depths and supplemented these observations at a single farm with targeted root biomass and moisture measurements up to 40 cm soil depth. The soil moisture monitoring was carried out for three seasons across 2021-2023 (cover cropping-cash cropping-cover cropping) across different farms with varying soil texture ranging from fine sandy loam to clay loam soil type. Furthermore, the weather stations installed at each experimental site provided us with necessary rainfall and weather data to study their impacts on soil moisture under cover cropping system. We hypothesized that cover crops would have a negative impact on soil moisture conditional on fallow period precipitation which might lead to a cascading effect on the subsequent cash crop with lower soil moisture in cover crop treated areas. We also expected that the cover crop-induced soil moisture deficit would decrease at a greater soil depth with decreasing cover crop root biomass along the soil profile.

Materials and Methods

Study Site

The Lower Rio Grande Valley (LRGV) region in South Texas comprises four counties (Hidalgo, Starr, Cameron, and Willacy) featuring semi-arid to subtropical climate accompanied with hot and dry summer and scanty rainfall throughout the year. The participatory cover crop field trial was implemented in four different farms across in the LRGV region (Figure 2.1) covering ~700 acres of cover cropped area. The average temperature throughout the year mostly ranges from 10-37 °C with about 584.2 mm of annual rainfall. The valley is also regarded as a hotspot for agricultural crops and native biodiversity; increasingly dry climatic patterns, however, pose serious concerns amongst growers of this region in utilizing barely available water for farming purposes and therefore compelled to adopt rainfed agroecosystems. The soil types of selected sites for the cover crop trial ranged from fine sandy loam to clay loam. Table 2.1 presents a brief overview of the description of the site selected for this study.

Table 2.1. Details of the farms participating in the cover cropping experiment

Farm	County	Soil Types (Soil Survey Staff, 2021)	Coordinates	Total Land area (acres)	Cover crop area (acres)	Treatments
Farm 1	Starr	Fine sandy loam	26°24'36.0"N 98°31'35.5"W	7500	250	CC & C
Farm 2	Starr	Fine sandy loam	26°24'32.1"N 98°27'37.5"W	3200	400	CC & C
Farm 3	Willacy	Clay loam	26°27'31.9"N 97°53'22.2"W	12000	200	CC & C
Farm 4	Cameron	Sandy clay loam	26°17'57.1"N 97°50'11.5"W	8000	150	CC & C

C and CC stand for control and cover crop treatments respectively.

Experimental Design

A large-scale cover cropping experiment was initiated across four farms totaling 325 hectares along a sand-to-clay soil texture gradient in South Texas. The research sites in all four farms were installed with Teros 10 soil moisture sensors, ATMOS 41 weather station and ZL6 data loggers (Meter Group, Inc., Pullman, WA, USA). The Teros 10 soil moisture sensors were instrumented along three depths in the root zone (7cm, 15cm, and 25cm) at 6-9 replicate locations both within (treatment) and outside (control) cover cropped areas at each farm (Figure 1 (c)). Farms 2, 3, and 4 had one and Farm 1 had two ATMOS 41 weather stations to monitor and record precipitation data throughout the cropping seasons. Large farm operations such as cultivation, sowing of seeds, termination of cover crops, and harvesting of cash crops were accompanied with either removal or installation of sensors and other equipment. All the farm operations including cultivation, tillage, sowing of seeds, irrigation, residue management, spraying of herbicides and pesticides, termination of cover crops, harvesting of cash crops, and crop species selection were done in close cooperation with farmers. The cover crops were terminated before maturity using different means available to the farmers and residues were incorporated into the soil.

The experimental design would be continued for four years 2021-2025 as a part of the cover crop trial. However, data for three cropping seasons (cover crops (2021) - cash crops (2022) - cover crops (2022)) have been utilized for the purpose of this thesis. The data (soil water content (m^3/m^3) and precipitation (inch) were collected via Zl6 data loggers at 15 minutes interval and automatically uploaded to the Zentra cloud (Meter Group, Inc., Pullman, WA, USA) which allowed us to download and analyze the data remotely.

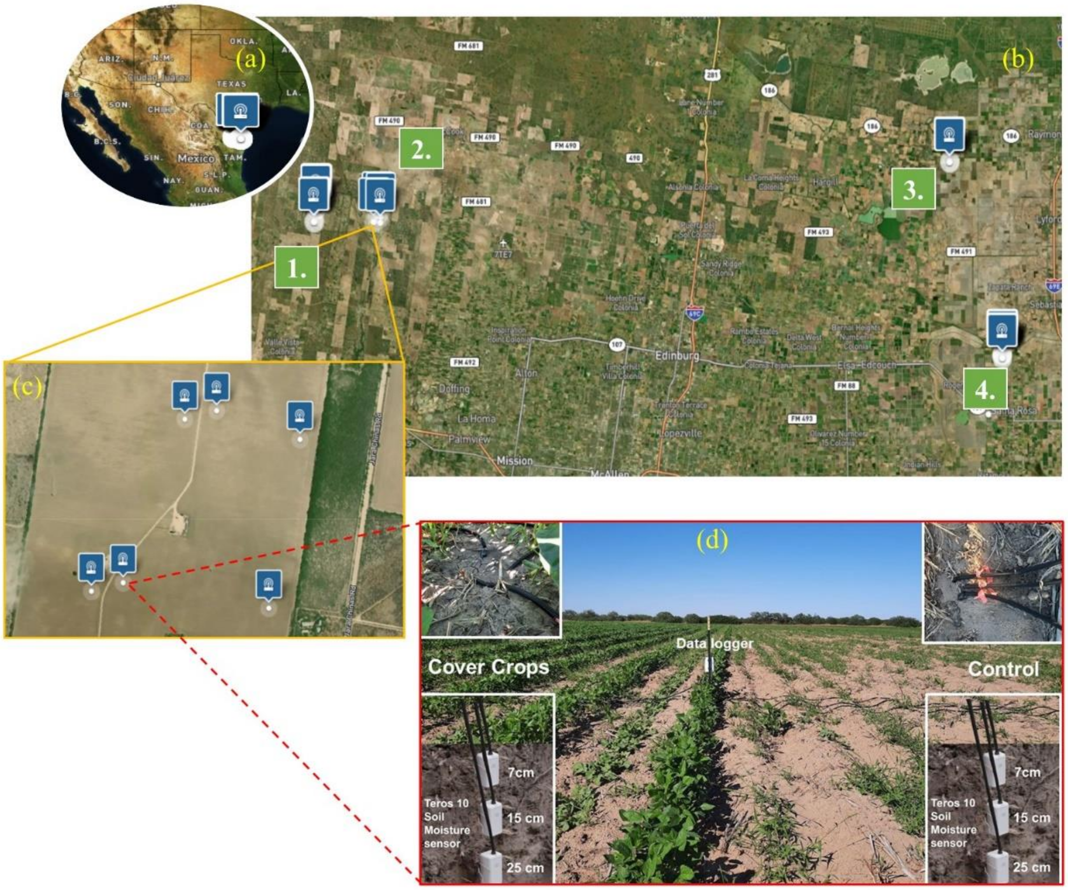

Figure 2.1. Study site and experimental design. (a)The Lower Rio Grande Valley Region (LRGV), the site of the research at the southern tip of the United States. (b) Location of four different farms (Farm 1, 2, 3, and 4) participating in the cover crop trial across the LRGV region.

Selected crop species

The first year of the trial was initiated during cover cropping season (2021: 1st year) and the major cover crops cultivated were cowpea (*Vigna unguiculata* L. Walp), sorghum-sudan grass (*Sorghum* × *drummondii* (Nees ex. Steud.) Millsp. & Chase), sun hemp (*Crotalaria juncea* L.*)*, tillage radish (*Raphanus spp.* L.) in different combinations (Table 2.2). The cover cropping season was followed by a small fallow period and subsequent cash cropping (2022) which consisted of sorghum (*Sorghum bicolor* L. Pers.) (Farms 1, 2, and 3) and Sunflower (*Helianthus annuus* L.) (Farm 4 only). The harvesting of cash crops in the second year was followed by a short fallow period and cover crops (2022: 2nd year) were planted around the same time as the first year. For second year, each farm adopted different combinations of cowpea, sun hemp, corn, sorghum-sudan grass, and sesame (*Sesamum indicum L.*) during the cover cropping season (Table 2.2).

Root assessment

Soil samples were collected at four depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm) for both treatments (control and cover crops) in Farm 1 using a post hole digger. Later, the soil samples were processed to extract the roots for cover crop treatment only since we did not find any roots in samples collected from control treatment due to prior cultivation by the farmer. The cover crop roots were subjected to root measurements using WinRHIZO (Regent Instruments Inc., Canada). The roots were also oven dried at 70°F for 48 hours and weighed to obtain their dry biomass. Likewise, spot soil water content measurements were also recorded at the same depths by using a Procheck device (Meter Group, Inch., Pullman, WA, USA).

Statistical Analysis

The soil water content (m^3/m^3) data were accessed remotely from Zentra cloud (Meter Group, Inch., Pullman, WA, USA) and imported to R version 4.2.2 (R Core Team, 2022) for further analysis. The large volume of data (> 1,000,000 table rows) necessitated the use of an appropriate data science package for effective system memory use; we used the R package “data.table” (Dowle & Srinivasan, 2021). Soil moisture curves were plotted in combination with precipitation to analyze the impact of cover crops on soil moisture and any unreliable data was excluded from further analysis. Welch Two Sample t-test was conducted for each cropping event to identify the significant effect of cover crops on soil water content during multiple cropping seasons throughout the study period. Simultaneously, analysis of variance (ANOVA) was conducted to examine the soil water content at different depths (7cm, 15cm, and 25 cm) during major cover cropping events (1st and 2nd year) at all farms.

We also conducted ANOVA to test the significant differences between different soil depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm) in terms of root biomass (g/m^3) and root length density (cm/m^3) for Farm 1 and test the effects of treatments (cover crops and control) on soil water content at same depths. The Shapiro Wilk test was conducted to validate the normal distribution of the data. A Pearson’s correlation test was run to highlight the relationship of relative change in soil water content with root biomass and root length density.

Table 2.2. Cropping details (cover and cash crops) for individual farms with their respective date of planting, termination (cover crops), and harvesting (cash crops) for two years (2021 and 2022)

Farm	Cover crops	Seeding rate	Planting date	Termination date	Termination method	Cash crops	Irrigation	Planting date	Harvest date
First year (2021-2022)									
Farm 1	Cowpea Tillag radish	12 lb/ac 5 lb/ac	9/7/2021	11/15/2021	Chisel and Tillage	Sunflower	Rainfed	2/12/2022	6/22/2022
Farm 2	Cowpea Tillage radish	15 lb/ac 5 lb/ac	9/17/2021	12/8/2021	Discing	Sorghum	Rainfed	3/5/2022	7/20/2022
Farm 3	Cowpea Sudan grass	12 lb/ac 5 lb/ac	9/7/2021	11/01/2021	Herbicide spray	Sorghum	Rainfed	3/10/2022	6/26/2022
Farm 4	Sun hemp Cowpea Sudan grass	12 lb/ac 5 lb/ac 5 lb/ac	9/7/2021	12/15/2021	Discing	Sorghum	Irrigated	3/1/2022	6/26/2022
Second year (2022-2023)									
Farm 1	Cowpea Sesame Sudan grass	15 lb/ac 2 lb/ac 1 lb/ac	8/29/2022	12/8/2022	Strip tillage	Sorghum	Rainfed	2/20/2023	6/20/2023
Farm 2	Cowpea Sun hemp	30 lb/ac 30 lb/ac	9/22/2022	12/13/2022	Cattle grazing & discing	Sorghum	Rainfed	3/7/2023	-
Farm 3	Cowpea Corn Sudan grass	12 lb/ac 1 lb/ac 4 lb/ac	9/13/2022	11/15/2022	Discing	Corn	Rainfed	-	-
Farm 4	Cowpea Sudan grass	12 lb/ac 5 lb/ac	10/11/2022	12/14/2022	Discing	Cotton	Irrigated	3/23/2023	-

Results

The average soil water content (m^3/m^3) across the soil profile (0-25 cm) was higher in Farm 3 (0.269 m^3/m^3) and 4 (0.271 m^3/m^3) as compared to Farm 1 (0.161 m^3/m^3) and 2 (0.166 m^3/m^3). In terms of the total amount precipitation received by each farm throughout the study period (2021-2022), the highest amount of rainfall was recorded in Farm 3 (316.39 mm) followed by Farm 2 (266.7 mm), Farm 1 (257.69 mm) and Farm 4 (178.41 mm) (Table 2.3). The critical rainfall amount (the amount of rainfall necessary to offset the difference in soil water content between control and cover crop treatments) was considerably different for each farm; a broad visual assessment of the amount of daily rainfall events and their impact on soil water content revealed that Farm 1, 2, 3 and 4 required 10 to 20 mm, 20-30 mm, 30-40 mm, and 30-40 mm of rainfall respectively in order to eliminate the differences in soil water content between cover crop and control treatment in the respective farms (Figure 2.3). A full analysis to address this question is beyond the scope of this paper and will be the subject of a subsequent manuscript.

Table 2.3. Precipitation (inches) and soil water content (m^3/m^3) in each farm throughout the study period (2021-2022).

Farm ID	Total precipitation (mm)	Average soil moisture (at 7 cm (m^3/m^3)	Average soil moisture at 15 cm (m^3/m^3)	Average soil moisture at 25 cm (m^3/m^3)	Average soil moisture (0-25 cm) (m^3/m^3)
Farm 1	178.41	0.144	0.168	0.183	0.161
Farm 2	266.70	0.125	0.166	0.253	0.166
Farm 3	316.39	0.238	0.284	0.30	0.269
Farm 4	257.69	0.251	0.280	0.295	0.271

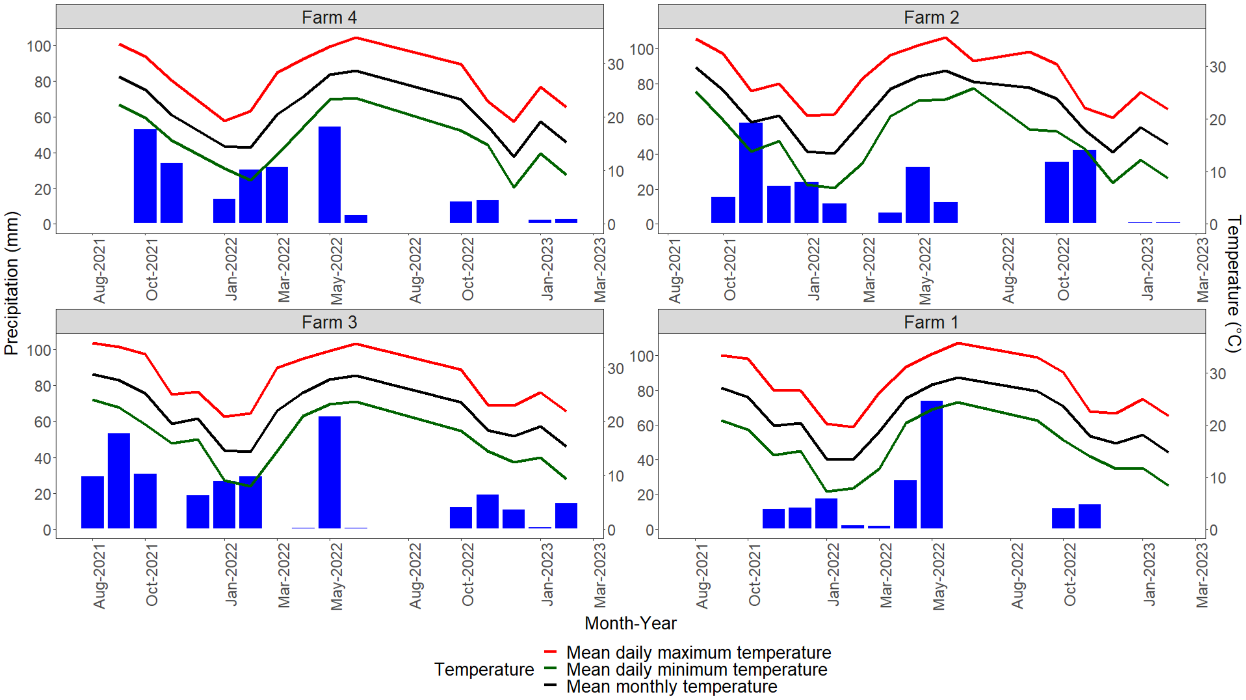

Figure 2.2. Monthly precipitation, average monthly temperature, mean daily minimum temperature, and mean daily maximum temperature for each farm throughout the study period (2021-2023).

Figure 2.2 shows the overall climatic conditions of the farms during the study period. The monthly average temperature ranged from 12.58 °C to 29.70 °C across all the farms. The lowest temperature was 6.8 °C in Farm 4 during December 2022 while the highest temperature of 35.8 °C was recorded in Farm 1 in June 2022.

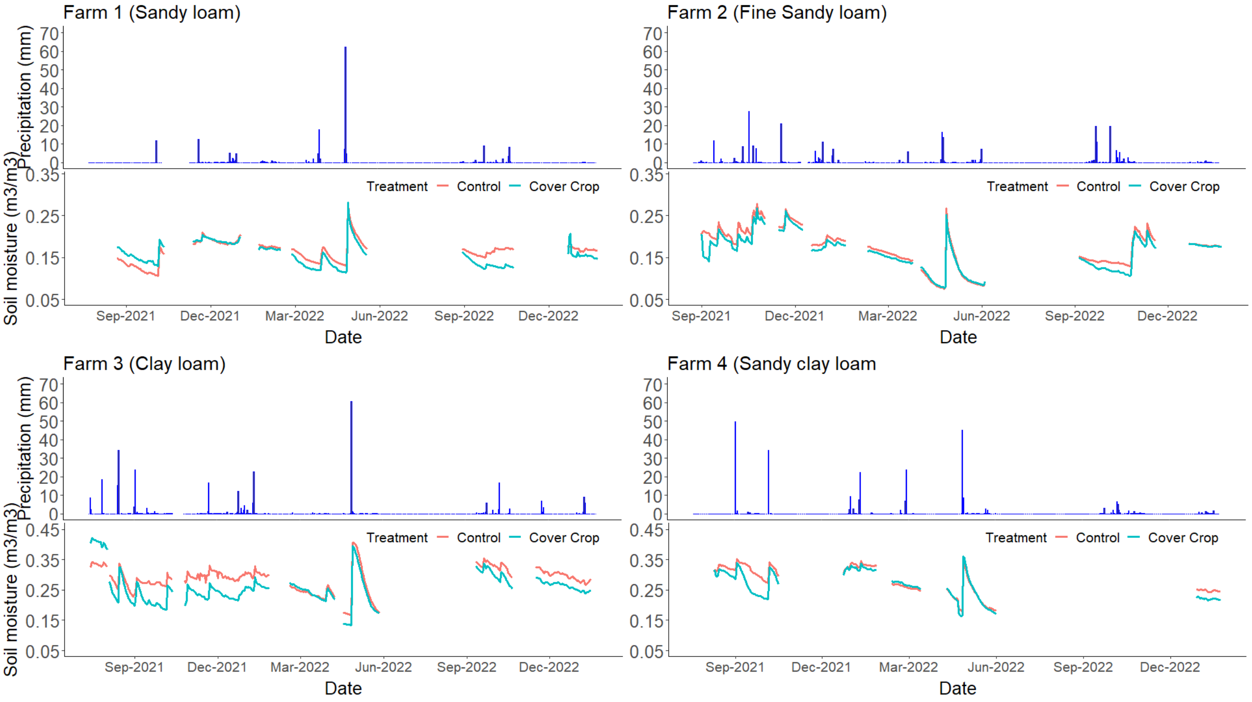

Figure 2.3. Soil water content (m^3/m^3) and total precipitation received by each farm under study.

The cover crop-induced soil moisture deficit was closely examined under different cropping events starting from cover crop planting for 1st year to the fallow period after cover cropping season in 2nd year. The results (Welch Two Sample t-test) showed that cover crops had significant negative impact on soil water content during CC termination 1st year (df = 7.184, p = 0.014), CC fallow 1st year (df = 8.1215 ,p = 0.034), and CC growing 2nd year (df = 8.073,p = 0.034) in Farm 3 (clay loam soil type) and CC growing 1st year (df = 21.624, $p < 0.001$) and CC termination 1st year (df = 20.34, p = 0.004) in Farm 4 (sandy loam soil type) (Figure 2.4).Contrary to these results, the cover crops showed a positive impact on soil water content during CC planting 1st year (df = 3.7611, p = 0.024) at Farm 3 (Table 2.4). At the same time, there was no significant effect of cover crops on soil water content at Farm 1 (sandy loam soil type) and Farm 2 (fine sandy loam soil type).

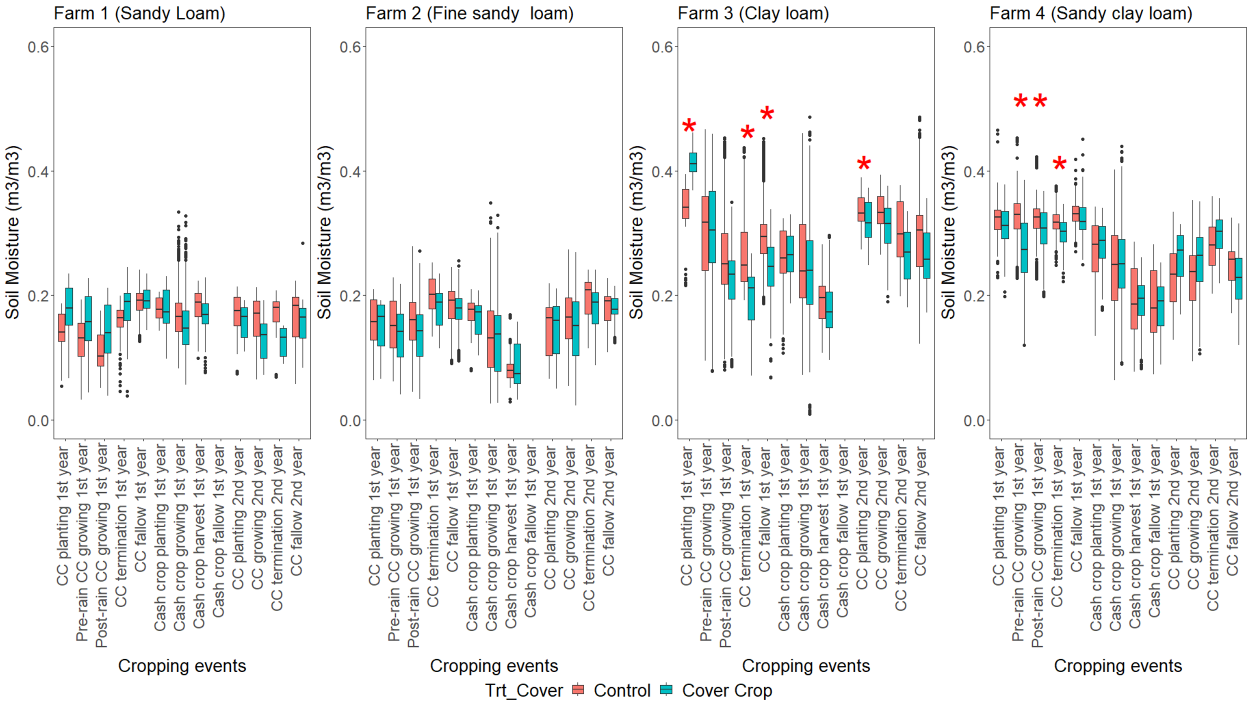

Figure 2.4. Soil water content (m^3/m^3) in different cropping events (cover cropping season 1st year- cash cropping season 1st year - cover cropping season 2nd year) for individual farms. CC stands for cover crops. The significant effect of cover-crops during cropping events is represented by (*).

Table 2.4. Welch Two Sample t-test for different cropping events in each farm

Farms	Cropping events	df	Mean Control	Mean Cover crop	95% CL Lower	95% CL Upper	t value	p-value
Farm 1	CC planting 1st year	6.168	0.143	0.172	-0.064	0.007	-1.949	0.098
	Pre-rain CC growing 1st year	6.560	0.125	0.151	-0.067	0.013	-1.597	0.157
	Post-rain CC growing 1st year	6.712	0.108	0.138	-0.07	0.00/8	-1.900	0.101
	CC termination 1st year	6.482	0.156	0.178	-0.049	0.006	-1.915	0.100
	CC fallow 1st year	9.283	0.188	0.191	-0.020	0.015	-0.342	0.739
	Cash crop planting 1st year	7.133	0.178	0.176	-0.030	0.033	0.118	0.909
	Cash crop growing 1st year	8.108	0.165	0.150	-0.003	0.032	1.917	0.091

Table 2.4, cont.

	Cash crop harvest 1st year	9.522	0.182	0.165	-0.014	0.047	1.204	0.258
	Cash crop fallow 1st year	-	-	-	-	-	-	-
	CC planting 2nd year	8.968	0.165	0.160	-0.020	0.030	0.480	0.642
	CC growing 2nd year	8.928	0.153	0.133	-0.008	0.049	1.608	0.143
	CC termination 2nd year	3.483	0.163	0.130	-0.022	0.088	1.779	0.160
	CC fallow 2nd year	6.237	0.159	0.158	-0.028	0.030	0.088	0.933
Farm 2	CC planting 1st year	7.368	0.203	0.175	-0.074	0.130	0.636	0.544
	Pre-rain CC growing 1st year	9.896	0.199	0.187	-0.118	0.142	0.210	0.838
	Post-rain CC growing 1st year	9.926	0.207	0.189	-0.114	0.15	0.305	0.767
	CC termination 1st year	9.996	0.247	0.230	-0.102	0.136	0.317	0.758
	CC fallow 1st year	9.908	0.207	0.200	-0.055	0.070	0.270	0.792
	Cash crop planting 1st year	9.985	0.173	0.167	-0.016	0.030	0.643	0.535
	Cash crop growing 1st year	9.678	0.130	0.130	-0.027	0.026	-0.044	0.965
	Cash crop harvest 1st year	7.718	0.085	0.090	-0.035	0.028	-0.418	0.687
	Cash crop fallow 1st year	-	-	-	-	-	-	-
	CC planting 2nd year	9.098	0.151	0.146	-0.023	0.032	0.379	0.713
	CC growing 2nd year	6.916	0.159	0.143	-0.012	0.043	1.360	0.217
	CC termination 2nd year	8.639	0.196	0.179	-0.007	0.042	1.591	0.147
	CC fallow 2nd year	8.714	0.180	0.179	-0.021	0.023	0.127	0.901
Farm 3	CC planting 1st year	3.7611	0.347	0.414	-0.119	-0.015	-3.677	**0.024 ***
	Pre-rain CC growing 1st year	9.277	0.299	0.285	-0.039	0.066	0.562	0.588
	Post-rain CC growing 1st year	6.609	0.264	0.224	-0.017	0.096	1.658	0.1439
	CC termination 1st year	7.1836	0.267	0.198	0.019	0.120	3.230	**0.014 ***
	CC fallow 1st year	8.1215	0.300	0.241	0.006	0.112	2.555	**0.033 ***

Table 2.4, cont.

	Cash crop planting 1st year	7.625	0.258	0.265	-0.057	0.042	-0.360	0.728
	Cash crop growing 1st year	9.843	0.252	0.239	-0.024	0.050	0.789	0.448
	Cash crop harvest 1st year	7.905	0.192	0.183	-0.026	0.044	0.603	0.563
	Cash crop fallow 1st year	-	-	-	-	-	-	-
	CC planting 2nd year	9.808	0.337	0.319	-0.011	0.046	1.344	0.209
	CC growing 2nd year	8.0733	0.336	0.307	0.003	0.055	2.540	**0.034** *
	CC termination 2nd year	4.799	0.307	0.263	-0.009	0.096	2.177	0.084
	CC fallow 2nd year	9.304	0.256	0.292	-0.019	0.090	1.477	0.172
Farm 4	CC planting 1st year	21.651	0.325	0.309	-0.001	0.033	1.9184	0.068
	Pre-rain CC growing 1st year	21.508	0.327	0.275	0.033	0.071	5.748	**<0.001** ***
	Post-rain CC growing 1st year	21.275	0.324	0.303	0.002	0.041	2.244	**0.036**
	CC termination 1st year	20.34	0.321	0.300	0.007	0.035	3.224	**0.004** **
	CC fallow 1st year	12.404	0.330	0.322	-0.008	0.024	1.111	0.288
	Cash crop planting 1st year	18.098	0.270	0.283	-0.042	0.017	-0.89	0.385
	Cash crop growing 1st year	16.046	0.241	0.246	-0.026	0.016	-0.552	0.589
	Cash crop harvest 1st year	15.595	0.185	0.182	-0.022	0.029	0.274	0.787
	Cash crop fallow 1st year	13.218	0.180	0.175	-0.023	0.033	0.367	0.719
	CC planting 2nd year	18.582	0.227	0.258	-0.064	0.001	-2.011	0.059
	CC growing 2nd year	18.766	0.229	0.255	-0.063	0.010	-1.480	0.155
	CC termination 2nd year	18.247	0.278	0.298	-0.048	0.008	-1.462	0.161
	CC fallow 2nd year	12.832	0.245	0.227	-0.018	0.055	1.087	0.297

The significant effect of cover-crops during cropping events is represented by (*). Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘’ 0.1 ‘ ’ 1. CC stands for cover cropping treatment.

Table 2.5. Analysis of variance for difference in soil water content (m^3/m^3) between cover crop and control treatment at different soil depths (7,15, and 25 cm) for major cover cropping events.

Farms	Cropping events	df	7 cm	15 cm	25 cm	F value	p-value
Farm 1	CC planting 1st year	102	0.027± 0.005	0.037± 0.005	0.019±0.007	2.16	0.121
	Pre-rain CC growing 1st year	378	0.027± 0.003^{b}	0.033± 0.003^{b}	0.011± 0.004^{a}	8.924	**<0.001** ***
	Post-rain CC growing 1st year	151	0.025±0.004^{ab}	0.036±0.005^{b}	0.013±0.007^{a}	4.408	**0.014** *
	CC termination 1st year	96	0.014 ± 0.005	0.027± 0.006	0.017± 0.007	1.43	0.244
	CC planting 2nd year	75	-0.022± 0.005	-0.007± 0.005	-0.019± 0.006	2.719	0.073
	CC growing 2nd year	468	-0.041± 0.002^{a}	-0.026± 0.002^{c}	-0.034± 0.003^{b}	11.16	**<0.001** ***
	CC termination 2nd year	21	-0.064 ± 0.007	-0.049± 0.007	-0.051± 0.007	1.29	0.296
Farm 2	CC planting 1st year	75	-0.006 ± 0.005^{a}	-0.01± 0.004^{a}	0.015 ± 0.015^{b}	4.573	**0.013** *
	Pre-rain CC growing 1st year	252	-0.018± 0.002^{a}	-0.017± 0.002^{a}	-0.002 ± 0.003^{b}	12.89	**<0.001** ***
	Post-rain CC growing 1st year	445	-0.023± 0.001^{a}	-0.021± 0.001^{a}	-0.088± 0.002^{b}	16.78	**<0.001** ***
	CC termination 1st year	95	-0.017± 0.002	-0.018± 0.002	-0.009± 0.004	2.266	0.109
	CC planting 2nd year	87	-0.004 ± 0.004	-0.007± 0.007	0.002 ± 0.004	0.709	0.495
	CC growing 2nd year	957	-0.0145 ± 0.001	-0.0169 ± 0.001	-0.0167 ± 0.002	1.079	0.34
	CC termination 2nd year	72	-0.0191 ± 0.002	-0.0179 ± 0.002	-0.0118 ±0.004	1.489	0.232
Farm 3	CC planting 1st year	45	0.122 ±0.009^{b}	0.0835± 0.009 ^{a}	0.082± 0.009 ^{a}	5.918	**0.005** **
	Pre-rain CC growing 1st year	297	0.01± 0.007^{a}	-0.014± 0.007^{b}	-0.023± 0.009^{b}	5.287	**0.006** **
	Post-rain CC growing 1st year	537	-0.035± 0.004^{a}	-0.038± 0.004^{b}	-0.072± 0.006^{c}	13.79	**<0.001** ***

Table 2.5, cont.

	CC termination 1st year	132	-0.075± 0.008^{a}	-0.063± 0.008^{b}	-0.097± 0.001^{b}	2.816	0.063
	CC planting 2nd year	95	-0.03± 0.004^{a}	-0.008± 0.004^{b}	0.008± 0.008^{b}	11.3	<0.001***
	CC growing 2nd year	264	-0.034 ±0.003^{a}	-0.009± 0.003^{b}	-0.001 ±0.006^{b}	20.68	<0.001***
	CC termination 2nd year	16	-0.025 ± 0.01	-0.0163 ± 0.011	-0.0176 ± 0.02	5.721	0.825
Farm 4	CC planting 1st year	224	-0.021± 0.004^{a}	-0.004± 0.005^{ab}	-0.004± 0.006^{b}	3.624	0.028*
	Pre-rain CC growing 1st year	660	-0.057 ± 0.003^{a}	-0.044 ± 0.003^{b}	-0.041 ±0.005^{b}	5.559	0.004**
	Post-rain CC growing 1st year	432	-0.031± 0.003^{a}	-0.010± 0.005^{b}	-0.016± 0.004^{b}	9.659	<0.001***
	CC termination 1st year	192	-0.020± 0.003	-0.016± 0.003	-0.024± 0.005	0.96	0.385
	CC planting 2nd year	121	0.021± 0.007^{a}	0.043± 0.007^{b}	0.016± 0.011^{a}	3.619	0.0297*
	CC growing 2nd year	683	0.012± 0.003^{a}	0.0370± 0.003^{b}	0.007± 0.005^{b}	22.38	<0.001***
	CC termination 2nd year	95	0.018± 0.007	0.018± 0.007	0.001± 0.011	3.275	0.395

Means with different grouping letter are significantly different from each other. Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘’ 0.1 ‘ ’ 1. CC stands for cover cropping treatment.

Soil depth had statistically significant effect on the difference in soil water content between cover crops and control during Pre-rain CC growing 1st year, and Post-rain CC growing 1st year in Farm 1; CC planting 1st year, Pre-rain CC growing 1st year, and Post-rain CC growing 1st year in Farm 2; CC planting 1st year, Pre-rain CC growing 1st year, Post-rain CC growing 1st year, CC planting 2nd year, and CC growing 2nd year in Farm 3; CC planting 1st year, Pre-rain CC growing 1st year, Post-rain CC growing 1st year, CC planting 2nd year, and CC growing 2nd year in Farm 4 (Table 2.5). Figure 2.5 shows the difference in soil water content across three different soil depths (7cm, 15cm, and 25 cm) between cover crop and control treatment. The difference in soil water content decreased along the soil depth during Pre-rain CC growing 1st year and Post-rain CC growing 1st year in Farm 1; Pre-rain CC growing 1st year and Post-rain CC growing 1st year in Farm 3; CC growing 2nd year in Farm 4. On the other hand, the difference increased along the soil depth during CC planting 1st year, Pre-rain CC growing 1st year, and Post-rain CC growing 1st year in Farm 2; CC planting 2nd year in Farm 3; Pre-rain CC growing 1st year in Farm 4. At the same time, there were inconsistent effects of soil depth on the soil water content differences between cover crop and control treatment during CC growing 2nd year in Farm 1; CC planting 1st year, and CC planting 2nd year in Farm 4.

Table 2.6. Changes in soil water content (m^3/m^3) between cover crop and control treatment during different cover cropping events in all farms.

Farms	CC planting 1st year	Pre-rain CC growing 1st year	Post-rain CC growing 1st year	CC termination 1st year	CC planting 2nd year	CC growing 2nd year	CC termination 2nd year
Farm 1		🟩	🟩			🟨	
Farm 2	🟥	🟥	🟥				
Farm 3	🟥	🟩	🟩		🟥	🟥	
Farm 4	🟨	🟥	🟥		🟨	🟩	

Green, Red and Yellow boxes indicates decreasing, increasing and inconsistent effect of soil depth on soil water content (m^3/m^3) between cover crop and control treatment along soil depth. Blank boxes represent non-significant impact of soil depths on the difference of soil water content (m^3/m^3) between cover crop and control treatment.

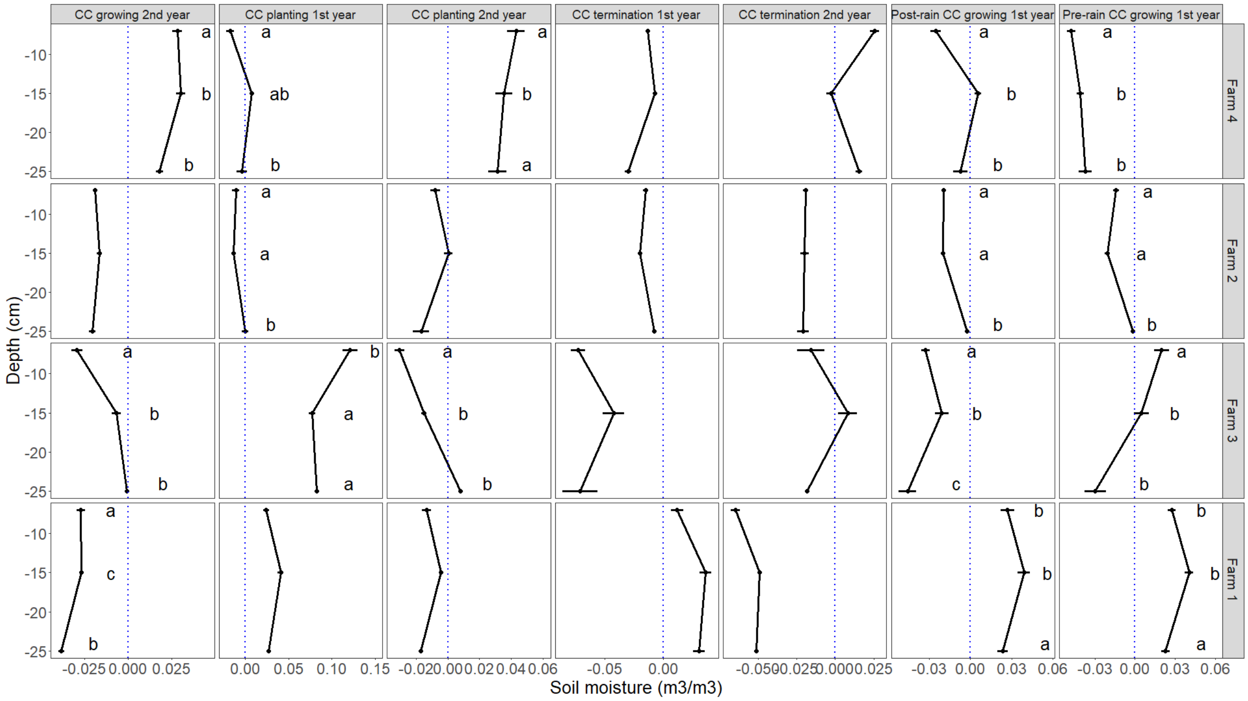

Figure 2.5. Difference in soil water content (m3/m3) between cover crop and control treatment (cover crop – control) at different soil depth (7cm,15cm, 25cm) for major cropping events in all farms. CC stands for cover cropping treatment.

Analysis of vertical soil moisture profile across different depths in Farm 1 revealed that soil water content in 0-10 cm soil depth was significantly less ($p < 0.005$) while 10-20 cm, 20-30 cm and 30-40 cm soil depth were statistically similar. The root biomass ($p = 1.37e-06$) and root length density of cover crops ($p = 0.0127$) were significantly higher at the top layer of the soil and decreased along the soil profile exhibiting a similar pattern to that of vertical soil moisture profile across the same depths. However, there was no significant correlation between the relative change in soil moisture with both root biomass (gm/m^3) and root length density (cm/m^3) (Figure 2.6).

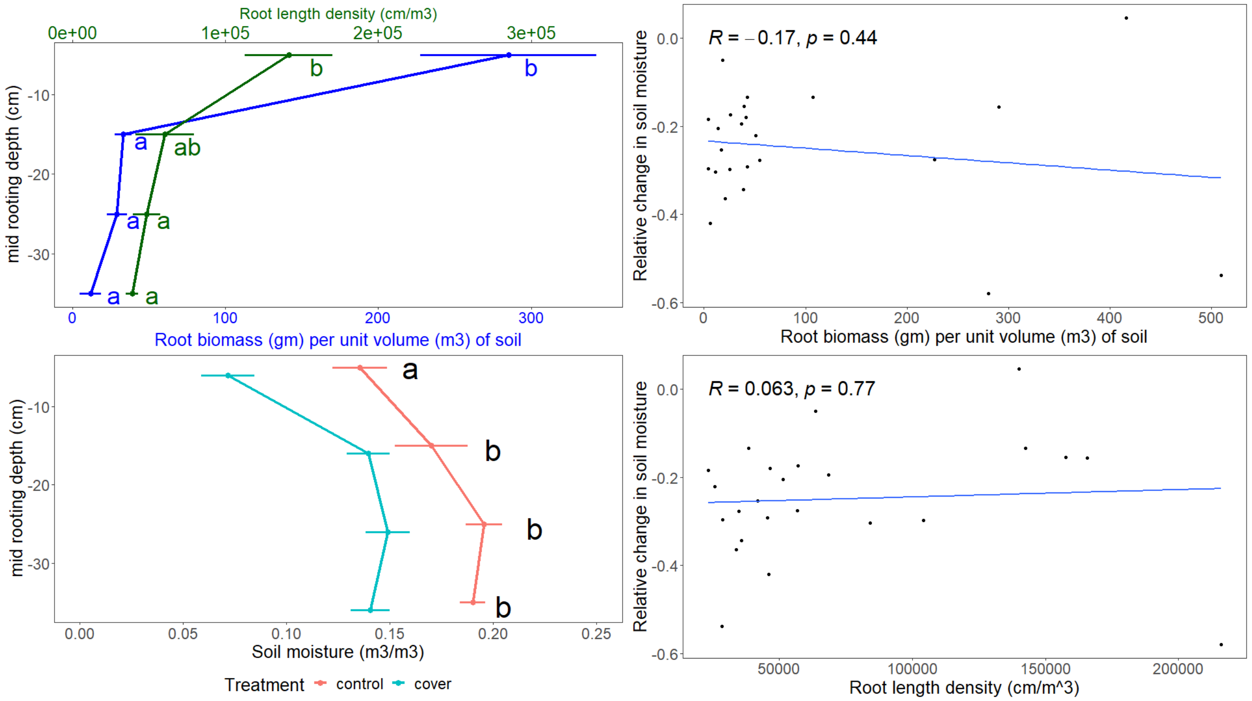

Figure 2.6. Root biomass (gm/m^3) and root length density (cm/m^3) across different depths (top left), correlation between root biomass (gm/m^3) and relative change in soil moisture between cover crop and control treatments (top right), soil water content (m^3/m^3) across different soil depths (0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm) (bottom left), and correlation between root length density (cm/m^3) and relative change in soil moisture between cover crop and control treatments (bottom right) in Farm 1.

Discussion

This participatory field-based experiment was conducted to assess the impact of cover cropping on soil moisture across four different farms in the Lower Rio Grande Valley (LRGV) region. The study was supplemented with a below ground assessment of cover crop rooting pattern along the vertical soil moisture profile in one of the farms to explore the intersection of cover crops and soil moisture availability throughout three different cropping seasons (Cover crops 1st year –

Cash crops 1st year – Cover crops 2nd year). The soil water content for each farm varied greatly throughout the year under cover crops and control treatments. Our study reveals that cover crops have a negative impact on soil moisture, and they decrease the soil water content during specific times of the year and cropping seasons. Contributing factors to this decline include soil texture, amount of precipitation received throughout the year, climatic region, and farm management practices. The principal among these contributing factors was precipitation. As expected, the difference between soil water content under cover crops and control was significantly higher (lower soil water content in cover crops compared to control) during drier seasons whereas, during second year cover cropping season when plenty rainfall was received, the difference became seemingly negligible in all farms. Kasper et al., (2022) also found that second year was more wet with ample precipitation as compared to the dryer first year; this resulted in negative impact of cover crops on soil moisture and consequently on sorghum germination and yield. This suggests that, although cover crops utilize the available soil water content for their own growth and development, the amount of rainfall received by the farms played a significant role in mitigating the negative impact of cover crops on soil water content.

We expected cover crops to exhibit lower soil water content in farms with sandy soil since soil texture with fine particles can hold more water compared to coarse soil (Rekwar et al., 2022). This prediction was supported by our data. Although the overall soil water content was indeed higher in two farms with finer soil texture (Farm 3 and 4), cover crop-induced soil water deficit was indeed more pronounced in Farm 3 (Clay loam soil type) and Farm 4 (Sandy clay loam soil type) particularly during the cover cropping season, with no significant impact during cash cropping season. Likewise, Wortman et al., (2012) reported the presence of water stress in cover crops during the growing season. While studies conducted in clay loam and silty clay loam soil type reported that soil water storage was significantly lower in cover crop treatment as compared to the fallow during the termination stage of cover crops (Gabriel et al., 2014; Mitchell et al., 1999), similar results have been reported by Kahimba et al., (2008) in sandy loam soil where berseem (*Trifolium alexandrium* L.) clover cover crop treatment was found to have 34.6% lower soil water content at 0-0.7 m depth as compared to oats only (*Avena sativa* L.). Despite soil texture determining the available soil moisture, sandy soils can often limit the soil water movement within the soil due to the formation of hardpans and impervious layers which, however, isn't always tied to the soil texture – hardpans from caliche layers can form irrespective of the overlaying soil texture. This could seriously limit the growth and development of roots of crops (Rekwar et al., 2022) as observed in Farms 1 and 2 in this experiment (M. Gautam, personal observation).

The cover crop-induced moisture deficit, therefore, should account for the inherent requirement of water for the root and shoot development of cover crops in addition to the transpiration losses resulting in reduced soil water content in the soil by the time of their termination (Sharma et al., 2017). For example, while Farms 3 and 4 had a greater cover crop density and biomass, Farm 1 did not have a good cover crop stand in the 1st year and cover crop rows in Farm 2 were spaced far apart which could have had a considerable influence on the water usage by cover crops thereby reducing the potential moisture deficit led by cover crops in sandy soil type in our experiment. It should be noted that the cultivation practices on each farm were carried out by the farmers which allowed non-uniform practices across the farms which could have influenced the variability in soil moisture values observed across different farms and along the soil profile. At the same time, the importance of timing and cover crops establishment became more obvious when the cover crops in a part of Farm 1 was terminated a month later than usual time; this almost led to the catastrophic failure of cash crops in terms of germination which was later mitigated to some extent by substantial amount of rainfall. Another similar study reported negligible soil moisture difference and no impact on cash crops after cover cropping even during drought conditions which was most likely due to poor crop growth and establishment during cover cropping season (Camarotto et al., 2018). Wang et al., (2021) also suggested an early termination of cover crops since increment in cover crop biomass can lead to higher extraction of available soil water and reduce the soil water storage for the succeeding cash crops. This highlights the need for careful consideration of the timing of cover crops planting and establishment when predicting their impact on soil water (Liebig et al., 2015; Reese et al., 2014; N. Xue et al., 2017). Kasper et al., (2022) highlighted a similar drastic effect of cover crop led soil moisture deficit on cash crop germination failure in the absence of enough rainfall during recharge period.

Given the primary importance of precipitation in determining the impact of cover crops on soil moisture, an important question is how much is required to offset the negative impacts. We observed that a certain amount of rainfall was able to mitigate the cover crop-induced soil moisture losses in all farms and there were no significant differences in soil water content between each treatment during cash cropping season in all farms. Based on visual assessment, Farm 1, 2, 3 and 4 required 10-20 mm, 20-30 mm, 30-40 mm, and 30-40 mm of rainfall respectively in order to offset the negative impacts of cover crops on soil moisture respectively (Figure 2.3), and a more quantitatively robust and in-depth study of this question will come later. Wang et al., (2021) suggested that precipitation during growing stage and recharge period after the termination of cover crops may assist in offsetting the soil moisture deficit in arid and semi-arid regions while even increasing the soil water storage in humid and sub-humid regions. Similarly, a study conducted by Sharma et al., (2017) reported a similar soil water storage for both cover crop and control treatment under substantial amount of rainfall and ultimately reduced the cover crop-induced soil moisture losses to some extent as well. Given these scenarios, we can deduce that limitation in the frequency and amount of precipitation during cover cropping season could lead to serious water stress in the subsequent cash cropping season, especially in water limited semi-arid regions (Liebig et al., 2015; Wortman et al., 2012).

Cover crops-induced moisture deficit varied considerably at different times of the year during cover cropping seasons at all farms in our study. During certain cover cropping events, depth had significant impact on the soil water content difference between two treatments. The differences in soil moisture between cover crops and control either decreased or increased along with increasing depth in most events suggesting that the impact of cover crops on soil moisture is highly variable with depth. The inconsistent impact of cover crops on soil water content along the soil profile could be due to their rooting distribution, cover crops species, density of cover crops, and other soil properties such as porosity and infiltration. From our assessment, we observed that that shallowest soil layer (7 cm) had the lowest soil water content in all farms with significantly higher water usage from the surface soil layer (0-10 cm) which gradually decreased up to 40 cm soil depth in our experiment. Our findings of highly concentrated root biomass and root length density in the topmost layer of the soil (0-10 cm) also suggests that root distribution is an integral factor in determining the impact of cover crops on soil water across vertical soil moisture profile (Figure 2.6). Xue et al., (2017) observed that control treatments (bare) had significantly higher water content at 0-20 cm soil depth before planting (8.9% - 47.06%) and harvesting the wheat cash crops (33%-51.47%) as compared to other legume cover crop treatments. Several other studies report the moisture losses led by cover crops in the topmost layer of the soil while there is almost non-significant effect on water content in deeper soil layers (Nielsen et al., 2015; Wortman et al., 2012). Bodner et al., (2007) surmised that cover crops uptake water up to an average depth of 60 cm while root concentration (biomass and root length density) was the highest in upper soil layers. Although we expected higher root biomass and root length density to significantly affect the soil moisture losses, we did not observe a significant relationship between the root length density and root biomass with relative change in soil moisture. This might be affected due to soil samples being collected in the dryer time of the year in sandy loam soil which could have highly influenced the cover crop growth both above and below the ground ultimately affecting the change in soil water content along the vertical soil moisture profile. Root hydraulic lift, in which deep roots of plants extract water from the deeper soil layer and bring it to the surface layer by exuding the water through shallow roots to upper dryer soil layer (Yao et al., 2023), could potentially explain the discrepancy in the variation of soil moisture across the soil profile in this study. It has been observed that cash crops like wheat and maize can go up to 1.4 m and 80 cm (Thidar et al., 2020; Xue et al., 2003) soil depth as well which gives such cash crops with deep roots to go beyond the cover cropping rooting depth and tap into the soil moisture for their growth and development. And yet another possibility is the wicking action of the surface layers pulling up soil moisture from the deeper, more moist layers. So even though the root water uptake is concentrated at the surface, the water moves down the water potential gradient (in the soil), which in this case, is upward, and can potentially equalize the soil moisture across the vertical moisture gradient (Kumar et al., 2019). Therefore, a proper assessment of cover crop rooting pattern is essential to accurately analyze the impact of cover crops on soil water content across the vertical soil moisture profile.

Cover crop root distribution is also dependent on the types of cover crops and suitability of the region and climate to support their growth and development. It has been found that cover crops led moisture deficit is dependent on the species of cover crops used as well; forage pea, triticale, and tillage radish incur greater water deficit compared to sun hemp, clover, and vetch (Kasper et al., 2022). Generally, cover crops with high biomass production also extract more water and nutrients from the soil (Khan & McVay, 2019) which varies according to the species of the cover crops. This might have been an imperative factor in our experiment in determining the role of cover crops in affecting soil water availability. Non-uniform farming practices, unique termination techniques and use of cover crop mixtures with different species could also influence the results obtained in this experiment. Nevertheless, although some species are expected to do better than the other, cover crop mixtures, however, are found to have similar water usage compared to single species (Khan & McVay, 2019; Nielsen et al., 2015). On the other hand, cover crop species do have differential impact on soil water based on the climatic region they are cultivated in since climatic factors such as rainfall and temperature are unpredictable and ever changing with climatic region and location. While some studies report cover crop growth resulting in moisture deficit in water limited regions like semi-arid and arid climatic regions (Bodner et al., 2007; Liebig et al., 2015; Reese et al., 2014), others suggest that cover crops enhance infiltration, and coverage of soil with the residue to reduce the evaporation thereby increasing the soil water storage under irrigated conditions and humid region (Sharma et al., 2017; Wang et al., 2021). Therefore, although cover crop benefits have been realized in terms of promoting overall soil health, it may seriously limit the crop productivity in water limited regions.

In our current study, we focused on cover crop-induced water deficit in South Texas, a semi-arid water limited region and found that cover crops may exacerbate moisture limitation in dryland farms. Future works should consider the crop species, methods of termination and timing of cover cropping to accurately assess the situation in our study. Given that rainfall has such a big role to play in this cover crop-soil water interaction, the role of precipitation must be thoroughly explored and evaluated in the future. It is evident that cover crops pose a threat to cash crop yield and production in dryland farming system, but it is also imperative to take into consideration for other benefits provided by the cover crops to enhance soil health and fertility, promoting biodiversity, and carbon sequestration. Further analysis of other factors such as evapotranspiration, and infiltration along with an expanded study for root assessment in all farms would be an advancement to this study.

Conclusion

This study conducted across multiple cropping seasons in south Texas confirms that cover crops induce soil moisture deficit in water limited faming systems of Lower Rio Grande Valley. The results from the current experiment suggest that cover crop-soil moisture relationship is greatly influenced by climatic conditions (temperature, precipitation), crop species, and farm management practices (tillage, timing of planting and termination, intercultural operations, irrigation). Therefore, these factors should be considered when assessing the suitability of cover crops, especially under dryland farming systems where water is a limiting factor for agricultural production. Although moisture limitations refrain farmers from adopting cover crops readily in south Texas, they may also provide soil health benefits, promote biodiversity, and suppress weed gradually over time which might outweigh the negative impact on soil moisture. While considering the feasibility of cover crops in such rainfed dryland farms of arid and semi-arid water deficient regions, it is also essential to consider the potentially high risk of cash crop failure associated with severe moisture limitation in the absence of adequate amount of rainfall. Future experiments should study soil water content up to the maximum depth for cover crops, quantify the amount of rainfall required to offset the negative impact of cover crops on soil moisture and assess the impact on cash crop yield to inform the farmers about the feasibility of adoption of cover crops in south Texas and other semi-arid water limited regions globally.

CHAPTER III

HOW DEEP DO COVER CROPS DEPLETE SOIL MOISTURE ACROSS DIFFERENT CLIMATIC REGIONS? A META-ANALYSIS – SHORT COMMUNICATION PAPER

Introduction

Cover cropping is globally recognized as a sustainable agricultural management practice which may enhance soil health (Ghimire et al., 2019). The studies on cover crops and their impact on soil abiotic and biotic variables have expanded considerably (Camarotto et al., 2018; Flood & Entz, 2019; Gabriel et al., 2019; Jian et al., 2020; Kasper et al., 2022; Ruis et al., 2018; Wegner et al., 2018; Wunsch et al., 2017). Previous studies suggest that cover crops, as compared to no cover crops (control), have a greater influence on soil physical and biological properties improving soil characteristics such as porosity, infiltration, bulk density, soil organic matters (Chalise et al., 2019; Gabriel et al., 2019; Kahimba et al., 2008; Soti et al., 2016; Sultani et al., 2007) while enhancing the microbial activity (García-González et al., 2016; P. G. Soti et al., 2016) at the same time. Moreover, the benefits of cover crops have been widely realized to enhance nutrient availability, particularly nitrogen (biological nitrogen fixation by legume cover crops) (Frasier et al., 2017; Plaza-Bonilla et al., 2017; Wang et al., 2019; Xue et al., 2017). Another potential benefit of cover crops is to increase labile soil organic carbon, albeit a slower process (Chalise et al., 2019; Duval et al., 2016; Fageria et al., 2005; Jian et al., 2020;

Návar, 2008; Zhou et al., 2012), which is important for carbon sequestration and thus climate regulation (Kaye & Quemada, 2017; Muhammad et al., 2019). The impact of cover crops on soil variables have been studied as a function myriad of factors such as cover crop species, root distribution, soil texture, climatic regions, precipitation, and management practices (residue management, fertilization, irrigation, tillage, mulching) (Jian et al., 2020; Kaye & Quemada, 2017; Thidar et al., 2020). Under the influence of these several factors, the impact of cover crops on soil moisture, however, has been unable to be clearly distinguished, thereby rendering the farmers in dilemma about cover crops adoption.

Most of the studies reported that cover crops decrease soil moisture (Sharma et al., 2017; Wortman et al., 2012) whereas others suggested that cover crops might have positive or no negative impact on soil moisture (Joyce et al., 2002). Wang et al., (2021) observed a context dependent cover crop impact in different regions and cover crops were able to increase the water use efficiency with a negligible impact on the subsequent cash crop yield. Additionally, Wang et al., (2021) also stated that cover crops showed a varying degree of effect on soil moisture at different soil depth: soil water storage decreased by 13.2% for the entire soil profile while water storage increased at a depth of 30 cm by 6% as compared to no cover crop. Likewise, at a depth of 55 cm, similar moisture levels were reported for cover crop and control treatments and throughout the monitoring period (Camarotto et al., 2018) resulting in a negligible impact of cover crops on soil moisture. This shows that the cover crops can have non-uniform impact on soil moisture at different soil depths. However, although numerous studies have focused on soil moisture dynamics and tested different variables, soil depth, as a factor in cover cropping system hasn’t been fully understood yet. The cover crop-soil moisture dynamics along the vertical soil moisture profile is crucial to accurately understand the depth up to which cover crops have a significant impact on soil moisture; if the cash crops can tap into the soil moisture untouched by the cover crops, cover cropping system could be exploited for greater benefits without needing to worry about their negative impacts on the soil moisture availability. It is, therefore, plausible to consider soil depth and climatic regions as crucial factors which could significantly affect the soil moisture dynamics in cover cropping system.

The rooting depth of both cover crops and cash crops can also affect the root biomass engaged in absorption of soil moisture at different levels of soil depth which are further affected by soil properties, and climatic conditions (Benjamin & Nielsen, 2006; Halli et al., 2021). The method of planting, size of furrow, and soil type can have great influence on the root architecture and rooting distribution of plants. For example, (Halli et al., 2021) observed that greater number of brace roots might have been induced due to deeper and loose soil around the maize plants under different irrigation treatments. Another aspect to consider is the penetration of soil layers by the roots; water deficit condition can induce roots to be confined in wetter areas of the soi while ample soil moisture promotes root growth and development in the soil (Benjamin & Nielsen, 2006). Past literatures in this field show that cover crops are more likely to steal the soil moisture from upper layers of the soil (Kahimba et al., 2008; Wang et al., 2021). However, there always lies the potential for the cover crops to go deeper and steal the soil moisture from deeper layers as well which are in fact the most crucial reservoir of soil moisture for the subsequent cash crops. Moreover, under drought conditions, it has been observed that phenomena such as root hydraulic lift and wicking action could result into root hairs moving water from deeper wet soil depth to upper dryer soil layers thereby reversing the usual flow of water from upper layers deeper into the soil (Yao et al., 2023). Hence, understanding the soil water distribution along the soil profile and how rooting pattern of crops affect these dynamics, is essential to accurately unravel the potential impacts of cover crops on soil moisture.

Wang et al., (2021), in his meta-analysis, reported the impact of cover crops on precipitation storage efficiency (PSE), soil water storage at succeeding crop planting (SWSP), yield of succeeding crops, evapotranspiration, and water use efficiency under various soil and climatic conditions. Cover crop-soil moisture dynamics along the soil depth profile, however, haven’t been considered as imperative as other factors influencing the soil moisture under cover cropping system. We, therefore, conducted a meta-analysis of data published in literatures relating cover crops impact on soil moisture at different soil depths for four main climatic regions and intend to build upon the previous meta-analysis of Wang et al., (2021). We hypothesized that the negative impact of cover crops on soil moisture would decrease along the soil depth and the cover crop-induced moisture deficit would be most pronounced with increasing aridity. Another important question we asked is: At what depth the effect of cover crops disappears, an important question for farmers particularly in semi-arid regions who are ambivalent about adoption of cover crops.

Materials and methods

Data collection

Current study was built upon the studies referred by Wang et al., (2021) and 117 studies from 99 publications were used initially as the starting database for the data collection to answer our questions. Out of those studies, a total of 53 publications from arid/semi-arid regions and 21 publications from humid/sub-humid regions were picked out for further steps. Additional literature was searched using Google Scholar to increase the pool of studies for humid/sub-humid regions. The keywords used in the search included cover crops, soil moisture, humid, sub-humid, and different depths. The search left us with 15 additional papers for humid/sub-humid regions and all the publications from arid/semi-arid regions and humid/sub-humid regions were subjected to screening before data analysis. The individual studies were further subjected to screening based on following criteria:

i. Field based experiment that included cover cropping system and reported soil moisture data in different metrics (soil water content, soil volumetric content, available soil moisture) along with associated management practices (fertilization, tillage, residue management).
ii. Data included the comparison of cover crops vs. no cover crops (fallow) and their impact on soil moisture at different soil depth.
iii. Studies classified into different climatic regions (humid, sub-humid, arid, and semi-arid) and conducted in field conditions.

After screening the studies based on these criteria and excluding the studies in mandarin and those not able to be utilized for data extraction, we were left with 41 literatures from arid/semi-arid regions and 31 literatures from humid/sub-humid regions. Different soil parameters relating to soil moisture such as soil available water, volumetric water content, soil water content, soil water storage, and soil water in response to cover crops and no cover crops were extracted using Web Plot Digitizer Version 4.6 (https://automeris.io/WebPlotDigitizer).

The climatic regions for most of the studies were classified into arid, semi-arid, humid, and sub-humid (Wang et al., 2021); other studies, on the other hand, explicitly mentioned the climatic zones the experiments were conducted in. There were several soil parameters extracted from the studies which were converted into standardized soil parameters for analysis of the data.

The references used to extract data for this study are available as supplementary information (Supplemental Table S3.1 and Supplemental Table S3.2).

Table 3.1. Different soil parameters obtained from the individual studies.

Soil parameters
Available soil water (mm)
Available water (cm)
Plant available water (mm)
Residual soil water content (cm3/cm3)
Soil available water (mm)
Soil moisture (%)
Soil moisture content (m3/m3 * 100)
Soil moisture (m3/m3)
Soil relative water content (%)
Soil water % (w/w)
Soil water balance (mm)

Table 3.1, cont.

Soil water content (%)
Soil water content (cm)
Soil water content (g/g)
Soil water content (m3/m3)
Soil water content (mm)
Soil water content (mm/cm3)
Soil water depletion (mm)
Soil water retention Ɵv (cm3/cm3)
Soil water storage (cm)
Soil water storage (mm)
Soil water (kg/kg)
Unfrozen (TDR) water content (m3/m3)
Volume water fraction Ɵv (cm3/cm3)
Volumetric soil moisture content (vol/vol %)
Volumetric soil water content (cm3/cm3)
Volumetric soil water content (m3/m3)
Volumetric water content (%)

Data analysis

The standardized soil parameter with different units of measurement were further converted to general standards of soil moisture measurements with similar units. The irregular units were made uniform by converting the soil moisture parameters such as plant available water (mm, cm), soil water (mm, cm), volumetric soil water (mm/cm^3, %, cm^3/cm^3), and gravimetric soil water (%, g/g) into a standardized volumetric water content (cm^3/cm^3) by first converting those units in to cm and then dividing them by depth interval in cm by using R version 4.2.2 (R Core Team, 2022).

Log response ratio (LRR) (Hedges et al., 1999) was calculated for each climatic region (arid, semi-arid, humid, and sub-humid regions) as:

Log response ratio: $log\frac{soil\ moisture\ in\ cover\ crop}{soil\ moisture\ in\ control}$

The LRR was plotted along the soil depth to observe the impact of cover crop on the vertical soil moisture profile in different climatic regions.

Results

The soil moisture curves for majority of the individual studies demonstrated the cover crop-induced soil moisture losses whereas few of them also showed positive impact of cover crops on soil moisture (Figure S3.1). This depicted that the cover crop-soil moisture dynamics is highly context dependent and influenced by climatic variability of the region. LRR for each climatic zone revealed that cover crop-induced soil moisture losses are more pronounced in arid and semi-arid regions as compared to humid and sub-humid regions (Figure 3.1).

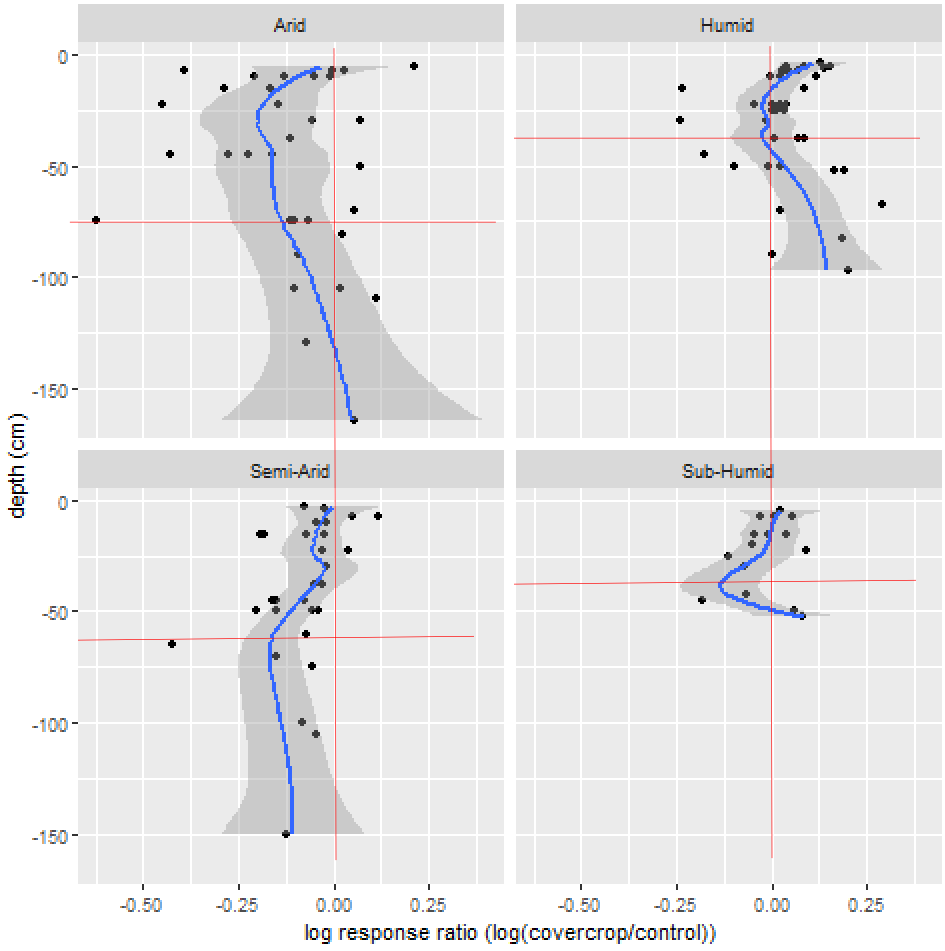

Figure 3.1. Log response ratio (LRR) for each climatic region (Arid, semi-arid, humid, and sub-humid). The vertical red lines represent the breakeven line, data points on its right represent that soil moisture values under cover crops were greater than control and data points on its left represent that soil moisture values under cover crops were less than control. The horizontal lines were drawn to determine the depth where cover crops impact on soil moisture starts to disappear.

However, the impact of cover crops on soil moisture seems to be decreasing along the vertical soil moisture profile in all climatic regions. It was also observed that the cover crop-induced soil moisture losses were mostly prominent in the to a depth of ~ 85 - 95 cm in arid and semi-arid climatic regions whereas there were no evident soil moisture losses due to cover crops throughout the soil profile in humid/sub-humid region (Figure 3.2). On the contrary, in humid/sub-humid region, the cover crops may have positive effect on soil moisture beyond a depth of 50 cm. These results suggested that the negative impacts of cover crops might disappear beyond this critical soil moisture zone along the soil profile leaving an opportunity for the cash crops to tap into the soil moisture beyond the zone of influence of cover crops.

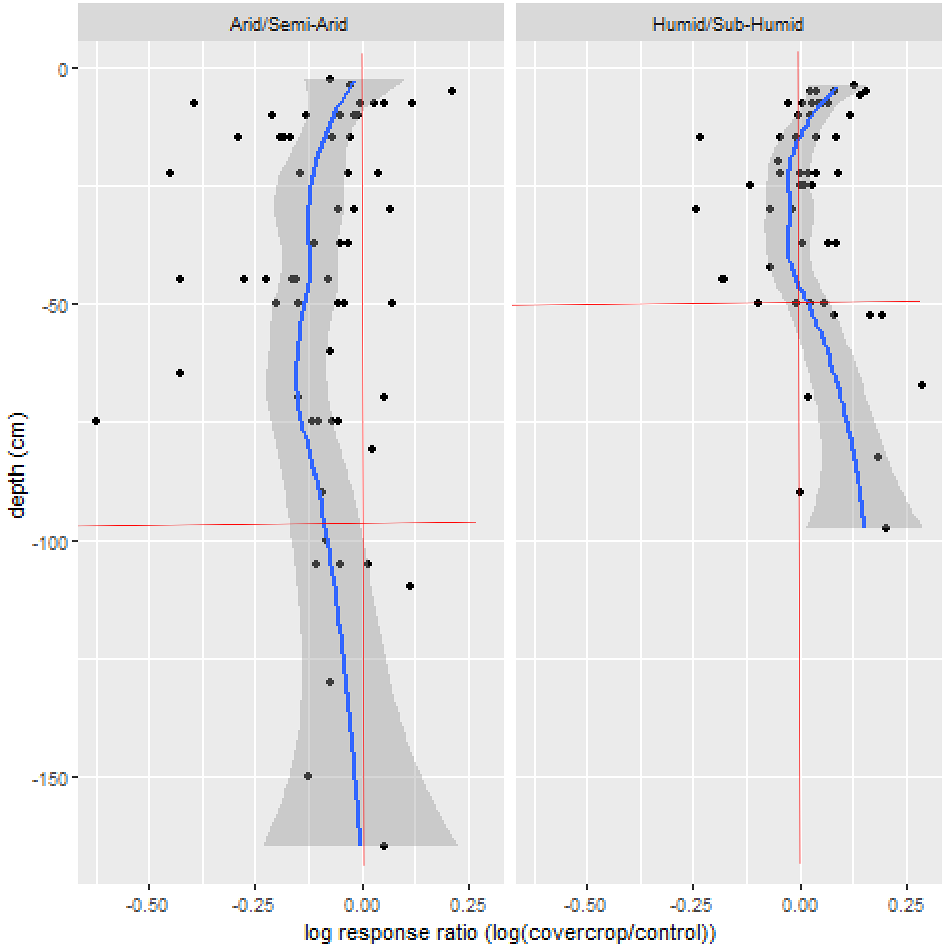

Figure 3.2. Log response ratio for combined arid/semi-arid and the humid/sub-humid climatic regions. The vertical red lines represent the breakeven line, data points on its right represent that soil moisture values under cover crops were greater than control and data points on its left

represent that soil moisture values under cover crops were less than control. The horizontal lines were drawn to determine the depth where cover crops impact on soil moisture starts to disappear.

Discussion

We hypothesized that cover crops impact on soil moisture would vary along with soil depth profile under the influence of changing aridity/climatic regions. As expected, cover crop-induced soil moisture losses were reported by most of the studies while a few reported positive consequences of cover crops on soil moisture as well. Additionally, the results from current study revealed that the negative effect of cover crops on soil moisture decreases along the soil depth profile in all climatic regions. In arid regions, the cover crops-induced moisture deficit was greater and persisted much deeper as compared to other regions. We speculated that, at certain soil depth, the cover crop-induced soil moisture losses would start to diminish. In line with this hypothesis, current study revealed that the cover crop-induced soil moisture losses were mostly pronounced up to ~85 - 95 cm soil depth in arid and semi-arid climatic regions while cover crops may have positive impact on soil water along the vertical soil moisture profile beyond a depth of 50 cm in humid/sub-humid region. This would, therefore, provide an opportunity for the cash crops in the subsequent cropping season to tap into the soil moisture at those depths where cover crops have relatively weaker influence upon the soil moisture.

The impact of cover crops on soil moisture is largely attributed to the rooting zone of the cover crops. Wang et al., (2021) reported a slight decrease in water content upto 45 cm soil depth when corn was sown, but observed that the soil water content increased significantly in the deeper soil layers in cover cropped areas under different nitrogen application. Furthermore, multiple studies assert that cover crop-soil moisture dynamic is highly context dependent relying on myriad of factors such as the amount of precipitation during cover crop growing period, aridity of the cultivating region (arid, semi-arid, humid, and sub-humid), soil textures, retention of residues, and soil depth (Wang et al., 2021). Soil depth, however, has gone unnoticed in several studies as one of the principal drivers of the cover crop-soil moisture dynamics. It has been reported that the root length density of cover crops may differ depending upon species (Khan & McVay, 2019) making each cover crops species restricted to the water content available up to a specific soil depth only (Bodner et al., 2007). Burgess et al., (2014) reported a disproportionate soil water extraction at a similar soil depth between pea and lentil when used as cover crops indicating that rooting system of cover crops along the soil depth profile indeed plays a vital role in determining the effect of cover crops on soil moisture. At the same time, Bodner et al., (2007) also suggested that cover crops, under water stress, may show increase in root density at deeper soil layers for better access to soil water. In another study conducted by (Benjamin & Nielsen, 2006), it was reported that roots of soybean, cowpea, and field pea grew by greater proportion to deeper soil layers under water deficit conditions; in contrast, they grew normally up to 23 cm soil depth under irrigated condition. Soil water depletion due to cover crop-induced soil moisture losses is therefore not only interrelated with root density along the soil layer, but also with the amount of precipitation received by the region based on aridity (arid, semi-arid, humid, and sub-humid). Since cover crops with shallow roots deplete the soil moisture at upper soil layers (Benjamin & Nielsen, 2006; Khan & McVay, 2019), adopting cover crops with shallow root system would restrict the soil moisture depletion at upper soil layers, thereby making soil moisture easily accessible to the subsequent cash crops with deeper rooting system.

Cash crops such as sorghum, sunflowers, wheat possess the ability to go beyond the rooting zone of cover crops up to a depth of 1.85 m, 2.49 m (Stone et al., 2001), 1.4 m (Xue et al., 2003) while maize have majority of their rooting density concentrated on the upper 30 cm depth of the soil layer. Cash crops with deep root systems are bound to tap into the deeper soil moisture unaffected by the cover crops in their preceding cropping season. However, during water stressed conditions, the increasing aridity render the crops unable to penetrate the soil layers and prevent substantial access to the soil moisture at deeper soil layer (Moroke et al., 2011; Stone et al., 2001). Bodner et al., (2007) highlighted that the amount of precipitation is extremely important in determining the soil water storage at deeper layers, particularly in dryer climatic regions, thereby suggesting the need to select the cover crops and cash crops based on their rooting system and water use efficiency (Moroke et al., 2011). The differential ability of the cash crops and cover crops, therefore, necessitates an assessment of crop specific root distribution along the vertical soil moisture profile of both cash crops and cover crops to get a better assessment of the water use efficiency of these crops in different climatic regions. Considering the water use efficiency coupled with suitable rooting system for specific climatic regions and adoption of management practices such as irrigation, residue management, and termination of cover crops would allow the farmers to minimize the cover crops induced soil moisture losses and adopt cover cropping system as a sustainable agricultural management practice.

Current study depicts a pronounced cover crop-induced soil moisture losses along the soil profile in arid and semi-arid regions as compared to humid and sub-humid climatic zones, possibly due to available soil water content for the crops, which could potentially have a profound impact on the subsequent cash crops. Assessment of cover crop-soil moisture dynamics coupled with root distribution along the soil profile in different climatic regions could be the potential way forward in unraveling the dilemma regarding the adoption of cover crop in arid and semi-arid regions. Moreover, should these cover crops and cash crops be selected based on their root distribution and water use efficiency, it is certainly possible to minimize the cover crops induced soil moisture depletion, thereby reducing the potential negative impacts of cover crops on available soil water. This requires a rigorous study of root distribution of several cover crops as well as cash crops species and selection of suitable crops based on climatic variability, precipitation, soil texture, and other factors correlated with cover crop-soil moisture dynamics. Future studies should incorporate spatiotemporal adoption of cover crop mixtures followed by cash crops with varying rooting depth which could help us infer the ability of the cash crops in accessing the soil moisture at deeper soil layers in different climatic regions.

Conclusion

In conclusion, the impact of cover crops on soil moisture varies along the soil depth profile and dependent on the aridity of the region of cultivation. Based on the amount of precipitation and climatic variability, the cover crops-induced soil moisture losses are confined to a certain depth into the soil and may confer an opportunity for the cash crops to tap into the soil moisture at a greater soil depth. If appropriate consideration is given to the factors that drive the cover crop-soil moisture dynamics such as cover crop species, timing of termination, management practices (irrigation, residue management, tillage), and soil properties, the adoption of cover crops could certainly lead to sustainable management of agriculture.

Supplemental information

Table S3.1. References used for meta-analysis of cover crop impact on vertical distribution of soil moisture in arid and semi-arid regions globally.

Author	Article title	Climatic region
(Khan & McVay, 2019)	Productivity and Stability of Multi-Species Cover Crop Mixtures in the Northern Great Plains	Arid
(Gabriel et al., 2019)	Assessing the cover crop effect on soil hydraulic properties by inverse modelling in a 10-year field trial	Arid
(Flood & Entz, 2019)	Effects of a fall rye cover crop on weeds and productivity of Phaseolus beans	Semi-Arid
(Chalise et al., 2019)	Cover Crops and Returning Residue Impact on Soil Organic Carbon, Bulk Density, Penetration Resistance, Water Retention, Infiltration, and Soybean Yield	Semi-Arid
(Xue et al., 2017)	Effects of green manures during fallow on moisture and nutrients of soil and winter wheat yield on the Loss Plateau of China	Arid
(Ruis et al., 2018)	Impacts of Early- and Late-Terminated Cover Crops on Gas Fluxes	Semi-Arid
(Krstić et al., 2018)	The Effect of Cover Crops on Soil Water Balance in Rain-Fed Conditions	Semi-Arid

Table S3.1, cont.

(Camarotto et al., 2018)	Conservation agriculture and cover crop practices to regulate water, carbon and nitrogen cycles in the low-lying Venetian plain"	Semi-Arid
(Barker et al., 2018)	Cover Crops have Negligible Impact on Soil Water in Nebraska Maize–Soybean Rotation	Semi-Arid
(Plaza-Bonilla et al., 2017)	Innovative cropping systems to reduce N inputs and maintain wheat yields by inserting grain legumes and cover crops in southwestern France	Semi-Arid
(Frasier et al., 2017)	Vetch-rye biculture is a sustainable alternative for enhanced nitrogen availability and low leaching losses in a no-till cover crop system	Semi-Arid
(Zhang et al., 2016)	Soil Water Balance and Water Use Efficiency of Dryland Wheat in Different Precipitation Years in Response to Green Manure Approach	Semi-Arid
(Mooleki et al., 2016)	Effect of green manure crops, termination method, stubble crops and fallow on soil water, available N and exchangeable P	Arid
(Duval et al., 2016)	Winter cover crops in soybean monoculture: Effects on soil organic carbon and its fractions	Semi-Arid
(Nielsen et al., 2015)	Cover Crop Mixtures Do Not Use Water Differently than Single-Species Plantings	Arid

Table S3.1, cont.

(Liebig et al., 2015)	Short-Term Soil Responses to Late-Seeded Cover Crops in a Semi-Arid Environment	Semi-Arid
(Azevedo et al., 1999)	The effect of cover crop and crop rotation on soil water storage and on sorghum yield	Semi-Arid
(Power et al., 1991)	Hairy Vetch as a Winter Cover Crop for Dryland Corn Production	Semi-Arid
(Whish et al., 2009)	Do spring cover crops rob water and so reduce wheat yields in the northern grain zone of eastern Australia?	Arid
(Wunsch et al., 2017)	Can legumes provide greater benefits than millet as a spring cover crop in southern Queensland farming systems?	Semi-Arid
(Brandt, 1996)	Alternatives to summer fallow and subsequent wheat and barley yield on a Dark Brown soil	Semi-Arid
(Sharma et al., 2017)	Soil-Water Dynamics, Evapotranspiration, and Crop Coefficients of Cover-Crop Mixtures in Seed Maize Cover-Crop Rotation Fields. I: Soil-Water Dynamics and Evapotranspiration	Semi-Arid
(Restovich et al., 2012)	Introduction of cover crops in a maize–soybean rotation of the Humid Pampas: Effect on nitrogen and water dynamics	Semi-Arid
(Currie & Klocke, 2005)	Impact of a terminated wheat cover crop in irrigated corn on atrazine rates and water use efficiency	Arid

Table S3.1, cont.

(Alonso-Ayuso et al., 2018)	Weed density and diversity in a long-term cover crop experiment background	Arid
(García-González et al., 2016)	Arbuscular mycorrhizal fungal activity responses to winter cover crops in a sunflower and maize cropping system	Arid
(Wortman et al., 2012)	Optimizing Cover Crop Benefits with Diverse Mixtures and an Alternative Termination Method	Semi-Arid
(Sultani et al., 2007)	Evaluation of soil physical properties as influenced by various green manuring legumes and phosphorus fertilization under rain fed conditions	Semi-Arid
(M. M. Williams et al., 2000)	No-tillage soybean performance in cover crops for weed management in the western Corn Belt	Semi-Arid
(Zhou et al., 2012)	The short-term cover crops increase soil labile organic carbon in southeastern Australia	Arid
(Ghimire et al., 2019)	Soil Health Response of Cover Crops in Winter Wheat–Fallow System	Arid
(Nielsen et al., 2016)	Cover Crop Effect on Subsequent Wheat Yield in the Central Great Plains	Arid
(Krueger et al., 2010)	Growth Stage at Harvest of a Winter Rye Cover Crop Influences Soil Moisture and Nitrogen	Semi-Arid

Table S3.2. References used for meta-analysis of cover crop impact on vertical distribution of soil moisture in humid and sub-humid regions globally.

Authors	Publication	Climatic type
(Rankoth et al., 2019)	Cover Crop Effects on Corn Plant Sap Flow Rates and Soil Water Dynamics	Humid
(Wang et al., 2019)	Subsequent nitrogen utilisation and soil water distribution as affected by forage radish cover crop and nitrogen fertiliser in a corn silage production system	Humid
(Wells et al., 2014)	Cultural Strategies for Managing Weeds and Soil Moisture in Cover Crop Based No-Till Soybean Production	Humid
(Wells et al., 2016)	Planting Date Impacts on Soil Water Management, Plant Growth, and Weeds in Cover-Crop-Based No-Till Corn Production	Humid
(Martinez-Feria et al., 2016)	Rye cover crop effects on maize: A system-level analysis	Sub-humid
(Basche et al., 2016)	Soil water improvements with the long-term use of a winter rye cover crop. Agricultural Water Management	Sub-humid
(Mitchell et al., 2015)	Trade-offs between winter cover crop production and soil water depletion in the San Joaquin Valley, California	Sub-humid
(Daigh et al., 2014)	Soil water during the drought of 2012 as affected by rye cover crops in fields in Iowa and Indiana	Sub-humid

Table S3.2, cont.

(Qi & Helmers, 2010)	Soil Water Dynamics under Winter Rye Cover Crop in Central Iowa	Sub-humid
(Krueger et al., 2010)	Growth Stage at Harvest of a Winter Rye Cover Crop Influences Soil Moisture and Nitrogen	Humid
(Odhiambo & Bomke, 2007)	Cover crop effects on spring soil water content and the implications for cover crop management in south coastal British Columbia	Humid
(Clark et al., 2007)	Effects of a Grass-Selective Herbicide in a Vetch-Rye Cover Crop System on Corn Grain Yield and Soil Moisture	Humid
(Stipešević & Kladivko, 2005)	Effects of winter wheat cover crop desiccation times on soil moisture, temperature and early maize growth	Humid
(Williams & Weil, 2001)	Crop Cover Root Channels May Alleviate Soil Compaction Effects on Soybean Crop	Humid
(Wagner-Riddle et al., 1994)	Rye cover crop management impact on soil water content, soil temperature and soybean growth	Humid
(Ewing et al., 1991)	Tillage and Cover Crop Management Effects on Soil Water and Corn Yield	Humid
(Corak et al., 1991)	Legume Mulch and Nitrogen Fertilizer Effects on Soil Water and Corn Production	Humid
(Sanders et al., 2018)	Water Use Efficiency in Living Mulch and Annual Cover Crop Corn Production Systems	Humid

Table S3.2, cont.

(Silva, 2014)	Screening Five Fall-Sown Cover Crops for Use in Organic No-Till Crop Production in the Upper Midwest	Humid
(Acharya et al., 2019)	Winter cover crops effect on soil moisture and soybean growth and yield under different tillage systems	Humid
(Nouri et al., 2019)	Thirty-four years of no-tillage and cover crops improve soil quality and increase cotton yield in Alfisols, Southeastern USA	Sub-humid
(Alfonso et al., 2020)	Water productivity in soybean following a cover crop in a humid environment	Humid
(Caspari et al., 1997)	Cover crop management in vineyards to enhance deficit irrigation in a humid climate	Humid
(Payero et al., 2021)	Effect of Rye and Mix Cover Crops on Soil Water and Cotton Yield in a Humid Environment	Humid
(Hatch et al., 2011)	Cover Crop, Rootstock, and Root Restriction Regulate Vegetative Growth of Cabernet Sauvignon in a Humid Environment	Humid
(Karuku et al., 2014)	EFFECT OF DIFFERENT COVER CROP RESIDUE MANAGEMENT PRACTICES ON SOIL MOISTURE CONTENT UNDER A TOMATO CROP (Lycopersicon esculentum)	Sub-humid
(Barker et al., 2018)	Cover Crops have Negligible Impact on Soil Water in Nebraska Maize–Soybean Rotation	Sub-humid

Table S3.2, cont.

(Camarotto et al., 2018)	Conservation agriculture and cover crop practices to regulate water, carbon and nitrogen cycles in the low-lying Venetian plain	Sub-humid
(Yang et al., 2019)	Long-term effect of cover crop on rainwater balance components and use efficiency in the no-tilled and rainfed corn and soybean rotation system	Humid
(Leuthold et al., 2021)	Cover crops decrease maize yield variability in sloping landscapes through increased water during reproductive stages	Sub-humid

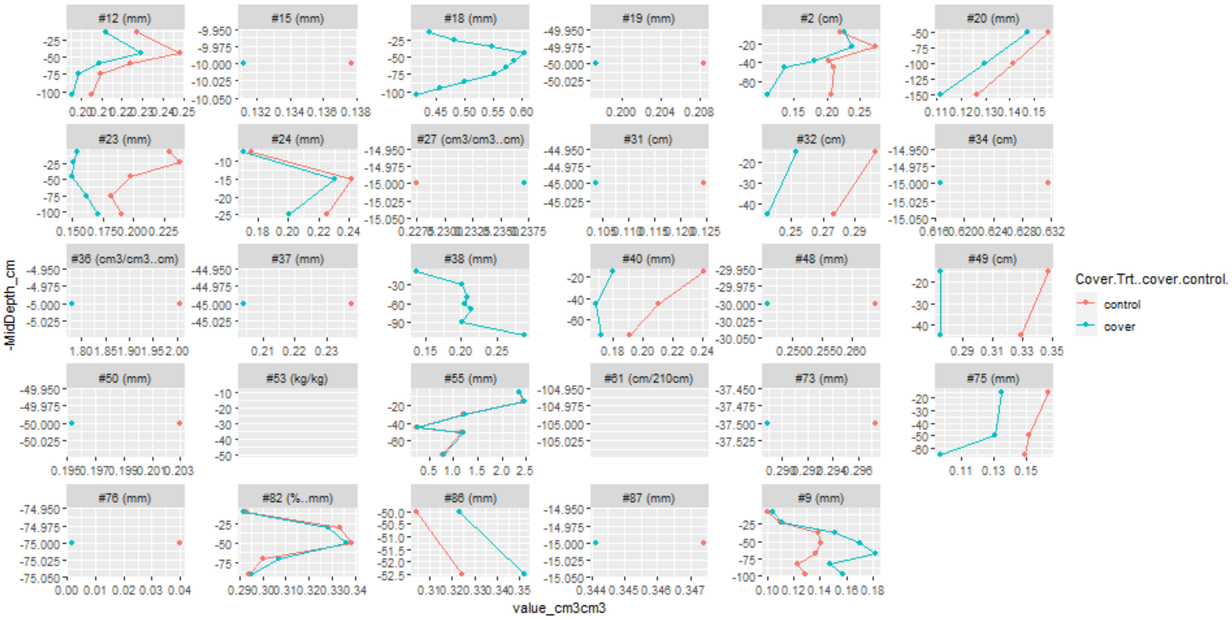

Figure S1. Soil water content (cm^3/cm^3) under cover crops and control treatment in individual studies at different depths.

CHAPTER IV

CONCLUSIONS

We investigated the impacts of cover crops on soil moisture in the Lower Rio Grande Valley (LRGV), a region characterized by semiarid conditions and limited water resources. Our study encompassed field experiments conducted on four different farms in the LRGV, as well as a comprehensive meta-analysis examining the effects of cover crops on soil moisture dynamics at various depths in different climatic regions worldwide. By addressing these objectives, we aimed to determine the suitability and potential impacts of cover crops on soil moisture on a local and global scale.

Based on the findings from our field experiments, it is evident that cover crops indeed reduce the soil water content in dryland farms, especially during cover cropping seasons. These impacts may vary depending upon the amount and frequency of rainfall which could potentially offset the negative impact of cover crops on soil moisture. Additionally, our meta-analysis confirmed the results obtained from our field experiment about the negative impact of cover crops on soil moisture in arid and semi-arid regions. We also found that cover crops may cease to steal moisture after a certain depth which also provides an opportunity for the cash crops to go beyond the cover cropping root depth to utilize the available soil water. Although it has been established that rooting distribution plays a significant role in governing the soil moisture dynamics in different climatic regions, not many studies have attempted to explore the below ground aspects of cover cropping systems.

Moreover, studies have been confined to a particular climatic region and one way or another failed to integrate all the factors (precipitation, soil type, soil depth, crop species, management practices) to study the impact of cover crops on soil moisture. Cover crop benefits have been widely realized to promote soil health in the long term but the short terms of negative impact on soil moisture should also be equally emphasized to accurately disseminate information about potential risks to the farmers. While cover crops may do better in humid and sub-humid regions, they may exacerbate the moisture limitations in arid/semi-arid water limited regions cush as south Texas. There is a need to study and optimize cover cropping systems suitable for each region based on the factors which contribute to drive the cover crop-soil moisture dynamics.

While our study provides valuable insights into the impacts of cover crops on soil moisture in the LRGV, there are still certain knowledge gaps that require further investigation. Future research should focus on assessing the long-term effects of cover crops on soil moisture dynamics, evaluating the economic feasibility of cover crop integration, and exploring the potential interactions between cover crops and other management practices, such as irrigation systems. Similarly, with how uneven rainfall events are, it is also imperative to assess what amount of rainfall is required to mitigate the impacts of cover crops on soil moisture. In the face of climate change and global warming, adopting cover crops in dryland farms could be a challenge which can lead to catastrophic losses of agricultural production in south Texas and worldwide if not managed wisely. Therefore, it is of utmost importance to determine whether cover crops are water wise in such water limited regions, although they may provide other long terms benefits in the future.

In conclusion, our study highlights that cover cropping should be further studied to confirm its suitability in the Lower Rio Grande Valley and other semi-arid regions worldwide. The short-term water deficit may be outweighed by other benefits in the long term; however, the farmers who wish to adopt the cover cropping systems should be incentivized by the government in such cases enabling them to bear any potential losses incurred due to moisture limitations. To surmise, the current field experiments and the meta-analysis inform about the suitability of cover crops as a sustainable agricultural management strategy in arid and semiarid regions. The findings from this research contribute to the growing body of knowledge on cover crop utilization and provide valuable insights for farmers, policymakers, and researchers interested in optimizing water resources and fostering agricultural sustainability in water-limited environments on a local ang global scale.

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BIOGRAPHICAL SKETCH

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