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Soil Carbon Sequestration Efforts in Arid and Semi-Arid Climates Under Conservation Agriculture and Reforestation

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SOIL CARBON SEQUESTRATION EFFORTS IN ARID AND SEMI-ARID CLIMATES UNDER CONSERVATION AGRICULTURE AND REFORESTATION

A Thesis

by

SAMANTHA LYNN COLUNGA

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May 2024

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ABSTRACT

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Soil organic carbon (SOC) plays a vital role in the global carbon cycle and aids in climate change mitigation. However, deforestation and intensive agricultural practices threaten topsoil and carbon (C) pools through soil disturbances releasing vast amounts of carbon dioxide (CO_2) by enhancing the decomposition of organic materials. Degraded soils typically lack stable aggregates, nutrient and water retention, and overall low fertility. In arid and semi-arid regions, soils are in an even more dire situation, as low precipitation and high temperatures slow down the accumulation of SOC. This thesis has two objectives: 1) to evaluate whether conservation tillage practices increase C accumulation in sandy soils of arid and semi-arid climates through a global meta-analysis approach and 2) to quantify C accumulation rates in reforested subtropical thorn woodlands through the use of three chronosequence sites spanning from 4 to 36 years. For objective 1, our results support the significant increase of SOC by 9% in sandy soils of arid and semi-arid climates in 10 years after converting to conservation tillage practices. For objective 2, reforestation of abandoned croplands resulted in a significant increase of SOC by approximately 20% in 10 years after reforestation, although rates vary based on previous land use. These results underscore the potential of targeted soil management practices to significantly enhance SOC storage, this providing crucial insights for soil conservation and restoration.

DEDICATION

The completion of my thesis would not have been possible without the love and support of my family and God. To my mom, who continuously inspired and motivated me to continue my education and was always by my side through my trials and triumphs. To the rest of my family and God, for the continuous love, strength, and support throughout this journey. Words cannot express my love and gratitude for you all.

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CHAPTER I

INTRODUCTION

Soil Carbon and Edaphoclimatic Challenges

Soil, an essential and finite natural resource, plays a vital role in nutrient cycling of carbon (C) and nitrogen (N) to support diverse ecosystem functions (Bach et al., 2020; Usharani et al., 2019). Soils serve as the largest terrestrial C reservoir, storing approximately 1,550 Pg SOC out of 2,500 Pg C, which exceeds the combined total of 1,360 Pg C found in plants, animals, and the atmosphere (FAO & ITPS, 2015; Gougoulias et al., 2014; Ontl & Schulte, 2012). The capacity of soil to sustain above- and below- ground biomass, facilitate nutrient cycling, retain moisture, sequester C, and support microorganisms depends on soil organic matter (SOM) and soil organic C (SOC) content (Usharani et al., 2019; Wiesmeier et al., 2019). Both SOM and SOC play a crucial role in enhancing soil fertility, improving soil structure, reducing erosion, and mitigating climate change (Lorenz et al., 2019; Obalum et al., 2017). Key factors influencing SOM and SOC levels include climate, soil properties, and anthropogenic activities (Gelybó et al., 2018**;** Wiesmeier et al., 2019; Xue & An, 2018).

Identifying a specific climatic region to better understand the influences of climate and soil properties on soil C dynamics is crucial. Arid and semi-arid climates, comprising more than 35% of Earth's terrestrial environments, represent critical areas for C sequestration (Abdelhak, 2022; Salem, 1989; Gaur & Squires, 2017). Arid and semi-arid climates, recognized for high temperatures and low annual precipitation, comprise 900 million hectares of sandy soils and minimal vegetation coverage (Abdelhak, 2022; Singh & Chudasama, 2021; Yost & Hartemink, 2019). Sandy soil properties include low water and nutrient retention, high permeability, and naturally low soil C, ranging from 2 – 5% (Abdelhak, 2022; Huang et al., 2021a; Yost & Hartemink, 2019). Despite these edaphoclimatic challenges, approximately 200 million hectares are used as cropland in arid and semi-arid climates (Huang & Hartemink, 2020). These climatic regions are being targeted for climate-smart agricultural practices and reforestation sites, as these regions are predicted to expand by 5 – 15% in coming decades due to climate change and anthropogenic disturbances, such as agriculture and deforestation (Lian et al., 2021; Plaza et al., 2018; Yildiz et al., 2022).

The Rio Grande Valley (RGV) of Texas has a semi-arid, subtropical climate that has experienced intensive agricultural practices, leading to high percentage rates of deforestation. This region is located in South Texas along the U.S. – Mexico border, where a rich agricultural region has largely supplanted the historic landcover, resulting in the removal of over 90% of native Tamaulipan thorn forests that had existed into the early decades of the 20th century (Jahrsdoerfer & Leslie, 1988; Vora, 1992, Wahl-Villarreal & Dale, 2021). On spatial scales beyond the RGV, global deforested and cultivated sites have shown the largest losses of SOM, particularly the loss of approximately 30 – 50% SOC (Amundson et al., 2015; Guo & Gifford, 2002; Haddaway et al., 2017; Bispo et al., 2023), shifting soil status from a C sink to a C source (Amundson et al., 2015; Gougoulias et al., 2014; Lal, 2009). Therefore, it is imperative to begin implementing climate smart agricultural practices, such as conservation tillage, to conserve soil resources, sustain food production, and increase reforestation initiatives to restore soil health, sequester C, and restore forest ecosystems.

Conventional and Conservation Agriculture

Regions under cultivation, such as the RGV, often use conventional tillage systems, which is the mechanical turnover of soil that results in the breakdown of soil aggregates, facilitates the decomposition of SOM, and reduces C stocks (Hussain et al., 2021; Page et al., 2020; Mehra et al., 2018; Six et al., 2000). These practices leave soils loose and rough without vegetation coverage or crop residues, leading to poor aggregate stability, reduced nutrient availability, low water retention, and SOC reductions (Amundson et al., 2015; Osanai et al., 2020; Lorenz et al., 2019). These physical disruptions of conventional tillage, especially in arid and semi-arid climates, have resulted in global soil C losses amounting to 0.3 – 1.2 Pg C yr^{-1} (Basile-Doelsch et al., 2020; Chappell et al., 2016; Sun et al., 2020; Zomer et al., 2017), thus further exacerbating climate change and soil degradation (Lorenz et al., 2019; Obalum et al., 2017).

To aid in climate change mitigation, C sequestration, and soil health restoration, soil conservation tillage practices are vital in reducing soil turnover and disturbances to maintain crop productivity, while also retaining crop residues (Osanai et al., 2020; Page et al., 2020). Implementing climate-smart farming practices, such as no tillage, plays a vital role in preserving soil aggregates, sequestering C, and enhancing crop yields (Bach et al., 2020; Six et al., 2000; Usharani et al., 2019). In semi-arid climates with depleted SOC, these practices offer potential to sequester C and land restoration (Bai et al., 2019; Lal, 2009; López-Fando & Pardo, 2011). Conservation tillage effectively reduces soil erosion, preserves soil structure, and increases SOC content, while also improving soil nutrient availability and moisture retention by utilizing residues (Gachene et al., 2019; Huang & Hartemink, 2020; Sharma et al., 2016). Other examples of conservation tillage include reduced tillage, mulch tillage, ridge tillage, minimum tillage, and zone tillage, each with distinct forms of implementation (Francaviglia et al., 2023). Other meta-analysis studies have shown that CST practices can increase the SOC by 10% – 17% in sandy soils and semi-arid climates (Bai et al., 2019; Luo et al., 2010; Sun et al., 2020; Tadiello et al., 2023).

Reforestation

By practicing conservational tillage in arid and semi-arid climates, soil health can be improved and aid in the conservation of SOC and other soil properties. Currently, however, most croplands are under conventional tillage systems. Over time, these cultivated soils can lose their fertility and result in low crop production, especially under these edaphoclimatic limitations, which can ultimately lead to land abandonment (Cerdà et al., 2018; Gachene et al., 2020; Lana-Renault et al., 2020). Before these agricultural areas were croplands, many of these sites were once forests. Thus, other soil conservation efforts, such as reforestation, can be implemented to restore soil health and continue mitigating climate change by sequestering C.

Forests are crucial ecosystems that facilitate nutrient cycling, provide habitat for various organisms (above- and below- ground), and mitigate climate change impacts (Cunnigham, 2015; Hui et al., 2017). Forests in general, covering approximately 4 billion hectares globally, store approximately 70% of soil organic C (SOC) (Liu et al., 2018; Qiu et al., 2015; Six et al., 2002b). Approximately 500 million hectares of forests are located in regions with semi-arid climates (Bastin et al., 2017; Guirado et al., 2022), thus having the potential to support the reforestation of abandoned agricultural land (Rohatyn et al., 2021; Yildiz et al., 2022; Yosef et al., 2018).

Through time, reforestation can improve nutrient availability, soil quality, and sequester more C (120 Mg C ha^{-1}) than agricultural fields (90 Mg C ha^{-1}) (Cunningham et al., 2015; Silver et al., 2000). However, the success of reforestation is impacted by edaphoclimatic limitations of semi-arid climates, invasive grasses, and low soil fertility (Contreras, 2020; Bell et al., 2021; Silver et al., 2000). When reforesting abandoned agricultural lands, soils typically lack structure, aggregation, soil C, and organic matter, all of which affects the survival of native tree seedlings, therefore resulting in the uncertainty of long-term soil C storage (England et al., 2016; Wahl-Villarreal & Dale, 2021; Yang et al., 2020). As a result of climate change, characterized by rising temperatures and reduced precipitation, thorn woodlands are expected to expand and encroach into subtropical forest areas (Navarro et al., 2024). Consequently, these areas have become critical for reforestation efforts, given their resilience to drought and high biodiversity, as observed in regions like the Rio Grande Valley (TCP, 2022) . The reforestation of abandoned cropland in the RGV has resulted in over 6,400 hectares of land being restored with subtropical thorn woodland species (Albrecht et al., 2022; Wahl-Villarreal & Dale, 2021).

Given the importance of preserving and restoring SOC in combating climate change, conservation tillage and reforestation efforts in drought-resilient regions have gained significant attention to improve soil quality and reduce CO_2 emissions (Lal, 2010; Lal, 2020a; Malhi et al., 2021). Therefore, conservative land management practices should aim to restore or minimize soil disturbance through conservation tillage or reforestation efforts to reduce CO_2 emissions and promote soil C sequestration.

Objectives

The overarching objective of this thesis is to evaluate the benefit of conservation agricultural practices and reforestation efforts on C accumulation under arid and semi-arid conditions (Figure 1). Specifically, Objective 1 aims to verify to what extent conservation tillage practices are effective at enhancing soil C levels in sandy soils of arid and semi-arid climates through a meta-analysis approach. Findings from this component will provide insights into potential conservation practices that can be implemented in arid and semi-arid climates to conserve soil resources. Objective 2 studies three reforestation sites on abandoned croplands in the RGV to determine the quantity and rate SOC has changed over the years through a chronosequence approach. It is unknown if the RGV reforestation sites have sequestered soil C since their initial reforestation stage within a semi-arid, subtropical climate, however, evidence has suggested that these regions can accumulate soil C after a few decades. Due to the predicted expansion of arid and semi-arid regions with climate change, it is crucial to elucidate the amount of C accumulation expected from these practices.

Hypotheses

For Objective 1, it was hypothesized that:

1) Conservation tillage practices, especially no tillage, will increase SOC in sandy soils of semi-arid climates due to less soil disturbance of soil particles and input of plant residues.

For project two, it was hypothesized that:

1) Reforestation will increase SOC accumulation over time across each chronosequence site due to increasing tree cover and forest litter input.
2) Sites with a larger proportion of clay content will accumulate a larger amount of C due to clay's capacity to retain carbon, water, and nutrients more efficiently.

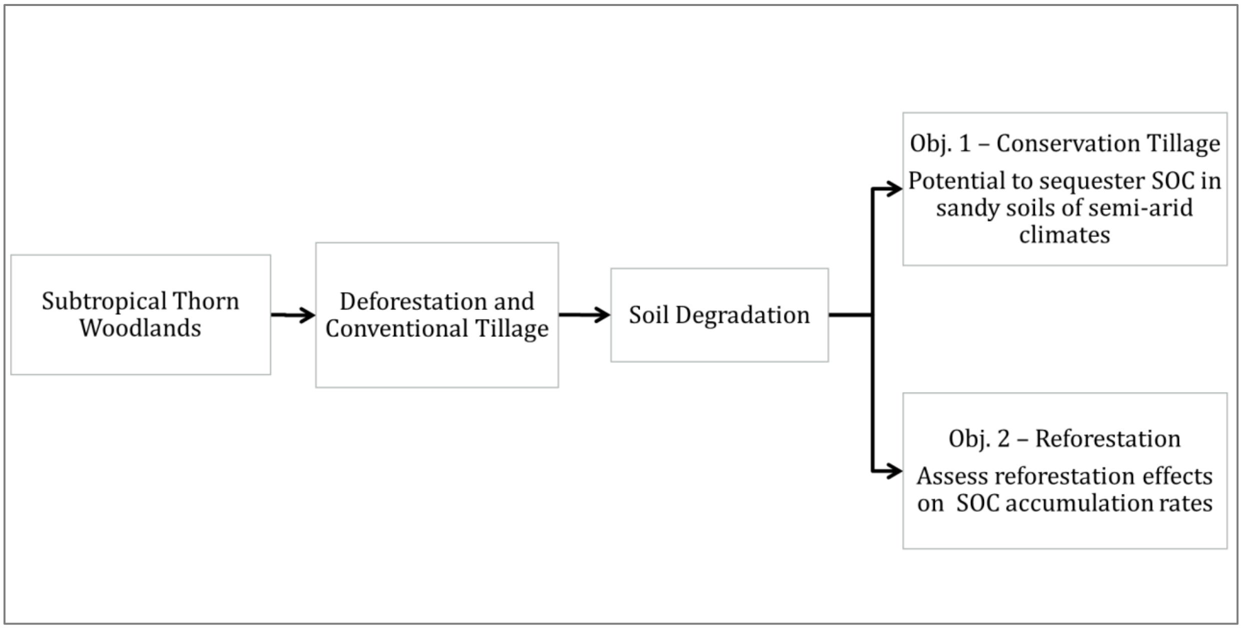

Figure 1: Schematic diagram for the two thesis objectives.

CHAPTER II

CARBON SEQUESTRATION THROUGH CONSERVATION TILLAGE IN SANDY SOILS OF ARID AND SEMI-ARID CLIMATES: A META-ANALYSIS

Abstract

This meta-analysis assessed soil organic carbon (SOC) percent changes in sandy soils, transitioning from conventional tillage (CT) to conservational tillage (CST) in arid and semi-arid climates. High levels of SOC in sandy soils are difficult to attain especially when precipitation levels are very low, contributing to low biomass production, and increased decomposition of organic matter. While CT practices are known to reduce SOC through the breakdown of soil aggregates, accelerated decomposition of soil organic matter, and promote erosion, CST methods (i.e., mulch tillage, no tillage, reduced tillage, ridge tillage, etc.) offer the potential to preserve soil aggregates and increase SOC concentration. Analyzing 55 peer-reviewed publications in arid and semi-arid climates with ≥ 45% sand content, this study compared SOC content between CST and CT over short- and long-term periods (349 paired observations). Results showed that CST increased SOC in sandy soils, with an estimated 12.74 ± 1.46% increase. Specifically, reduced tillage (RdT), mulch tillage (MchT), and no tillage (NT) exhibited the highest increases of SOC by 18.94 ± 2.48%, 11.45 ± 2.46%, and 10.06 ± 2.46%, respectively, compared to CT. Studies with durations of up to 15 years (n = 297) showed a progressive increase in SOC concentrations under CST; however, the long-term stability of the accrued carbon content in sandy soils of arid and semi-arid climates is still uncertain, as studies extending beyond 15 years (n = 52) did not demonstrate significant changes in SOC levels. CST significantly raised SOC concentrations in precipitation up to 600 mm, though no significant changes were observed for precipitation over 600 mm. In soils with over 56% sand content, CST increased SOC by approximately 13%. This study highlights both positive and limited impacts of CST practices for soil conservation and climate change mitigation, emphasizing their significance for both existing agricultural areas in arid regions and those in parts of the world where aridity is on the rise.

Introduction

Carbon (C) plays a vital role in supporting soil fertility, plant productivity, and the cycling of nutrients, such as phosphorus and nitrogen (Kumar et al., 2017; Ontl & Schulte, 2012). Carbon sequestration in soils has the potential to mitigate climate change, prevent soil erosion, and assist in the restoration of degraded lands (Jagadamma, 2009). Soils are the largest terrestrial reservoir for C, storing about 2,500 Pg of C (1,550 Pg organic C), more than the atmosphere and biosphere combined (Jagadamma, 2009; Ontl & Schulte, 2012). However, intensive agricultural practices, such as conventional tillage (CT), can destabilize soil aggregates, resulting in the loss of nutrients, water, soil C, and an overall decrease in soil health (Abbas et al., 2020; Mehra et al., 2018). Alterations in soil conditions could affect the amount of CO_2 in the atmosphere, potentially making soils under agriculture both a C sink and C source (Jagadamma, 2009; Nabuurs et al., 2022).

Sandy soils (> 45% sand content), particularly prevalent in arid and semi-arid climates which make up 30 – 35% of the terrestrial environment (Salem, 1989; Nielsen & Ball, 2015), inherently have a low capacity to form aggregates due to their low clay content, constraining their ability to store soil C (Hussain et al., 2021; Lewis, 2023). Globally, these soils span over 900 million hectares under arid and semi-arid climates (Huang & Hartemink, 2020; Yost &

Hartemink, 2019). In these regions, limited precipitation often restricts primary productivity, consequently constraining C inputs, and resulting in a reduced accumulation of surface organic C of less than 2% (Delgado-Baquerizo et al., 2018; Jafari et al., 2017). These edaphoclimatic conditions, in addition to the physical disruptions of CT that degrade soil aggregates, can result in global C losses amounting between 0.3 – 1.2 Pg C yr^{-1} (Basile-Doelsch et al., 2020; Chappell et al., 2016; Sun et al., 2020; Zomer et al., 2017). Hence, considering the large scale of sandy soils and the expansion of dryness with higher temperatures under climate change, it is paramount to investigate the potential of conservation agricultural practices in enhancing the low C baseline.

Presently, more than 75% of arable land is under CT while 12 – 15% is under conservation tillage (CST) (Kassam et al., 2019; Prestele et al., 2018; Sumberg & Giller, 2022). In CT, soils are physically disturbed and overturned, resulting in the destabilization of soil aggregates and less than 15% crop residues on the surface (Figure 2A) (Mehra et al., 2018; Wang et al., 2020; Yu et al., 2020). Various forms of CT include moldboard plow, chisel plow, or cultivator tillage (Figure 2B). The breakdown of soil aggregates facilitates the decomposition of soil organic matter (SOM) reducing C stocks (Ayoubi et al., 2020; Hussain et al., 2021; Page et al., 2020). In contrast, CST can minimize soil disturbance and promote C sequestration in sandy soils, contributing to water and nutrient retention, soil health, and plant productivity (Lal, 2020b; Page et al., 2020). Practices of CST that can contribute increases in soil organic carbon (SOC) include no tillage, ridge tillage, reduced tillage, minimum tillage, mulch tillage, and zone tillage (Francaviglia et al., 2023).

Each form of CST has its own distinctive characteristics in how it is applied. No tillage disturbs up to 1/3 of the arable soil surface, where seeding occurs on un-tilled soil by opening the soil to a certain depth and width, which effectively controls erosion and runoff with crop residue retention (Derpsch, 2003; NRCS, 2006). Ridge tillage involves leaving the soil undisturbed between harvest and planting, where crops grow on a ridge and residue is left in between ridges to protect the inner rows of soils (Alagbo et al., 2022). Mulch tillage is full-width tillage that leaves varying levels of residues in the soils after seeding (Derpsch, 2003; Carter, 2005). Zone tillage is another CST practice that involves the completion of narrow rows (less than 1/3 row width) for tillage planting, while rows and residues in between seeding rows are left undisturbed (Francaviglia et al., 2023; NRCS, 2006). Lastly, reduced tillage involves less frequent tillage, leaving 15 – 30% of residues on the soil surface (Derpsch, 2003). Reduced tillage is also called minimum tillage, in which the soil is tilled to a certain depth (Claassen et al., 2018; Francaviglia et al., 2023).

Globally, cultivated soils have the potential to annually sequester between 0.12 – 1.8 Pg C yr^{-1} (Luo et al., 2010; Poeplau & Don, 2015). Across previous meta-analyses, CST has been demonstrated to accumulate soil C on cropland under sandy soils and under arid or semi-arid climates (Bai et al., 2019; Luo et al., 2010; Sun et al., 2020; Tadiello et al., 2023). For instance, transitioning from CT to CST, such as reduced or no tillage, led to an average increase of 0.48 Mg C ha^{-1} yr^{-1} in the top 30 cm, with SOC 10% – 12% greater than CT under semi-arid conditions (Tadiello et al., 2023). According to a global meta-analysis involving 260 paired-experiments in semi-arid croplands, CST increased SOC in the top 30 cm with an average of 0.35 Mg C ha^{-1} yr^{-1} (Sun et al., 2020). According to the study by Bohoussou et al. (2022), NT and reduced tillage significantly increased SOC under warm, semi-arid climates by 17% and 12%, respectively. These studies support the potential of sandy soils to accumulate SOC under arid or semi-arid conditions.

Considering the widespread occurrence of sandy soils in arid and semi-arid regions, it is crucial to estimate the magnitude and timescale of potential carbon C storage enhancements through CST, as well as identify the most effective CST practices for maximizing soil organic C content. Such estimates are vital for guiding the development of carbon markets, conservation initiatives, and incentive programs. Therefore, the objective of this study was to estimate SOC changes when converting from CT to CST in sandy soils of arid and semi-arid climates through a meta-analysis approach. This study also offers quantitative insight into the efficacy of various CST practices, climatic influences, timescales, soil depths, and fertilizer application rates in enhancing SOC.

Materials and Methods

Data Search and Collection

For this meta-analysis, we identified peer-reviewed studies using keyword searches within Google Scholar and Web of Science. Key search words included soil AND carbon AND sandy OR sand AND tillage AND arid OR semiarid OR semi-arid. For this meta-analysis, 500 articles were assessed (Figure 3), based on the following inclusion criteria:

i. Field trials should have been conducted in arid or semi-arid climates, as characterized by the mean annual precipitation (MAP) and mean annual temperature (MAT) detailed in Table 1.

ii. The soil in the study must either comprise a minimum of 45% sand content or be described in terms of texture as sandy, loamy sand, sandy loam, sandy clay loam, or sandy clay.

iii. The study must specifically measure SOC, excluding metrics like inorganic C, total C, or SOM.

iv. There should be a comparison of SOC changes between CT (control) and CST (experiment).
v. Review articles or meta-analyses are not considered.
vi. Experiments must include a minimum of three field replicates.

By following this criteria, a total of 55 articles were selected for this meta-analysis (Table 2), totaling 349 paired observations for SOC % changes. The SOC from all studies were standardized to g C kg^{-1}. Most MAP and MAT data was obtained from the studies, however those that did not provide MAP or MAT were searched based off geography, coordinates, and climate information from Climate Data (https://en.climate-data.org/).

Majority of the studies provided particle size ranges, however if only the textural class was provided, the sand percentage was estimated by averaging the sand range for the particular textural class. All raw data from original studies were collected from text, tables, or figures. From figures of the selected articles, data was collected using Web Plot Digitizer version 4.6 (https://apps.automeris.io/wpd/). Many studies did not include standard deviation or standard errors. For those, we estimated the standard deviation using the test statistic (e.g., F-values or t-values with degrees of freedom and p-values).

Given the diverse stratified soil samples reported in the selected publications, we grouped sampling depths into surface (0 – 20 cm), subsoil (20 – 50 cm), and deep soil (50–100 cm) layers to analyze SOC content differences under CT and CST. To ensure accurate depth classification, we excluded SOC data from depths that overlapped our designated categories to avoid potential misclassifications. For instance, SOC observation points at depths such as 10 – 30 cm, 15 – 35 cm, and 10 – 25 cm (overlapped both 0–20 cm and 20–50 cm) were excluded. This resulted in the total number of observation points for soil depth analysis of SOC to be adjusted to 316 observation points, instead of the initial 349.

Most of the studies included in this meta-analysis did not use or mention the application of N fertilizers (n = 143) and were considered 0 kg N ha^{-1}. However, it is possible that there was fertilizer involved but not mentioned, therefore affecting our results. The remaining studies either applied N fertilizer as a standard agricultural practice or investigated SOC responses to N fertilizers.

The studies in this meta-analysis covered 12 countries (Argentina, Burkina Faso, China, India, Israel, Morocco, Munglinup, Pakistan, South Africa, Spain, United States, and Zimbabwe). The majority of the studies were conducted in Spain (36%; 125 observations), followed by China (18%; 61 observations), India (14%; 50 observations), and the United States (10%; 35 observations). Table 3 shows summary statistics of all data collected.

Meta-Analysis

The collected data was analyzed using Rstudio software (version 4.1.1) and meta-analytical guidelines for ecological data provided by Crystal-Ornelas (2020). Effect sizes of each experiment between CT and CST was calculated as the natural log of Response Ratio (ln(RR)), as seen in Equation [1] below. After collecting data of the ln(RR) effect sizes, they were converted to percentages to analyze the percent change of SOC between conventional and conservational tillage, as seen in equation [2] below.

$$[1]\ \ln(RR) = \ln\,(SOC_{CST}/SOC_{CT})$$

$$[2]\ 100 * (e^{\ln(RR)} - 1)$$

Mixed effect models were performed, as well as forest plots using the ‘metafor’ package to compare SOC % changes between different tillage practices, climatic conditions, soil texture, soil depth, time period of studies, and N fertilizer applications. The confidence intervals calculated were 95% intervals. On forest plots generated for this meta-analysis, the x-axis represents the percentage difference between CT and CST. A negative percentage suggests that CT has a higher SOC content than CST. Conversely, a positive percentage indicates a higher SOC content in CST than its CT counterpart.

Results

Conservation Tillage Practices

Most of the studies used in this meta-analysis mainly compared CT to NT (n = 211), while relatively few studies compared other CST practices – such as mulch tillage (MchT, n = 23), minimum tillage (MT, n = 48), reduced tillage (RdT, n = 53), ridge tillage (RdgT, n = 6), and zone tillage (ZT, n = 8) (Figure 4). Overall, SOC in CST increased by 12.74 ± 1.46% (SOC % change) compared to CT. When considering individual conservation practices, all methods significantly increased SOC in sandy soils of arid and semi-arid climates, except for zone tillage possibly due to the low number of observations (n = 8). Our results suggest that SOC had the most significant increase under RdT by 18.94 ± 2.48% ($p < 0.001$), followed by MchT (11.45 ± 2.47%), and NT (10.06 ± 2.46%). For MT (n = 48), there was a significant increase of SOC between CT and CST (4.91 ± 2.47%), though not as high as RdT, MchT, and NT. For RdgT, there was a significant increase in SOC by 11.97 ± 2.57%, though based on only 6 paired observations, which is similar to ZT with 8 paired observations.

Edaphoclimatic Properties

The driest regions with < 400 mm (n = 59) had the highest response to CST with a SOC% change of 13.34 ± 6.40% ($p < 0.05$) when compared to CT (Figure 5A). For the 401 – 600 mm precipitation gradient (n = 193), our analysis revealed a significant increase in SOC by 12.74 ±

3.33% ($p < 0.001$). As precipitation reached the upper range of 601 – 800 mm, no significant difference in SOC was observed (6.89 ± 4.48%, n = 97). Significant increases in SOC by CST were only observed in sites with a temperature range between 16°C to 25°C (n = 243) with a SOC % change of 13.55 ± 2.95% ($p < 0.001$) (Figure 5B). There were no significant differences in SOC (5.70 ± 5.39% and 5.52 ± 7.29%) for temperatures < 15°C (n = 66) and > 25°C (n = 40), respectively. In comparison to CT, CST did not significantly affect SOC in soils with 45 – 55% sand (n = 101). In soils with a 56 – 65% sand content (n = 98), CST led to a significant increase in SOC content by 15.20 ± 3.23% ($p < 0.001$) (Figure 5C). Additionally, for soils with a 66 – 75% sand content, there was still a significant increase in SOC by 10.90 ± 3.16% under CST. In soils with more than 75% sand content, a significant increase in SOC was also observed, amounting to 21.27 ± 10.56%, noting a large variation and small sample size (n = 11) for this category.

Experimental Conditions

The category spanning 1 – 5 years of CST transition exhibited a significant increase in SOC by 6.22 ± 2.92% ($p < 0.05$) under CST (Figure 6A). Studies conducting experiments for 6 – 10 years and 11 – 15 years also demonstrated significant increases in SOC by 13.40 ± 5.06% and 23.50 ± 3.02%, respectively. However, after 15 years of CST, there was no significant change in SOC (2.03 ± 2.96%). At surface sampling depths of 0 – 20 cm, CST significantly increased SOC by 15.37 ± 2.53% ($p < 0.001$) (Figure 6B). At sub- and deep soil sampling depths of 20 – 50 cm and 50 – 100 cm, SOC significantly decreased by -5.32 ± 2.56% and -14.42 ± 2.59%, respectively. Nonetheless, at sub- and deep soil sampling depths, there were relatively few observation points (n = 80) when compared to the surface layer (n = 236). In studies where CST was employed without any N fertilizer (0 kg N ha^{-1}), and with 1 – 50 kg N ha^{-1} and 51 – 100 kg

N ha^{-1}, SOC significantly increased by 7.95 ± 3.20%, 24.97 ± 3.36%, and 11.28 ± 3.35%, respectively (Figure 6C). However, at N fertilizer application rates of 101 – 150 kg N ha^{-1} and over 150 kg N ha^{-1}, there were no significant differences in SOC concentrations between CT and CST.

Discussion

SOC Responses to Conservation Tillage Methods

In this meta-analysis, five out of six CST practices significantly increased SOC contents in sandy soils under arid and semi–arid climates when compared to CT. Reduced Tillage (RdT) had the greatest effect on enhancing SOC concentrations showing an improvement of approximately 20% over CT. Moreover, most of these RdT studies were long-term, spanning 10 years or more (n = 45 out of 53). Although No Tillage (NT) also significantly increased SOC concentrations, it was less effective than RdT. This differential impact may arise from RdT's incorporation of crop residues plus belowground biomass (i.e. roots) into the soil, thereby augmenting soil organic matter and creating a conducive environment for the formation of soil aggregates (Huang et al., 2021b; Islam et al., 2023; Six et al., 2002a). In contrast, NT typically results in the accumulation of residues on the soil surface without integrating them into the soil (Bista et al., 2017; Okeyo et al., 2016; Six et al., 2004). The additional incorporation of surface residues in RdT leads to the formation of aggregates and subsequent C concentration increase within these aggregates, a process which happens in NT in a more limited manner where aboveground crop residue decomposition occurs primarily on the surface (Olchin et al., 2008; Six et al., 2004; Wingeyer et al., 2012). Consequently, RdT may be more effective in burying additional organic C with roots throughout the soil profile, thereby facilitating more stable C pools over time. Furthermore, the adoption of RdT offers an additional advantage to farmers by obviating the need for investment in new machinery and tillage operations (Bista et al., 2017; Carter, 2005), as labor, fuel, and tillage machinery use would be reduced (Claassen et al., 2018).

To meet goals of increasing SOC and other soil properties, NT is considered the most conservative approach, though results may depend on climate, soil texture and structure, topography, and other factors such as biological activity, irrigation methods, and residue type and amount (Claassen et al., 2018; Hartmann & Six, 2023). It is possible that the effect size of NT was not as pronounced as RdT's due to most NT studies being short-term (n = 142 out of 211, < 10 years, (Figure 7)). After transitioning from CT to NT, some studies in this analysis noted either decreases or no changes in SOC concentrations (Acosta-Martinez et al., 2011; Iqbal et al., 2010; Nyamadzawo et al., 2007; Ouedraogo et al., 2007; Wright et al., 2004), attributing these outcomes to the recent conversion from CT to NT. This highlights the importance of long-term trials for accurately assessing C gains in NT experiments.

In arid and semi-arid climates, surface crusting and compaction in coarse soils are common outcomes of implementing NT or RdT (Baudron et al., 2012; Mauget et al., 2021). These issues can be mitigated by employing Mulch Tillage (MchT) as crop residues are partially incorporated into the soil using tools like chisels, sweeps, or field cultivators leaving at least 30% of the crop residue cover on the soil surface after planting (Bista, et al., 2017; Serraj & Siddique, 2012). In our analyzed studies, which varied from 1 – 32 years post-conversion, MchT resulted in an increase of approximately 12% in SOC compared to CT. In addition to enhancing SOC concentration, some studies reported increased soil moisture retention (Chakraborty et al., 2019; Alhassan et al., 2021). Nevertheless, these studies did not offer detailed assessments of the quantity of water mulch conserves by reducing evaporation. Furthermore, while this meta-analysis does not encompass crop yields, some studies, such as Prasad et al. (2016), have raised concerns about the potential for reduced yields accompanying the soil carbon benefits of mulch tillage. In a long-term trial conducted in South Africa on sandy soil, a comparison of wheat yields over 32 years revealed that mulching resulted in an approximate 6% decrease in wheat yields compared to CT (Loke et al., 2012). Lower yields in conservation tillage systems, such as MchT, could be attributed to the potential increase in nitrogen immobilization, plus weed, pest, and disease pressures, which vary based on the implementation of other conservation agriculture principles (Pittelkow et al., 2015).

As for RdgT, the significant increase in SOC between CT and CST was unexpected due to the low number of studies implementing RdgT (n = 6), which was similar to the number of observations for ZT (n = 8). In a semi-arid region, Zhang et al., (2019a) showed that RdgT resulted in significant SOC increases with increasing depth when compared to NT and CT. However, there are inconsistent results when implementing RdgT across different regions and different growing seasons (Li et al., 2018). Our meta-analysis only had one study that compared CT to RdgT, and two studies by the same author comparing CT to ZT. Therefore, our conclusions are limited for both RdgT and ZT practices due to the low number of observations. Overall, long-term RdT, MchT, and NT may be the most promising practices to increase SOC in arid and semi-arid climates with sandy soils.

Interplay of Climate Factors and Conservation Tillage on SOC Content

Precipitation tends to positively influence SOC due to vegetation growth and residue inputs to the soils while being balanced with SOC decomposition. (Ren et al., 2017; Silva & Lambers, 2021). In our meta-analysis, at sites with precipitation rates up to 600 mm per year, CST practices significantly increased SOC concentrations compared to CT by approximately 13%. This is supported by meta-analyses by Huang et al., (2021) and Islam et al., (2023), which demonstrate significant SOC increases under NT in areas with precipitation less than 400 mm, particularly when residues are left on the surface. This aligns with our findings that show a significant 13% SOC increase under CST compared to CT in the 401 – 600 mm range, likely due to sufficient soil moisture for plant productivity and the beneficial impact of residue retention on soil surface, which slows SOC decomposition and reduces vulnerability to erosion (Álvaro-Fuentes et al., 2009; Arshad et al., 1999; Dachraoui & Sombrero, 2020; Corral-Fernandez et al., 2013; Jemai et al., 2012; Zhang et al., 2019b). This can also be attributed to reduced microbial activities at these relatively low precipitation levels, leading to lower soil respiration and decomposition in drier conditions (Cregger et al., 2012; Cruz-Paredes et al., 2021; Delgado-Baquerizo et al., 2018; Singh et al., 2021).

At sites receiving over 600 mm of rain annually, no significant differences were observed between CST and CT, likely due to the initial SOC content being relatively high in areas with higher precipitation, therefore having a less significant increase of SOC when transitioning from CT to NT (Cai et al., 2022; Das et al., 2022). Higher precipitation leads to increased primary productivity, residue inputs, and greater SOC. This, in turn, accelerates SOC microbial decomposition, and possibly indicates faster decomposition than C inputs leading to non-significant results (Cui et al., 2019; Kan et al., 2020; Ren et al., 2017).

Other potential explanations for the observed SOC trends include aggregate disruption and the effects of dry/wet cycles on microbial activity, particularly in sandy soils where high precipitation intensity might weaken soil aggregates, leading to loss-prone SOC pools (Huang et al., 2016; Parras-Alcántara et al., 2015). According to Denef et al. (2001), dry cycles allow soils to maintain stability, whereas wet cycles can reduce aggregation and increase leaching, especially in sandy soils. Dry soils have greater molecular interactions between organic residues and mineral soil particles, thus wet cycles or erratic precipitation can result in destabilized aggregates (Denef et al., 2001; Kan et al., 2020; Nielsen & Ball, 2015).

Enhanced SOC content can result from CST practices that moderate soil temperatures and conserve soil moisture (Hussain et al., 2021; Mehra et al., 2018) and support soil resilience under global climate changes (Baye et al., 2019; Deng et al., 2022). CST practices were only effective increasing SOC concentration in studies with mean annual temperature in the range of 16 – 25°C. This could be attributed to the ideal balance of C inputs from residues and outputs via soil respiration and decomposition (Zhang et al., 2022). This balance results from sufficient soil moisture maintained by CST, supporting primary production, and warm temperatures to increase microbial activity to decompose the organic matter provided by both above- and below-ground biomass (Veni et al., 2020; Yang et al., 2023).

In our meta-analysis, we observed no significant effects of CST practices on SOC concentration in environments with mean annual temperatures below 15°C. Notably, 51% of the studies were conducted in northern China and 42% in central-eastern Spain. The concentration of studies from just these two regions could limit the generalizability of our findings in temperatures below 15°C, as there is a risk that the conclusions may more accurately reflect the specific conditions of these areas rather than the broader impact of CST in cooler climates. Additionally, with 63% of studies focusing on no tillage and 25% on minimum tillage, our results might be predominantly indicative of these specific practices, potentially not representing the full spectrum of CST. To acquire a more comprehensive understanding of the impact of CST on SOC, particularly in cooler climates, it is crucial to include a broader array of tillage practices in future research.

At sites with mean annual temperatures exceeding 25°C, crop productivity is constrained by water availability, as indicated in various studies (Hatfield et al., 2011; Neenu et al., 2013; Ouedraogo et al., 2007; Wang et al., 2019; Zhou et al., 2016). About half of the studies in this meta-analysis were based on rain-fed systems (≈ 54%). In such conditions, high temperatures can lead to increased soil water evaporation, resulting in drier soils that inhibit microbial decomposition (Wang & D'Odorico, 2008; Dorau et al., 2022). This, combined with the likelihood of insufficient plant residue addition due to limited crop productivity in arid and semi-arid climates, could account for the minimal increases in SOC and the lack of significant impact of CST practices in these temperature ranges (Gougoulias et al., 2014; Zhou et al., 2016; Hou et al., 2016; Manzoni et al., 2012).

Soil Texture's Role in CST-Induced SOC Changes

Although sandy soils pose challenges for SOC accumulation and retention, our study indicates that trials conducted on soils with a 56 – 75% sand content have demonstrated significant increases in SOC concentrations from CST practices by approximately 13%. This further reinforces the concept of enhancing SOC in sandy soils through appropriate CST practices over time (Das et al., 2022; Wang et al., 2020). There were only 11 paired observations for soils with a sand content > 75%. Therefore, more research needs to be conducted in soils over 75% sand under arid and semi-arid climates to further address and understand SOC increases. However, in a meta-analysis by Bai et al., (2019), implementing NT or RdT in a variety of climate conditions on sandy loam or loamy sand soil resulted in a 7 – 12% increase in SOC, suggesting potential increases of SOC in soils with high sand contents lacking SOC.

We did not observe any significant differences between CST and CT in soils with less than 55% sand. With increasing levels of clay content, soils exhibit better structure and aggregation to retain SOC and water; therefore, there is a low potential for finer soils to further accumulate SOC (Bai et al., 2019; Li et al., 2019). This also indicates the possibility of saturation in soils under CST with a low sand content, thus explaining the non-significant increase of SOC with 45 – 56% sand (Angers et al., 2011; McNally et al., 2017). Essentially, finer soils store the most SOC, while coarse soils with low SOC content have the greatest potential to increase SOC (Castellano et al., 2015; Moinet et al., 2023).

Time-Dependent SOC Enhancement under CST

The effect of CST on enhancing SOC concentration progressively increased in studies where CST had been implemented for a duration ranging from 1 to 15 years. According to Basset et al. (2023), short-term CST (< 10 years) does not provide enough time for the formation and stabilization of soil aggregates. However, sandy and tilled soils, often characterized by a low initial SOC concentration, demonstrate a considerable potential for SOC enhancement when managed under CST practices (Moinet et al., 2023). The observed increases in SOC concentrations within the first five years following the transition to CST could be attributed to the augmentation of labile carbon and may thus form less stable aggregates (Arshad et al., 1999; Benbi et al., 2014; Li et al., 2021; Maia et al., 2019). According to Mondal et al. (2019) and Liu et al., (2021), SOC increases further after CST is implemented over 15 – 20 years that promotes the stabilization of aggregates. Increased aggregation results in the increased residence time of SOC (Almagro et al., 2021). The long-term stability of aggregate-associated C in sandy soils of arid and semi-arid climates remains uncertain, and estimating this stability requires an examination of aggregate turnover rates and the environmental drivers of SOM dynamics, which are crucial for understanding long-term C storage (Zhang et al., 2019b). Field studies monitoring the transition from CT to CST over periods exceeding 15 years have not revealed significant changes in SOC concentrations. This could be due to microbial communities adapting over time, becoming more efficient at decomposing organic matter and hence reducing SOC accumulation (Tao et al., 2023; Zheng et al., 2022).

Depth-Dependent SOC Changes under CST

In this study, CST significantly increased SOC concentrations by about 15% across sampling layers 0 – 20 cm, as the surface has increased quantity of organic residues from CST (Badagliacca et al., 2021; Baye et al., 2019; Carter, 2005) and the reduction in soil disturbances that can potentially enhance SOM decomposition. However, the significant decrease of SOC with CST in greater depths (20 – 50 cm and 50 – 100 cm) could be attributed to restricted root growth through compaction, especially in sandy soils (Blanco-Canqui et al., 2022; SQI, 2003). Under CT, soil turning and loosening of soil layers can result in increased root growth and more extensive distribution of SOC at greater depths (Luo et al., 2010). In contrast, CST preserves soil structure and increases soil strength, which can limit root penetration and limit the distribution of SOC to greater soil depths (Dignac et al., 2017; Fiorini et al., 2018; Haddaway et al., 2017; Six et al., 2000). While all publications in this meta-analysis sampled at the surface layer (236 observation points), only a total of 80 observation points were sampled at depths of 20 – 50 cm and 50 – 100 cm. Therefore, further research is needed at greater soil depths in sandy soils, where compaction susceptibility is greater.

N Fertilizer Use in CST: Impact on SOC Concentrations

Previous studies have shown that, under continuous cultivation, crop yields and SOC decrease without the use of N fertilizers (Fan et al., 2014; Govindasamy et al., 2023; Yang et al., 2011). The largest increase in SOC concentration was observed when 1 – 50 kg N ha^{-1} was applied, followed by 51 – 100 kg N ha^{-1} and 0 kg N ha^{-1}. Since N promotes above and belowground biomass in crop production (Naorem et al., 2023; Yang et al., 2011), and CST tends to maintain plant residue on the soil, it is expected that SOC concentrations would increase as well. Among the studies that used N fertilizers > 100 kg N ha^{-1}, there was no significant difference in SOC. An excess of N can enhance microbial activities that decompose soil organic matter (Singh, 2018; Poffenbarger et al., 2017). Hence, for optimized benefits of CST practices, this meta-analysis suggests that N fertilization rates should be lower than 100 kg N ha^{-1} to enhance SOC accumulation.

Conclusions

In conclusion, this meta-analysis reveals positive and limited impacts of CST for SOC accumulation in challenging soil conditions and climate scenarios. We found that CST methods led to a significant SOC increase of approximately 12%. Notably, RdT promoted the largest increase in SOC concentration by about 20%. The second most significant increase in SOC concentration was observed with NT, primarily in short term studies (< 10 years), which emphasizes the need for more long-term studies to assess SOC in sandy soils. Most CST practices were conducted in the short term, which resulted in a significant increase of SOC by approximately 10%. However, within 11 – 15 years, only RdT had a significant increase of SOC. Beyond 15 years, no specific CST practice resulted in a significant SOC increase, highlighting the uncertainty in long-term SOC stability in sandy soils and the necessity for further research.

Our results showed a significant increase of SOC in precipitation up to 600 mm with CST, despite limited water availability and sandy soils. Under CST, soils with over 56% sand content exhibited a significant SOC increase of approximately 13%. Despite the significant SOC increase with > 75% sand, there was a small sample size and wide variation, thus emphasizing the need for further research on sandy soils. These findings not only unravel the interactions between soil properties, tillage practices, and SOC dynamics but also lay a path for future research, especially in sandy soils and under long-term experiments. By outlining the most effective practices and highlighting areas requiring further exploration, this study significantly contributes to the global effort towards sustainable land management and climate resilience.

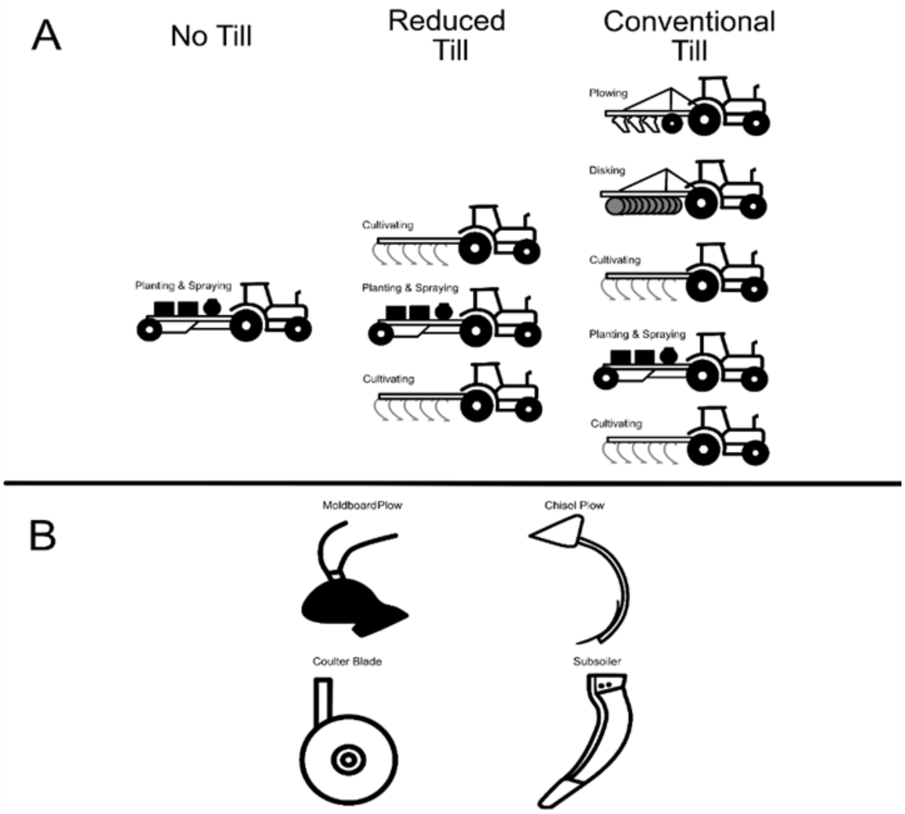

Figure 2: Conventional tillage (CT) vs conservation tillage (CST). (A) Mechanisms of different tillage systems, where no till and reduced till are conservation practices. (B) Different conventional tillage tools. Image by Leila Wahab.

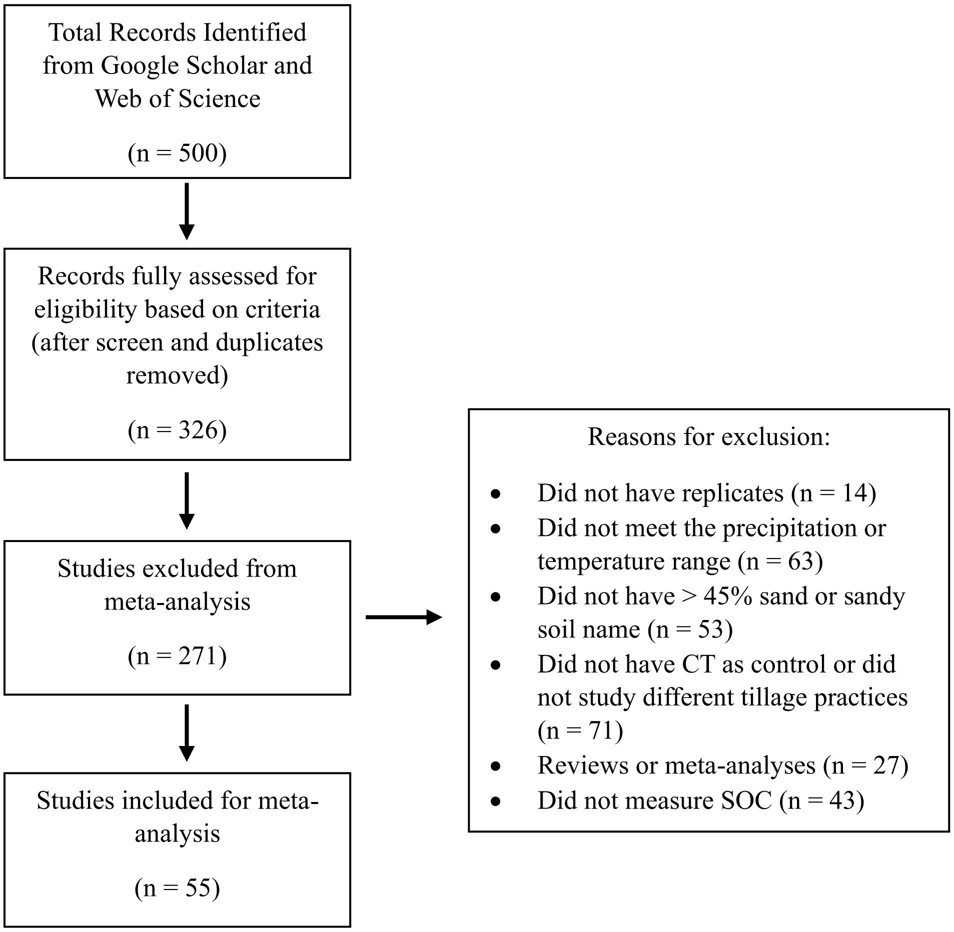

Figure 3: Flow diagram of literature search for meta-analysis.

Table 1: Estimated mean annual precipitation (MAP) and temperatures (MAT) across semi-arid and arid climates. MAP and MAT ranges estimated from Salem, (1989); Grove, (1997); Huang et al., (2012); Laity, (2008).

		MAP (mm)	MAT (ºC)
Semi-Arid	Minimum	≤ 300	15 – 22
	Average	200 – 500	20 – 25
	Maximum	500 – 800	30 – 45
Arid	Minimum	≤ 100	-50 – -30
	Average	200	25 – 30
	Maximum	300	45 – 49

Table 2: References of studies included in the meta-analysis within arid and semi-arid climates under sandy soils. Coordinates, estimated mean annual precipitation, estimated mean annual temperature, crops, and the conservation tillage implemented.

	Author(s)	**Country**	**Latitude**	**Longitude**	**MAP (mm)**	**MAT (°C)**	**Sand (%)**	**Crops**	**CT vs**
1	Acosta-Martinez et al., 2011	USA	33.70	-101.82	470	25	68	cotton, grain, sorghum, winter rye	NT
2	Alhassan et al., 2021	China	35.58	104.64	385	7	69	wheat	MchT, NT
3	Alvaro-Fuentes et al., 2013	Spain	41.79	1.10	435	16	47	barely	NT, RdT
4	Blanco-Moure et al., 2013	Spain	40.96	0.08	468	16	57	cereal	NT
5	Bono et al., 2008	Argentina	-36.61	-64.28	600	18	53	maize, oat, vetch, wheat	NT
6	Burke et al., 2019	USA	32.77	-101.93	486	16	70	cotton, pea, rye, vetch	NT
7	Chakraborty et al., 2019	India	28.64	77.17	750	33	75	cotton, maize, pigeon pea, wheat	MchT, NT
8	Chen et al., 2009	China	38.10	113.00	555	11	47	wheat	MT, NT
9	Du et al., 2018	China	38.10	113.00	555	12	46	wheat	MchT, NT
10	Eshel et al., 2014	Israel	31.33	34.68	230	21	69	wheat	NT

Table 2 continued

11	Gao et al., 2019	China	34.50	113.00	546	14	61	wheat	NT
12	Gwenzi et al., 2008	Zimbabwe	-20.35	32.35	482	38	78	cotton, sugarcane, wheat	MT, NT
13	Hernanz et al., 2002	Spain	40.48	-3.37	430	13	45	barley, vetch, wheat	MT, NT
14	Hernanz et al., 2009	Spain	40.48	-3.37	430	13	45	cereal, pea, vetch, wheat	MT, NT
15	Iqbal et al., 2010	Pakistan	31.43	73.08	367	25	75	wheat	MT, NT
16	Ishaq et al., 2002	Pakistan	31.43	73.08	526	25	55	cotton, wheat	MT
17	Loke et al., 2012	South Africa	-28.15	28.28	743	20	69	oat, wheat	MchT, NT
18	Loke et al., 2018	South Africa	-28.15	28.28	695	20	69	oat, wheat	MchT, NT
19	Loke et al., 2021	South Africa	-28.15	28.28	695	20	69	oat, wheat	MchT, NT
20	Lopez-Fando et al., 2007	Spain	40.05	-4.43	400	23	56	barley, grey pea	MT, NT, ZT
21	Lopez-Fando & Pardo, 2009	Spain	40.05	-4.43	400	16	58	barley, grey pea	MT, NT, ZT
22	Lopez-Fando & Pardo, 2011	Spain	40.05	-4.43	428	23	58	barely, pea	MT, NT

Table 2 continued

23	Lopez-Garrido et al., 2009	Spain	37.36	-5.99	484	17	55	pea, sunflower, wheat	NT, RdT
24	Lopez-Garrido et al., 2011	Spain	37.36	-5.99	485	17	58	pea, sunflower, wheat	NT, RdT
25	Lopez-Garrido et al., 2012	Spain	37.36	-5.99	547	17	58	cereal, legume, pea, sunflower, wheat	RdT
26	Lopez-Garrido et al., 2014	Spain	37.36	-5.99	486	17	54	barely, cotton, pea, sunflower, wheat	NT, RdT
27	Ma et al., 2016	China	36.10	103.69	119	17	49	maize, wheat	NT
28	Madejón et al., 2007	Spain	37.28	-6.05	484	25	75	pea, sunflower, wheat	RdT
29	Madejón et al., 2009	Spain	37.28	-6.05	500	18	50	pea, sunflower, wheat	RdT
30	Melero et al., 2009a	Spain	37.28	-6.05	484	17	75	cereal, legume, sunflower	RdT
31	Melero et al., 2009b	Spain	37.28	-6.05	484	17	75	cereal, legume, sunflower	RdT
32	Mina et al., 2008	India	29.60	79.67	100	19	59	lentil, millet	NT
33	Modak et al., 2020	India	28.63	77.17	670	25	64	soybean, wheat	NT
34	Morell et al., 2011	Spain	41.80	1.12	430	14	47	barley	MT, NT

Table 2 continued

35	Moreno et al., 2006	Spain	37.20	-6.10	483	19	52	sunflower, wheat	RdT
36	Moussadek et al., 2014	Morocco	33.57	-6.70	450	15	45	lentil, wheat	NT
37	Niu et al., 2019	China	35.00	114.40	615	14	69	maize, wheat	NT
38	Nyamadzawo et al., 2007	Zimbabwe	-19.58	31.23	750	18	71	Acacia, maize, Sesbaniasesban	NT
39	Ouedraogo et al., 2006	Burkina Faso	12.42	-1.35	773	28	52	maize, sorghum	NT
40	Ouedraogo et al., 2007	Burkina Faso	12.42	-1.35	773	28	52	maize, sorghum	NT
41	Parihar et al., 2016	India	28.67	77.20	650	23	64	chickpea, maize, mungbean, mustard, Sesbania, wheat	NT
42	Parihar et al., 2018	India	28.67	77.20	704	25	64	chickpea, maize, mungbean, mustard, Sesbania, wheat	NT
43	Patra et al., 2023	India	28.67	77.20	650	23	64	chickpea, maize, greengram, mustard, Sesbania, wheat	NT
44	Roper et al., 2013	Munglinup	-33.61	120.87	522	18	93	canola, barley, hybrid canola, wheat	NT
45	Roper et al., 2021	Munglinup	-33.61	120.87	522	18	93	canola, barley, hybrid canola, wheat	NT
46	Saha et al., 2010	India	28.63	77.17	515	23	69	maize, mustard	MchT, NT

Table 2 continued

47	Salinas-Garcia et al.,1997	USA	27.76	-97.50	765	22	69	cotton, maize	MT, NT
48	Sharma et al., 2009	India	17.30	78.60	750	26	69	mungbean, sorghum	RdT
49	Singh et al., 2014	India	27.65	74.45	509	25	65	rice, wheat	NT
50	Wang et al., 2019	China	37.00	112.00	462	16	69	maize	NT, RdT
51	Wright et al., 2004	USA	27.76	-97.50	765	22	69	cotton, maize	MT, NT
52	Yeboah et al., 2016	China	35.47	104.73	391	38	69	pea, wheat	MchT, NT
53	Zhang et al., 2017	China	35.00	114.40	615	14	52	maize, wheat	MchT, NT
54	Zhang et al., 2018	China	35.00	114.40	615	14	52	maize, wheat	NT
55	Zibilske et al., 2002	USA	26.15	-97.95	600	24	60	cotton, maize	NT, RdgT

MT - Minimum Till; MchT - Mulch Till; NT - No Till; RdgT - Ridge Till; RdT - Reduced Till; ZT - Zone Till

Table 3: Meta-analysis summary statistics. Summary statistics of MAP, MAT, sand content, N fertilizer, duration of experiments, and soil organic carbon (SOC) under conventional tillage (CT) and conservational tillage (CST).

						CT	**CST**
	MAP (mm)	**MAT (°C)**	**Sand (%)**	**N Fertilizer (kg N ha^{-1})**	**Duration (yr)**	**SOC (g kg^{-1})**	
Minimum	100	7	45	0	1	0.65	0.81
Maximum	773	38	93	250	32	17.47	27.69
Mean	531.14	20.27	61.36	63.01	9.32	6.22	6.95
SD	141.99	6.41	9.94	69.75	7.10	2.87	3.70
Skewness	0.08	0.80	0.08	0.97	1.09	0.42	1.19
Quartile 1	430	16	53	0	3	4.60	4.75
Quartile 3	615	25.00	69	105	14	7.86	9.05
CV	26.73	31.63	16.19	110.70	76.15	46.17	53.20

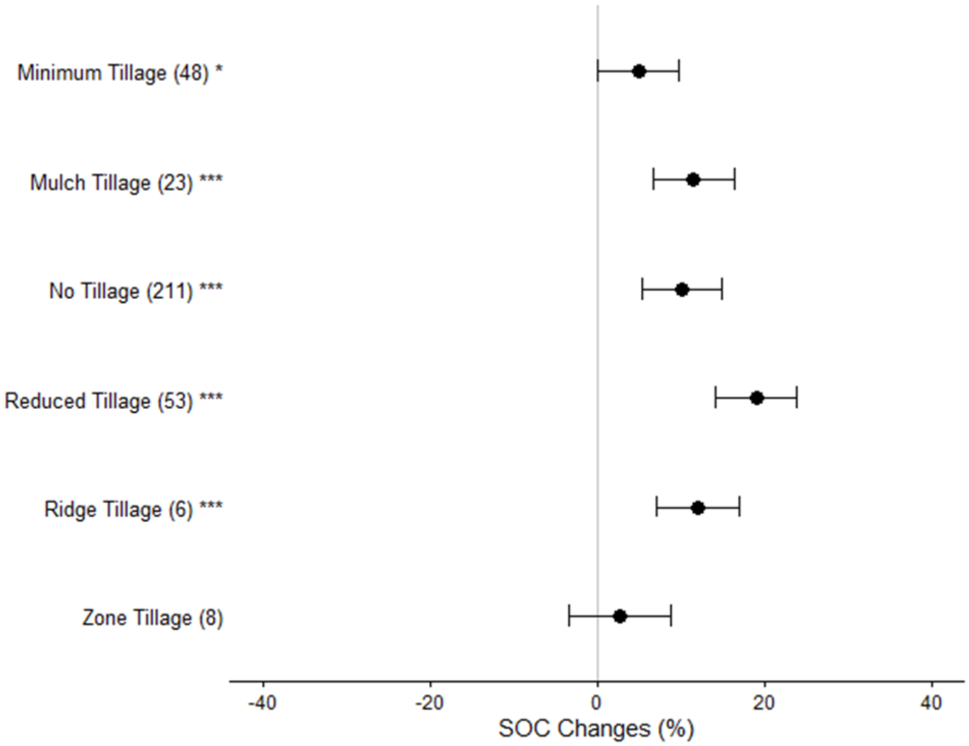

Figure 4: Soil organic carbon changes (SOC %) between conventional and conservational tillage. SOC % changes across different conservation tillage practices within 1 – 32 years. Numbers in the parentheses indicate the number of observations (349 observations total). Error bars represent 95% confidence intervals. Statistical significance was assessed at *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$.

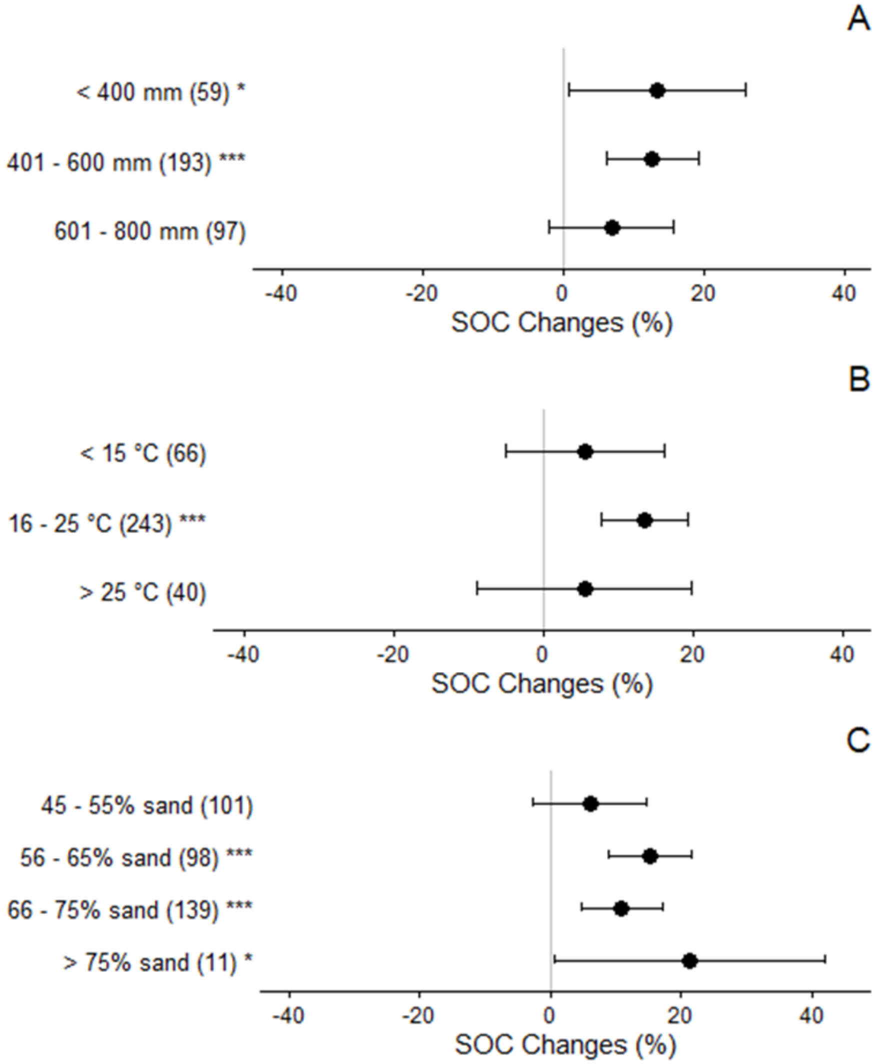

Figure 5: Soil organic carbon changes (SOC %) between conventional and conservational tillage across different edaphoclimatic gradients. SOC % changes across (A) different precipitation gradients, (B) different temperature gradients, and (C) different sand percentages. The numbers in the parentheses indicate the number of observations (349 observations total). Error bars represent 95% confidence intervals. Statistical significance was assessed at *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$.

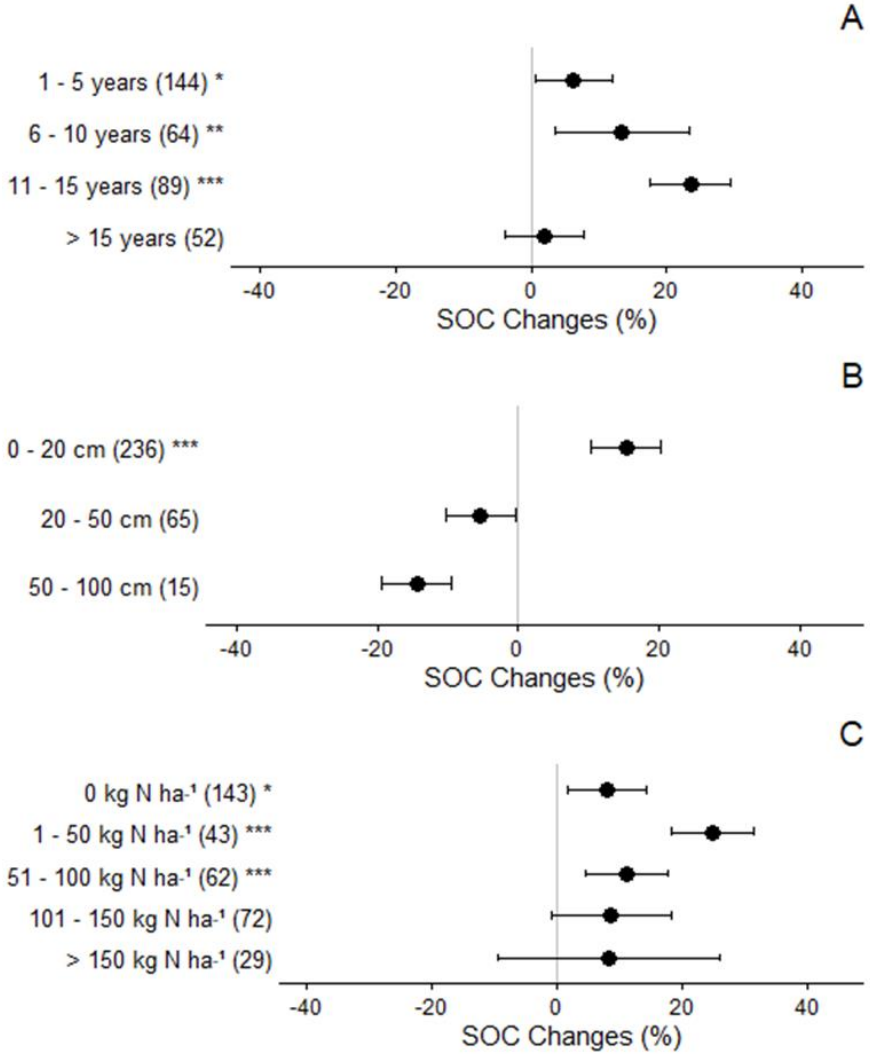

Figure 6: Soil organic carbon changes (SOC %) between conventional and conservational tillage across different experimental conditions. SOC % changes across different (A) durations in experiments (years), (B) depths of collected soil samples (cm), and (C) N fertilizer application rates (kg N ha^{-1}). The numbers in the parentheses indicate the number of observations (349 observations total, except B with 316 observations (see Materials & Methods Section 2.1). Error bars represent 95% confidence intervals. Statistical significance was assessed at *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$.

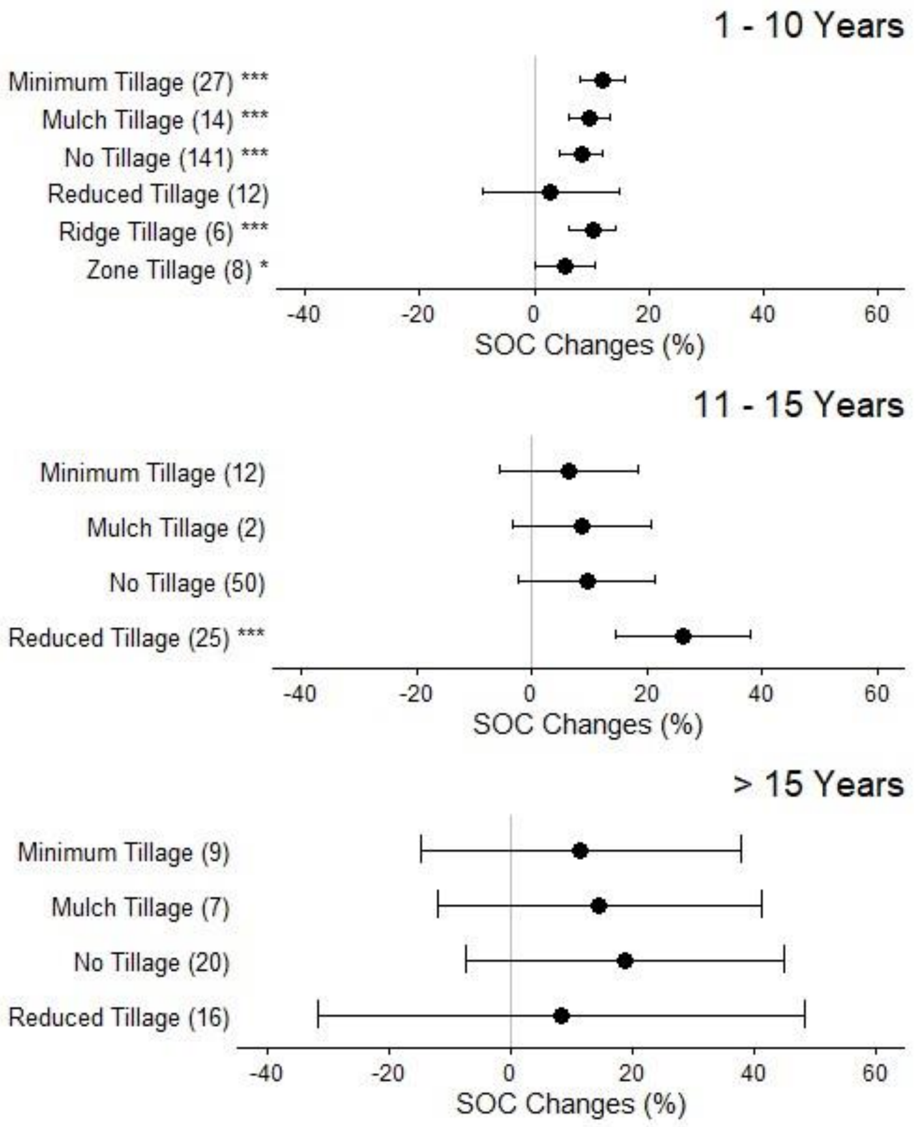

Figure 7: Soil organic carbon changes (SOC %) between conventional and conservational tillage across different time scales. Numbers in the parentheses indicate the number of observations (349 observations total). Error bars represent 95% confidence intervals. Statistical significance was assessed at *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$.

CHAPTER III

SOIL ORGANIC CARBON ACCUMULATION IN REFORESTED SUBTROPICAL THORN WOODLANDS: THE DUAL ROLES OF NITROGEN FIXATION AND LAND USE HISTORY

Abstract

Over the past few decades, millions of hectares of forests have become deforested worldwide attributed to agricultural expansion, resulting in CO_2 emissions, soil degradation, and biodiversity and habitat loss. Deforestation and soil degradation are global concerns, impacting the crucial role of soil in the global carbon (C) cycle. Degraded soils exhibit nutrient deficiencies, reduced water retention, structural issues, and low fertility, often resulting in crop failure and land abandonment. Reforestation on abandoned agricultural land, particularly in semi-arid climates, aims to address these issues. Despite the edaphoclimatic challenges of semi-arid climates, reforestation can enhance soil C sequestration through accumulated soil organic C (SOC) and improved soil structure. Here, we quantified the amount and rate of SOC accumulation in the established thorn woodland chronosequences of the Rio Grande Valley (RGV) after transitioning from cropland. The three chronosequence sites include Garza-Cavazos (GC), La Sal del Rey (SDR), and Southmost Preserve (SM), all of which have slight variations in reforestation ages and soil properties. This long-term study highlights the significant impact of reforestation on soil C sequestration in semi-arid regions, particularly highlighting the role of N fixation by leguminous trees and historic land use.

Introduction

In recent years, reforestation efforts have received significant attention for their role in climate change mitigation, improving soil health, and ecosystem restoration. Despite the potential benefits of reforestation initiatives, deforestation, primarily driven by urbanization and agricultural expansion, remains a significant challenge that has resulted in the global loss of approximately 420 million hectares of forests within the last three decades (Curtis et al., 2018; FAO, 2022; Kunte & Bhat, 2024). Deforestation has resulted in various environmental consequences, including soil degradation, reduced forest cover, biodiversity loss, habitat fragmentation, and increased CO_2 emissions (Chakravarty et al., 2012; Cochard, 2011).

As agriculture expands, land under crop cultivation often involves intensive tillage practices that disrupts soil aggregates, accelerates organic matter decomposition, and reduces SOC by 50% (Guo & Gifford, 2002; Kunte & Bhat, 2024; Li et al., 2012; Murphy et al., 2011; Six et al., 2000). These practices eventually result in low crop productivity and land abandonment, all of which are further exacerbated in semi-arid regions (Cerdà et al., 2018; Gachene et al., 2020; Lana-Renault et al., 2020). Semi-arid climates, constituting 15% of terrestrial land, support approximately one billion people and about 45% of global agricultural production across various dryland regions (Scholes, 2020; Singh & Chudasama, 2021). However, high temperatures limit vegetation growth with insufficient soil moisture, leading to reduced nutrient availability and carbon (C) input, typically less than 2% (Abdelhak, 2022; Ravi et al., 2011; Singh & Chudasama, 2021; Yost & Hartemink, 2019). Therefore, agricultural cropland under semi-arid climates does not remain productive for long periods and should be restored before irreversible soil degradation occurs.

Semi-arid climates comprise over 500 million hectares of forests (Bastin et al., 2017; Guirado et al., 2022), and are regions frequently being targeted for reforestation efforts (Rohatyn et al., 2021; Yildiz et al., 2022; Yosef et al., 2018). The predicted expansion of semi-arid climates, the potential to sequester C, and the need to restore ecosystem functions influences reforestation initiatives (Albrecht et al., 2022; Grünzweig et al., 2007; Liu et al., 2018; Korkanç, 2014). Studies have shown that semi-arid climates have increased by over 5% from the 1960s to the 2000s (Holzapfel, 2008; Huang et al., 2016; Gaur & Squires, 2017) and are predicted to expand in the next century by 5 – 15% under climate change (Lian et al., 2021; Plaza et al., 2018; Yildiz et al., 2022). Therefore, understanding the capacity of soils under reforestation to accumulate and recover C post deforestation and intensive agriculture, along with critical factors influencing soil C sequestration, is crucial in semi-arid regions.

Reforestation over time restores soil quality and enhances C sequestration, with forests storing 120t C ha^{-1} compared to 90t C ha^{-1} in agricultural fields (Cunningham et al., 2015). Over time, abandoned croplands can see an increase of SOC by 14 – 18% with reforestation (Grünzweig, 2007; Veldkamp et al., 2020). However, reforested sites under semi-arid climates struggle to reach 50t C ha^{-1} and recover from intensive agricultural practices (Bell et al., 2021; Novara et al., 2017).

In the Rio Grande Valley (RGV), urbanization and agricultural expansion have resulted in the loss of over 90% of native Tamaulipan thorn forests (Jahrsdoefer & Leslie, 1988). Tamaulipan thorn forests are unique to the RGV and northeastern Mexico (TCP, 2022). These ecoregions support over 1,200 native plant species, 500 bird species, 300 butterfly species, as well as 45 federal and state threatened or endangered species (Mohsin, 2020; TCP, 2022). These forests are dominated by thorny shrubs and trees, though vary in mixed vegetation of desert and forest like plant communities (Mohsin, 2020; TCP, 2022).

Since the 1960s, about 6,500 hectares of abandoned fields have been reforested, yet approximately 7,200 hectares still have the potential to be reforested (Albrecht, 2022; Wahl-Villarreal & Dale, 2021). These subtropical thorn woodlands are expected to expand due to rising temperatures and low precipitation rates (Lanuza et al., 2023; Navarro et al., 2024), thus making them critical targets for reforestation initiatives. With their resilience to drought, these forests can expand into tropical forests under water-stressed conditions (Navarro et al., 2024; TCP, 2022). Furthermore, these subtropical thorn woodlands in the RGV are crucial biodiversity hotspots and potential areas to sequester soil C, especially under climate change and anthropogenic influences (TCP, 2022).

Despite previous analyses of thorn woodland seedling survival, aboveground biomass, and species succession (Albrecht et al., 2022; Mohsin, 2020; Contreras, 2022), no studies, to our knowledge, have assessed soil C dynamics in these reforested woodlands of the RGV. Chronosequences are great settings to estimate the effects of reforestation on soil C dynamics, which are plots varying in time since reforestation planting, sharing similar environmental conditions (Dixon, 2022; Stevens & Walker, 1970). Therefore, the objective of this study was to quantitatively assess SOC accumulation rates through a reforestation chronosequence approach in the RGV to elucidate the long-term impacts of reforestation of subtropical thorn woodlands.

Materials and Methods

Site Descriptions

This study was implemented in the RGV, often described as a delta, gently sloping away from the meandering Rio Grande River, consisting of over 1,000,000 hectares (Richardson &

King, 2011; Vora, 1992). The RGV is one of the most biologically diverse region in North America with over 1,200 native flora and fauna species (Best, 2006; TCP, 2022). The RGV consists of four counties (Cameron, Hidalgo, Starr, and Willacy), though the selected reforested chronosequence sites are only within Cameron and Hidalgo County (Figure 8).

The RGV experiences a semi-arid, subtropical climate, with hot summers, erratic precipitation, droughts, and mild winters (Leslie Jr., 2016), resulting in the prevalence of Tamaulipan thorn forest ecoregions, which is a type of subtropical thorn woodland. The average annual temperature is 24.5°C (average minimum and maximum temperatures are 15°C and 31°C, respectively). Average annual precipitation is 530 – 700 mm per year (Cruce Alvarez & Plocheck, 2014), and is described as having a west to east gradient, in which subtle variations in aridity, soil composition, and moisture regimes occur between upland and floodplain soils (Best, 2006; Leslie Jr., 2016). Upland soils occur in the north and west regions of the RGV, which are mainly sandy or sandy loam soils that results in spiny, stunted trees and shrubs, while floodplain soils are silty or clay, alluvial soils that has greater forest coverage (Heep & Lester, 2011; Vora, 1992).

There are three main chronosequence sites – Garza Cavazos (GC), La Sal del Rey (SDR), and Southmost Preserve (SM). The reforestation sites comprise native species found in the RGV and subtropical thorn woodlands, which can be leguminous and drought-resilient species. Common species planted in reforestation sites include honey mesquite (*Prosopis glandulosa*), Texas ebony (*Ebenopsis ebano*), huisache (*Vachellia farnesiana*), retama (*Parkinsonia aculeata*), Blackbrush acacia (*Vachellia rigidula*), anaqua (*Ehretia anacua*), and tepeguaje (*Leucaena pulverulenta*) (Albrecht et al., 2022; Ewing & Best, 2004). Reforested sites also have the presence of invasive, C_4 grasses, such as guinea (*Megathyrsus maximus*), buffel (*Cenchrus ciliaris*), and bermuda (*Cynoden dactylon*) grasses (Best, 2006).

Most land abandonment in these sites occurred at least 2 years before reforestation. Each chronosequence has four reforested sites, though were reforested in different years (Figure 9). Old-growth forests representing reference plots of undisturbed patches of thorn woodlands were also included in this study to assess whether reforestation restored soil C. However, GC was the only chronosequence without an old-growth forest plot. Reforestation was originally done via direct seeding in the 1960s, though is now accomplished via transplanting of seedlings in tree shelter tubes in nurseries across the RGV (Ewing & Best, 2004; Wahl-Villarreal & Dale, 2021).

Garza Cavazos (GC). Chronosequence GC is located between the Rio Grande River and San Pedro, Texas (25.99503 N, -97.61229 W). Previous land use was under annual row crops with conventional tillage practices and flood irrigation. The site has floodplain characteristics comprising alluvial, loam soil with 25% clay, 40% sand, and 36% silt. The size of each reforested plot ranges from 4.3 hectares to 7.8 hectares.

La Sal del Rey (SDR). Chronosequence SDR is a part of a national wildlife refuge with the U.S. Fish & Wildlife Services, located near Linn, Texas (26.53687 N, -98.05694 W). Previous land use was also under annual row crops with conventional tillage practices, though under rainfed irrigation. The site has upland characteristics comprising loamy sands, with 87% sand, 6% clay, and 8% silt. The size of each reforested plot ranges from 1 hectare to 35 hectares.

Southmost Preserve (SM). Chronosequence SM is located in the Southmost Preserve at the southmost tip of Texas (25.85362 N, -97.39766 W). Previous land use was citrus production and less frequent tillage, resulting in fertile soil. The site also has floodplain characteristics, comprising an alluvial, clay loam soil, with 40% clay, 28% sand, and 32% silt. The size of each reforested plot ranges from 0.9 hectares to 3.4 hectares.

Soil Sampling and Analysis

For each plot within each chronosequence, 15 soil samples were collected up to 20 cm in a random transect every 5 meters for a total of 75 meters. Soil samples were collected in 2020 for the GC and SDR sites, while soil samples for SM were collected in 2022. A total of 210 soil samples were collected and analyzed in different sets to obtain SOC and N data in the reforested chronosequences of the RGV. Soil lab procedures include SOC, soil total N, stable isotopic signature of C (^{13}C) and N (^{15}N), soil respiration, and active C.

Soil Organic Carbon and ^{15}N Isotopic Signatures. To obtain SOC data, the first set of soil samples were dried and weighed at approximately 30 mg into silver (Ag) capsules using a microbalance. Based on the protocol by Harris et al., (2001), the soil samples were fumigated for 24 hours with 100 mL of concentrated Hydrochloric acid (12M HCl) to remove soil carbonates. After 24 hours, the soil samples were placed in the oven at 60°C to dry for 12 hours. Soil samples were combusted using a CHNS Elemental Analyzer to estimate the SOC content in the soil of each chronosequence. Although there was no available OF plot for GC, we estimated SOC saturation using the equation proposed by Hassink, (1997), where $SOC_{saturation}$ (g kg^{-1}) = 4.09 + 0.37 (clay + silt), thus resulting in the estimated value of 59.27t C ha^{-1} as a SOC saturation point for GC.

To analyze N and ^{15}N in the soil, an Elemental Analyzer (EA) – Isotope Ratio Mass Spectrometer (IRMS) was used at UC Davis. Stables isotopes are beneficial for tracing soil nutrient sources and cycling over time. Microbial activity, plant assimilation, and soil cycling processes cause C and N fractionation, resulting in distinct ^{13}C and ^{15}N signatures. Soil ^{15}N data helps analyze the N cycle, reflecting processes such as N fixation, nitrification, denitrification, or external inputs like fertilizers (Garten Jr. et al., 2007). The second set of soil samples were dried, grinded, and weighed as per UC Davis guidelines. The soil samples were encapsulated into tin (Sn) capsules (combustion catalyst) at 5.5 mm (5 x 9 mm). As the soil samples undergo combustion, soil oxidation results in the release of CO_2, N_2 and distinct isotopic ratios of C and N, which were compared to known standards of ^{13}C (VPDB) and ^{15}N (air). To avoid compromising ^{15}N data in the EA-IRMS (Harris et al., 2001), soil carbonates were retained in this set of soil samples. Therefore, our ^{13}C data was not shown, as most ^{13}C signatures were driven by the high inorganic C content (Harris et al., 2001).

Soil Texture. Using the hydrometer method, 50g of soil was grinded and sieved through a 2mm sieve. The 50g of soil was placed into a graduated cylinder and mixed with 100mL of sodium hexametaphosphate and 900mL of water. Each graduated cylinder was mixed, and a hydrometer was placed into each cylinder to measure the density of the mixture. The hydrometer first floats, as the mixture has high density, but begins to sink once the larger particles sink and decrease the density of the mixture. This is due to Stoke's Law, where large particles sink faster than smaller particles due to the forces of gravity, buoyancy, and drag in the soil water. Data was recorded from the hydrometer at 40 seconds, 4 minutes, 37 minutes, and 2 hours to calculate the percentage of sand, silt, and clay.

Soil Respiration. Soil respiration is a general indicator of soil microbial activity by trapping and quantifying CO_2 released from a re-wetted soil sample, as the moisture rapidly causes microbes to activate. A third set of soil samples weighed at 10g were prepped into jars with a vial of 10mL solution of 1M sodium hydroxide (NaOH), which were incubated for 10 days total. After 10 days, the NaOH vials were mixed with 2mL of 10% Barium chloride ($BaCl_2$)

and Phenolphthalein as an indicator (turning the solution pink) to begin titration. The NaOH was then titrated with 0.5M HCl and the amount of HCl was recorded once the solution became transparent. Greater CO_2 release indicates more microbial activity participating in nutrient cycling and the decomposition of organic material.

Soil Active Carbon (POXC). Analyzing permanganate oxidizable C measures labile (easily available) C as a food source for microbes to carry out microbial activity. This active C in the soil sample becomes oxidized by the potassium permanganate (KMnO4) solution. This oxidation results in the loss of the $KMnO_4$ solutions' purple color, indicating active C. All soil samples (2.5g) were processed and read in a colorimetric spectrophotometer at a wavelength of 550nm. A light, purple solution color absorbs less light meaning more active C, and vice versa.

Vegetation Coverage. The proportion of trees and shrubs vs grasses and bare soil was estimated in each chronosequence using ArcGIS Pro and the Land Use Land Cover (LULC) data from the Environmental Systems Research Institute (ESRI). For each site, vegetation data was gathered during the same period as the soil samples, guaranteeing that both datasets match in terms of their collection dates.

Results and Discussion

Analysis of SOC content across the reforested chronosequence sites revealed varying trends influenced by site-specific factors, such as clay content, tree percentage, and historical land use, which are related to soil C and N dynamics (Table 4). Despite experiencing similar climates and forest species composition, the differences in these site-specific factors contributed to the diverse trends observed in SOC across the chronosequences. Chronosequences GC and SDR each experienced significant increases in SOC, albeit at different rates, while SOC in SM remained unchanged over the 22-year chronosequence.

Chronosequence GC displayed the clearest and fastest SOC increase, with an accumulation rate of 0.46t C ha^{-1}yr^{-1} (Figure 10a) and reaching approximately 37t C ha^{-1} over 36 years. The initial gap in SOC between the younger sites and the estimated SOC saturation point was approximately 60%, with an old-growth site estimated to have 59.27t C ha^{-1} (Figure 13a). As the reforested sites matured, this SOC gap decreased by approximately 20% over the span of 28 years, indicating progressive trends toward the estimated SOC saturation. Although the oldest reforested site did not reach the estimated saturation, the continuous and significant accrual of SOC in this site emphasizes the effectiveness of reforestation on soil C sequestration in a semi-arid, subtropical climate. Other studies have also revealed SOC accumulation of 0.3 – 0.5t C ha^{-1}yr^{-1} within semi-arid, sub-tropical climates, though differed in plant composition and soil textures (Bell et al., 2021; Deng & Shangguan, 2017; Qiu et al., 2015; Shao et al., 2019).

Chronosequence SDR experienced smaller increments of SOC over time at a rate of 0.14t C ha^{-1}yr^{-1} (Figure 10b). Despite the slow accumulation over 24 years, SOC reached 9.78t C ha^{-1}, representing a 50% gap relative to its old-growth reference site, which we consider as the SOC saturation point. In the younger sites, there was a SOC gap of over 60% relative to its old-growth reference site, though within 24 years, the SOC gap decreased by 10% (Figure 13b). To reach the SOC levels of the old-growth reference site, it would take at least 80 more years before nearing its SOC saturation point, assuming there are no other stressors limiting the accumulation rate. The notably lower SOC accumulation rate in SDR compared to GC can attributed to the higher sand content in SDR, which leads to soils with reduced nutrient and moisture retention (Bassett et al., 2023; Lewis et al., 2019; Paul et al., 2008). This condition facilitates the spread of invasive grasses, which are also drought-resilient, that can have a competitive advantage when compared to the early stages of tree seedling growth (Garbowski et al., 2021; Miniat et al., 2021). Such grasses can affect the overall tree seedling survival and the long-term productivity of a reforested site, as they compete for the same water, nutrients, space, and light (Albrecht et al., 2022). Therefore, this results in sparser tree coverage and fewer C inputs in SDR, as detailed in Table 4. Thus, reforestation efforts can lead to soil C sequestration in sandy soils, though at much slower rates attributed to greater grass coverage and low clay contents (Deng & Shangguan, 2017).

In GC and SDR, the significant accrual of SOC is likely attributed to the N-fixing tree species promoting soil C and N (Figure 10 and 11), as evidenced by the decrease of ^{15}N (Figure 12a and b). High N losses results in the enrichment of ^{15}N, whereas N accumulation results in the depletion of ^{15}N (Park et al., 2023; Evans, 2007), thus supporting our results in Figures 11 and 12. Therefore, the presence of leguminous tree species associated with N-fixing microbes leads to ^{14}N accumulation and a gradual dilution of ^{15}N over time, resulting in a direct increase in N and SOC, (Figure 13a and 14a) (Choi et al., 2023; Cotrufo et al., 2019; Mudge et al., 2014; Xue & An, 2018). In the alluvial, loam soil of the GC chronosequence, the presence of leguminous trees enhanced N-fixation rates, which not only diluted ^{15}N from 7‰ to 5‰, but also significantly increased both TN and SOC (Figure 11a and 13a). Conversely, in chronosequence SDR, the high sand content and a larger presence of grass resulted in lower SOC, attributed to the slower N-fixation rates associated with minimal tree coverage (Figure 11b and 13b).

Despite its high clay content (40%), the SOC levels in chronosequence SM have remained stable over the years (Figure 10c), suggesting that the site may have reached its C saturation point, which represents its maximum C storage capacity (Angers et al., 2011; McNally et al., 2017). The SM chronosequence soils were likely less degraded than those at GC and SDR, exhibiting the highest SOC content among the three chronosequence sites across all years (approximately 45t C ha^{-1}) (Figure 15) and the smallest SOC gap relative to the old-growth reference site (approximately 10%). At SM, the youngest sites required an additional 15% SOC to match old-growth forest levels, though decreases to about 10% as the forests matured, as shown in Figure 13c. Unlike GC and SDR, where land was predominantly used for conventionally tilled annual row crops, SM's historical land use involved citrus groves that were infrequently tilled, primarily for weed control (Sauls, 2008), thus having more SOC than croplands (Hammad et al., 2020).

The C saturation limit in SM was possibly maintained over the years due to the balance between C inputs from above- and below-ground biomass and C outputs via microbial decomposition and respiration, as well as the possibility of increased aggregate protection of SOC (Jandl et al., 2007; Moinet et al., 2023; Rodriguez et al., 2023; Six et al., 2002a). As tree coverage increased over the years (Table 4), fresh C inputs increased, which resulted in sufficient energy sources for microbes to carry out their metabolic and respiration activities. As described by Tao et al., (2023), microbial C use efficiency can determine the accumulation or loss of SOC over time. Microbes can utilize C for growth, resulting in greater microbial biomass and by-products to accrue SOC; however, microbial enzymes could also be enhanced, which would result in SOC loss over the years (Tao et al., 2023). As such, our results revealed significantly higher soil respiration rates in SM (approximate average of 0.04g C $kg^{-1}day^{-1}$) than in GC and SDR (approximate average of 0.01g C $kg^{-1}day^{-1}$) (Table 4).

Greater respiration rates could be attributed to higher clay content retaining greater soil moisture and SOC levels to support microbial activity when compared to the lower clay contents in GC and SDR (Osman et al., 2023; Rodrigues et al., 2023). Although leguminous tree species are present in these reforestation sites, the increases in ^{14}N from atmospheric fixation are being utilized by the soil microbes, resulting in fractionation of ^{14}N over ^{15}N and the overall stable high values of ^{15}N in SM (Figure 12c and 14b) (Choi et al., 2023; Evans, 2007). These high, stable ^{15}N values suggest unchanged levels of N and SOC (Unkovich & Pate, 2001; Choi et al., 2020; Park et al., 2023).

Conclusions

This study has demonstrated that SOC accumulation is closely associated with N-fixation, highlighting the beneficial role of N-fixing species in enhancing SOC in degraded dryland ecosystems. The historical state of degradation and previous agricultural practices, such as annual row cropping and conventional tillage, critically determine the potential for SOC accumulation. These practices have left a significant portion of subtropical arid regions highly degraded, underscoring the pressing need for reforestation efforts that can significantly augment soil C stocks. Despite the challenges and the lengthy timeframe required to accumulate soil C in these highly degraded soils, our findings affirm that increasing SOC is feasible in soils with high degradation, especially with the presence of N-fixing species. The textural composition of the soil also plays a crucial role in this process. Soils with higher clay content retain more moisture that can facilitate the survival of trees and subsequent C inputs. Conversely, sandier soils tend to support a higher prevalence of grasses, which accumulate soil C at slower rates due to less favorable conditions for tree growth. In cases where the soil is only lightly degraded but high in clay content, the potential for additional carbon accumulation remains limited. This highlights the nuanced relationship between soil texture, moisture retention, and the capacity for C sequestration. In conclusion, the interplay of N-fixation and land use history not only shapes the potential for SOC accumulation but also points to the strategic importance of selecting appropriate reforestation species and managing land use histories for effective environmental restoration and carbon sequestration in subtropical thorn woodlands.

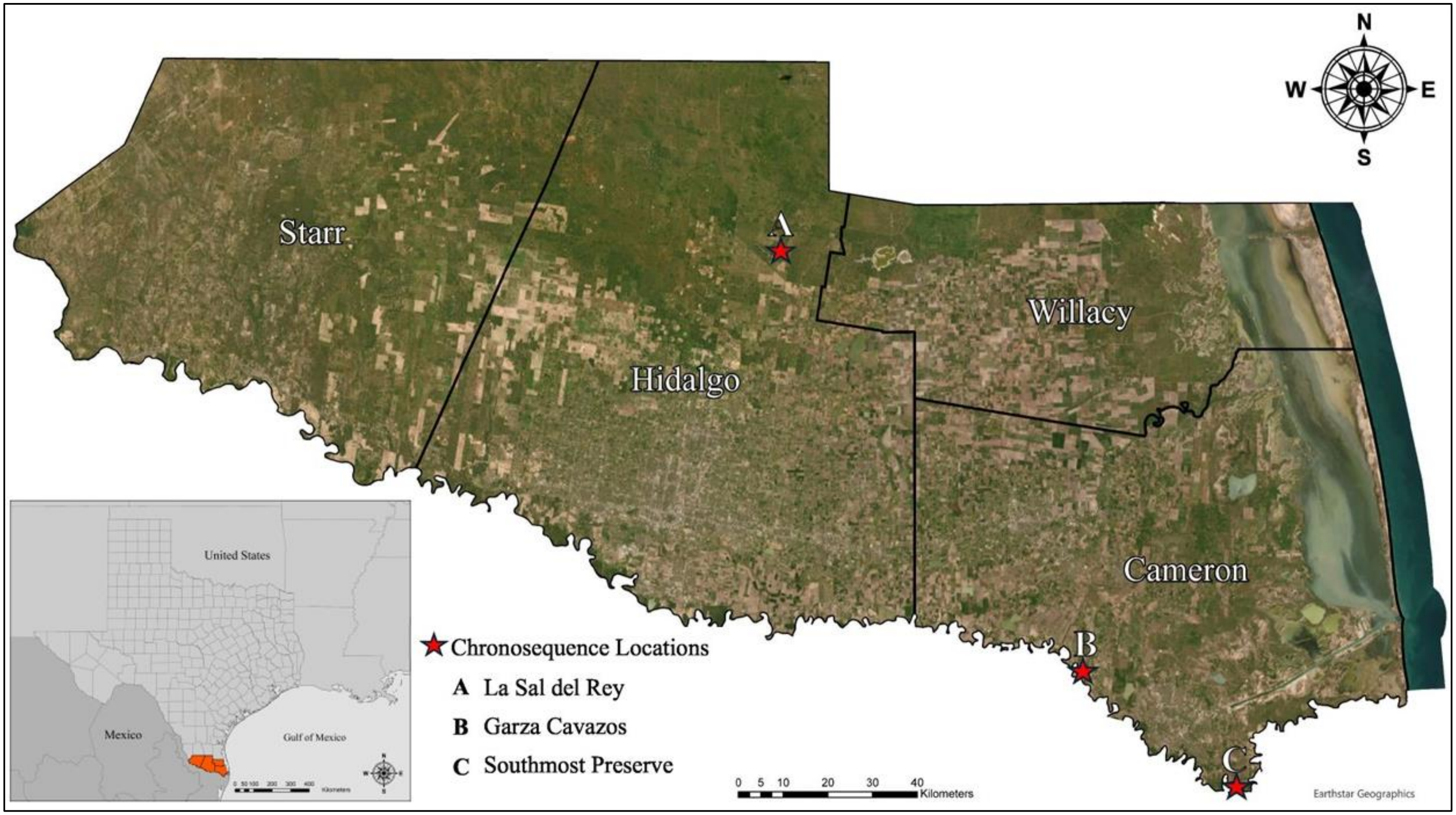

Figure 8: Location of the studied chronosequences in the Rio Grande Valley, Texas.

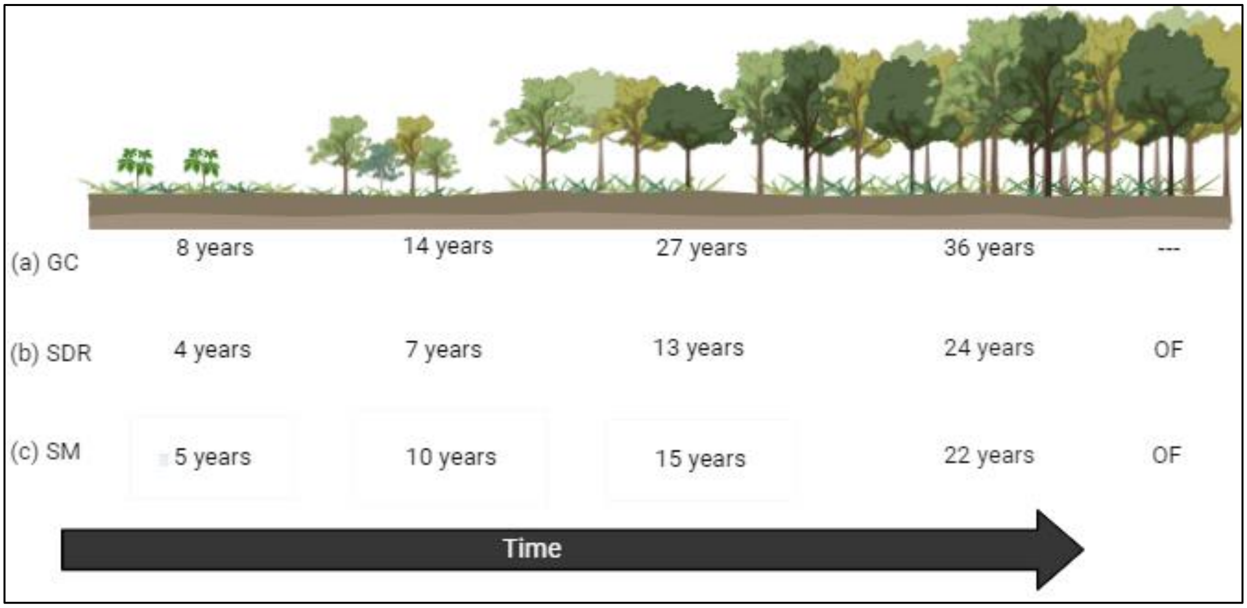

Figure 9: Age of reforested plots for each chronosequence. (a) Garza-Cavazos (GC) (b) La Sal del Rey (SDR) (c) Southmost Preserve (SM). Old-growth Forest (OF) is available for two sites.

Table 4: Estimated averages of soil C and N properties across chronosequence Garza Cavazos (GC), La Sal del Rey (SDR), and Southmost Preserve (SM).

Site	**Age**	**TC (ton ha^{-1})**	**TN (ton ha^{-1})**	**SOC (ton ha^{-1})**	**^{15}N (‰)**	**Respiration (g kg^{-1} day^{-1})**	**POXC (g kg^{-1})**	**Tree Cover (%)**	**Grass Cover (%)**
GC	8	59.19^{d}	2.07^{cd}	23.89^{e}	7.18^{de}	0.009^{c}	1.426^{de}	89.68	10.32
	14	71.70^{bc}	2.48^{c}	28.95^{d}	6.27^{ef}	0.013^{bc}	1.426^{de}	89.35	10.65
	27	88.30^{a}	4.06^{b}	35.65^{c}	5.67^{f}	0.014^{bc}	1.427^{cd}	99.07	0.93
	36	90.63^{a}	4.92^{a}	36.59^{c}	5.27^{f}	0.015^{bc}	1.427^{bc}	99.86	0.14
SDR	4	8.53^{e}	0.81^{e}	7.37^{f}	8.54^{bc}	0.006^{c}	1.425^{e}	2.83	97.17
	7	8.55^{e}	0.85^{e}	7.39^{f}	10.60^{a}	0.006^{c}	1.426^{e}	1.52	98.48
	13	12.47^{e}	1.29^{de}	10.77^{f}	9.08^{b}	0.014^{bc}	1.426^{e}	3.28	96.72
	24	11.32^{e}	0.96^{e}	9.78^{f}	7.85^{cd}	0.006^{c}	1.425^{e}	22.47	77.53
	OF	25.45	2.34	21.91	7.00	0.024	1.426	80.19	19.81
SM	5	73.69^{bc}	2.72^{c}	43.50^{ab}	8.41^{bc}	0.031^{ab}	1.428^{ab}	38.04	61.96
	10	67.48^{bcd}	2.52^{c}	39.68^{bc}	6.79^{e}	0.048^{a}	1.428^{abc}	65.89	34.11
	15	65.66^{cd}	2.33^{c}	38.65^{c}	6.73^{e}	0.029^{ab}	1.427^{cd}	80.78	19.22
	22	75.85^{b}	2.66^{c}	44.60^{a}	8.52^{bc}	0.043^{a}	1.429^{a}	98.11	1.89
	OF	85.58	5.04	50.71	10.74	0.052	1.429	98.17	1.83

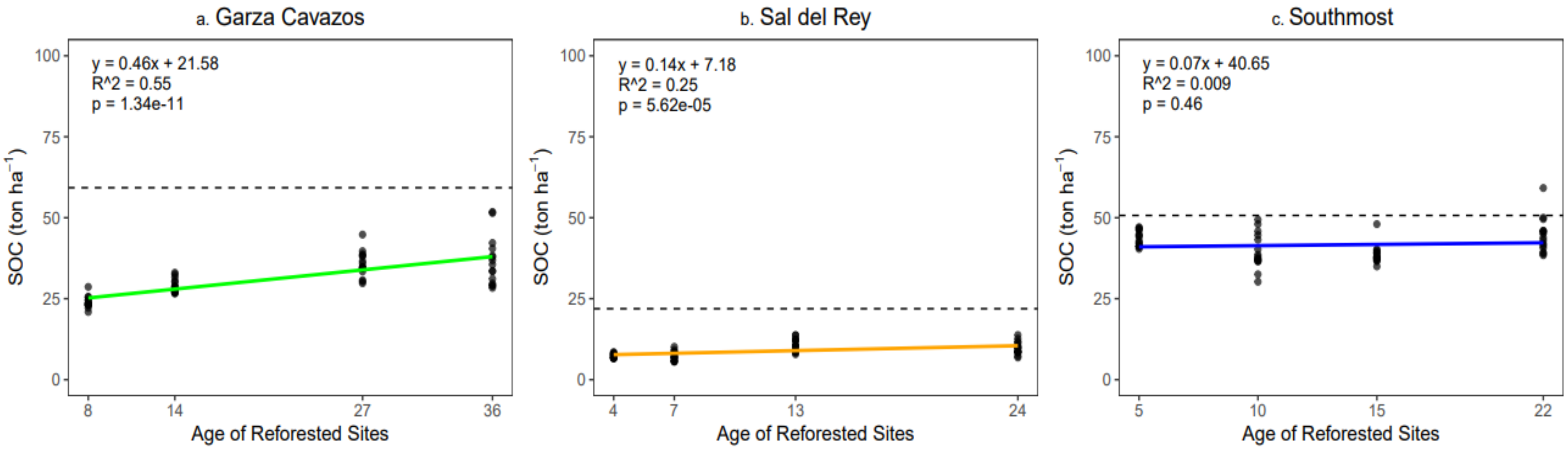

Figure 10: Linear trend analysis of SOC across each chronosequence. The dashed line represents the old growth forests SOC saturation limit for each chronosequence.

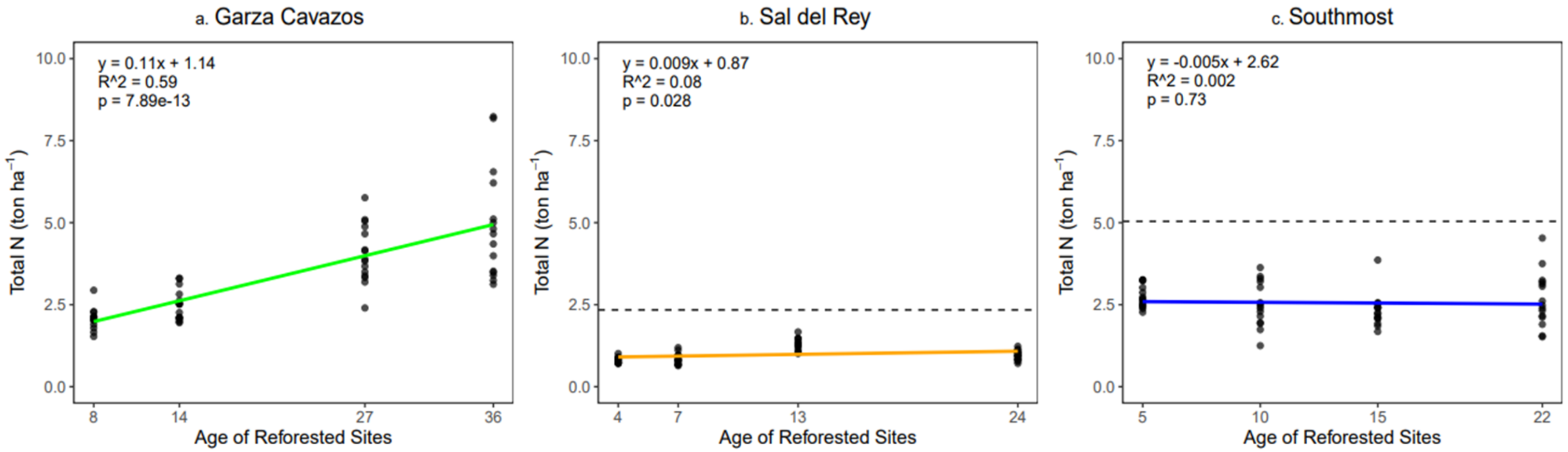

Figure 11: Linear trend analysis of total N across each chronosequence.

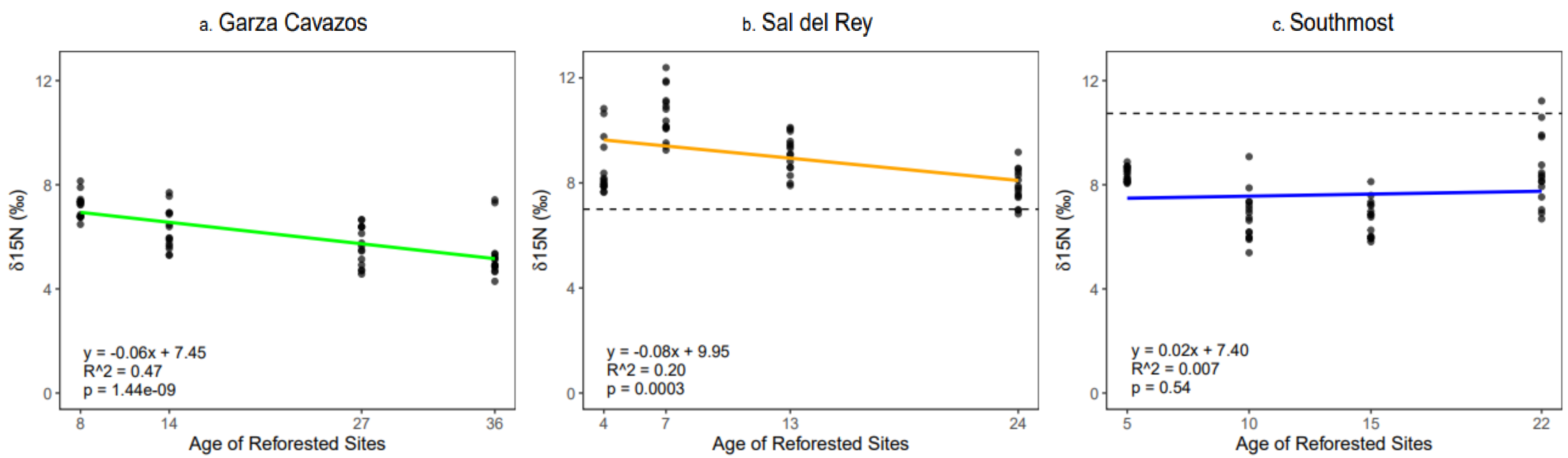

Figure 12: Linear trend analysis of ^{15}N across each chronosequence.

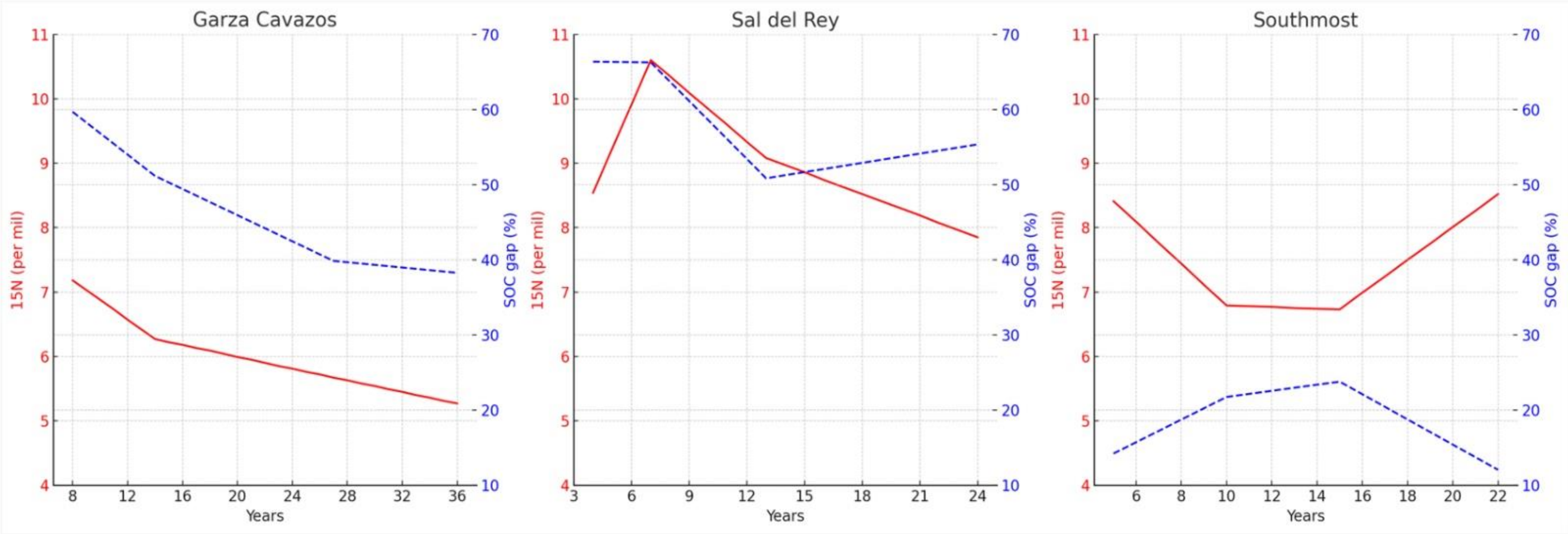

Figure 13: Relationship between SOC changes and ^{15}N. SOC gap is the percentage of SOC needed to reach reference site levels.

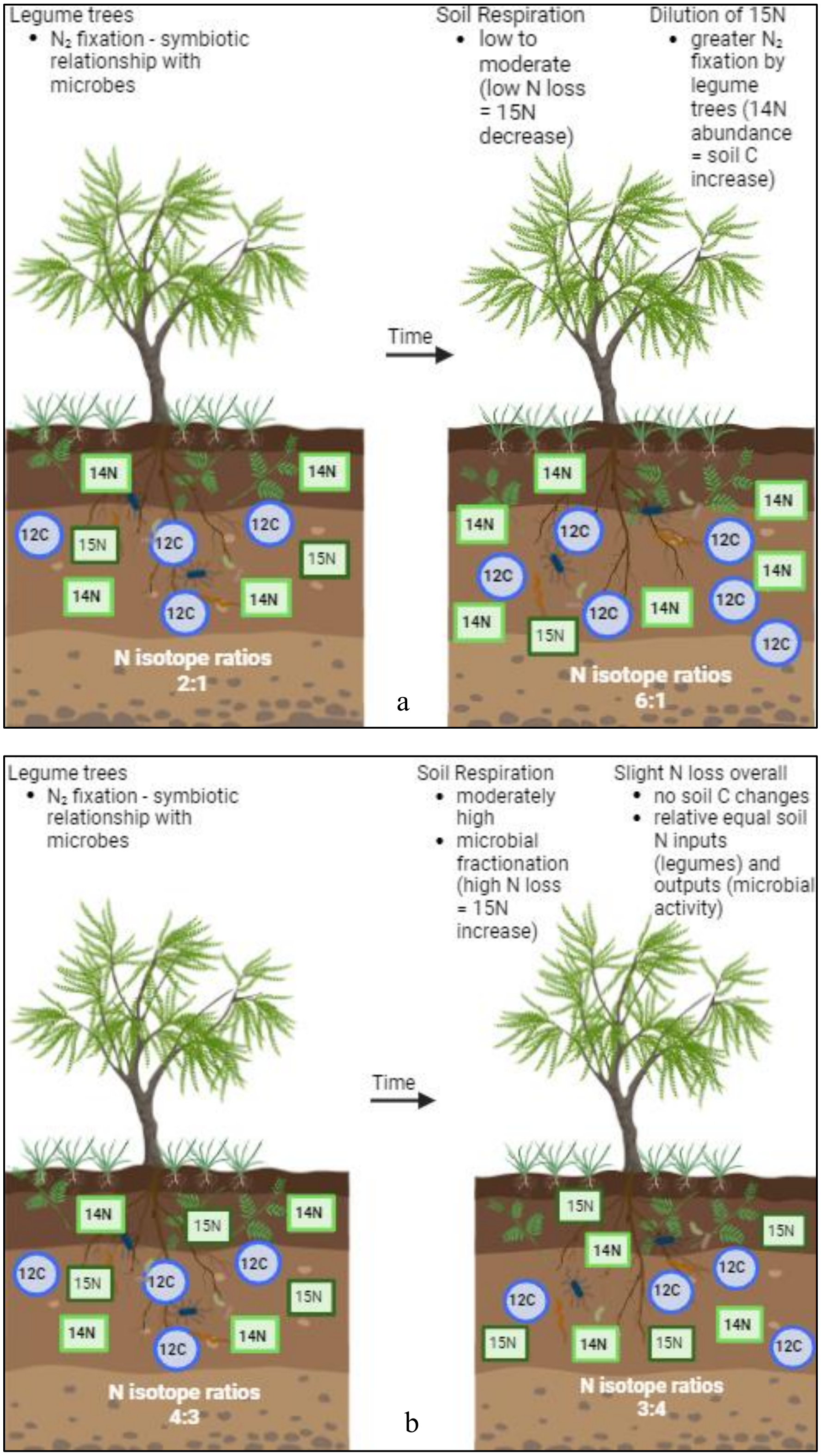

Figure 14: Visualization of C and N cycling scenarios under reforested chronosequences. (a) The top illustration represents both GC and SDR. (b) The bottom illustration represents SM.

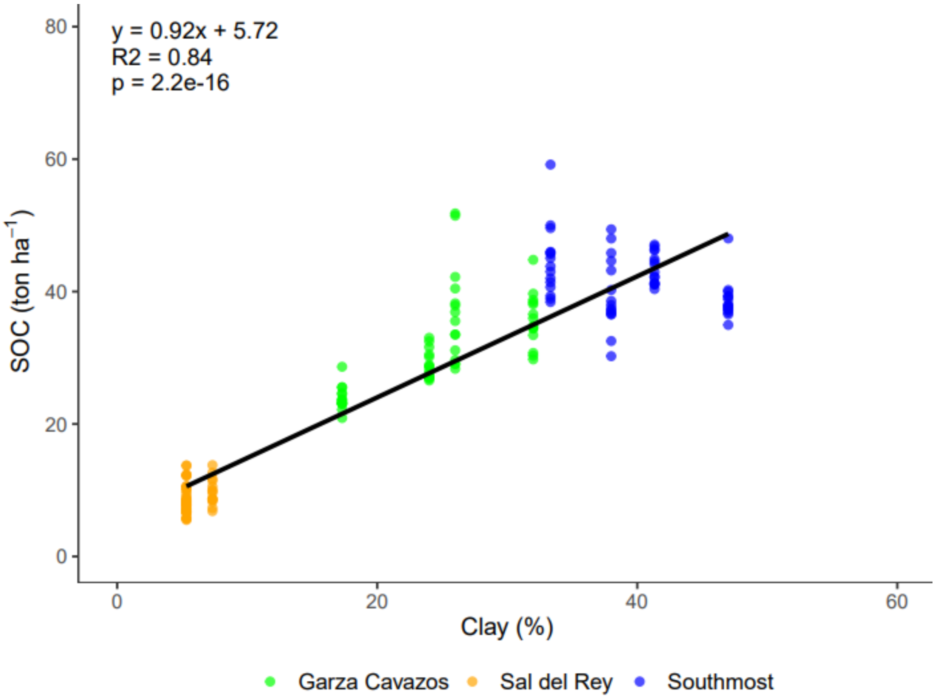

Figure 15: Influences of clay content on SOC across all chronosequence sites.

CHAPTER IV

CONCLUSIONS

This thesis investigate to what extent conservation tillage and reforestation improves SOC in degraded soils under arid and semi-arid cliamtes. Chapter 2 showed that conservation practices support the significant increase of SOC by 9% in sandy soil of arid and semi-arid climates within 10 years after converting to conservation tillage. By reducing tillage practices, soil health is improved as greater SOC storage results in greater nutrient and water retention abilities and greater aggregation to improve soil structure. Chapter 3 revealed that reforestation of abandoned croplands also resulted in a significant accumulation of SOC, though mostly under highly degraded soils. Based off our data, SOC was able to significantly increase by approximately 20% within 10 years after reforestation. This increase is attributed to the N-fixation of leguminous tree species resulting in the accumulation of soil N to support plant productivity, ultimately leading to soil C inputs. To conclude, soil is a finite and diminishing natural resource that must be preserved and restored. Conserving soil resources in agricultural land is imperative with a growing human population, as cultivated land is also diminishing due to soil degradation and is limited to expansion due to urbanization. To aid in soil conservation, restoration, and climate change mitigation, soil organic matter must increase in soils to result in sequestered soil organic C. Therefore, implementing land management practices, such as conservation tillage and reforestation, would aid in improving soil health and conserve soil resources (Figure 16), all of which would be beneficial for future generations.

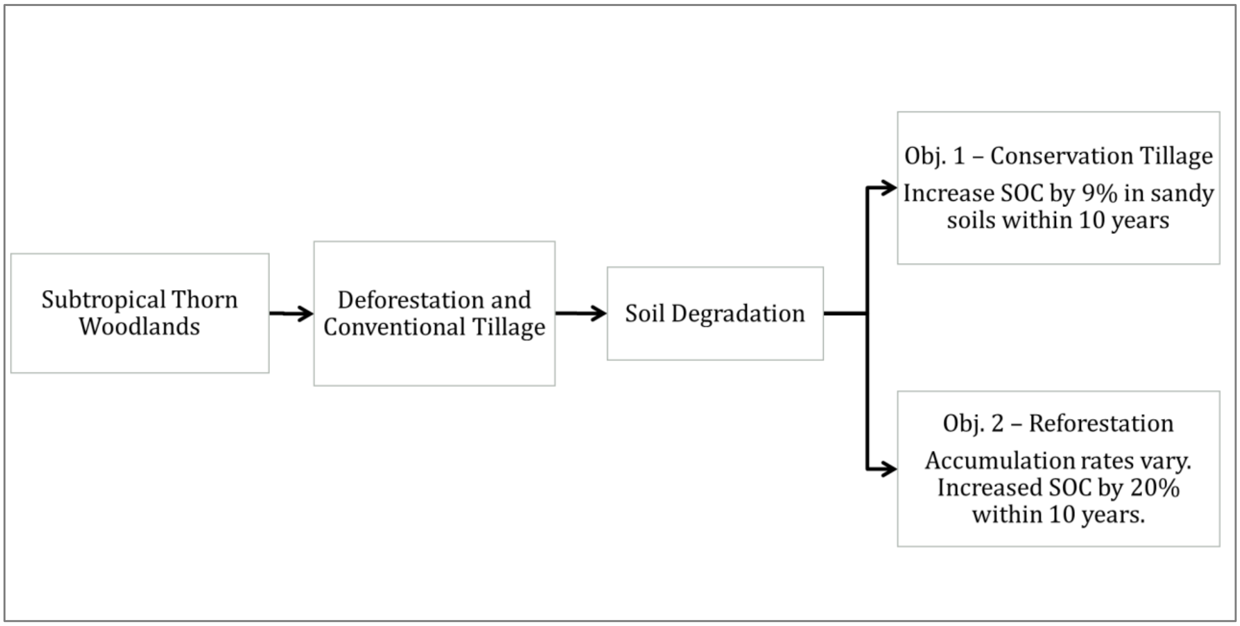

Figure 16: Schematic diagram of the SOC changes under the two thesis objectives.

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VITA

Samantha Lynn Colunga is a Rio Grande Valley native, raised in Monte Alto, Texas. She earned a Bachelor of Science degree in Environmental Science with Summa Cum Laude from the University of Texas Rio Grande Valley in December 2021. As an undergraduate, Samantha was able to work in the Soil Ecology Lab, where she began her own research of a literature review as preliminary research. In 2024, Samantha earned a Master of Science degree in Agricultural, Environmental, and Sustainability Sciences from the University of Texas Rio Grande Valley and received the Dean's Graduate Assistantship Award from the College of Science to support her education. As a UTRGV student, Samantha was an officer for the Environmental Awareness Club and a member of the Geology club. During her graduate studies, Samantha was a teaching assistant for physical geology, leading two solo labs for undergraduate students. In the Soil Ecology lab, Samantha assisted and guided undergraduate students collecting and analyzing soil samples via soil texture, soil respiration, soil active carbon, and soil enzyme activity via beta glucosidase. During the summer of 2023, Samantha was also an intern with the NRCS in Edinburg, Texas, where she gained valuable insights to the agency and land management practices. Samantha's graduate studies consisted of two objectives, which included the meta-analysis of soil organic carbon changes in sandy soils under arid and semi-arid climates, as well as the chronosequence study of carbon accumulation in reforested sites of the Rio Grande Valley. Samantha can be contacted at scolunga10@gmail.com