

ORIGINAL ARTICLE

Agricultural Soil and Food Systems

Soil carbon sequestration and biological health under pecan orchards of varying ages

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Abstract

Climate change and variability have affected crop production and soil health, specifically in arid and semiarid regions. Farmers have been planting crops with high market value and carbon (C) sequestration potential in orchards and plantations like pecan [*Carya illinoensis* (Wangenh.) K. Koch] in the southwestern United States, compared to row crops, to cope with climate change. However, their soil health and profile C sequestration potential have not been evaluated yet. We quantified responses of selected soil health indicators and profile C storage in pecan orchards of different ages (20, 40, and 80 years) and a nearby cotton (*Gossypium hirsutum* L.) field as a control. Soil samples were collected from 0- to 90-cm depth and analyzed for potentially mineralizable carbon (PMC), soil organic carbon (SOC), total labile N (TLN), soil organic nitrogen (SON), and soil microbial community structure. Results showed that soil PMC content in 15- to 90-cm depth was 83%–103% greater in the 20-year-old pecan orchard than in the cotton field. The 20-year-old orchard had 99%–190% greater SOC than cotton fields at 15- to 90-cm depth. However, soil TLN and SON storage were significantly higher under the cotton field at 0- to 90-cm depth. At 0- to 90-cm depth, SOC stock was 83% higher in the 20-year-old orchard, with 91% more mineral-associated and 78% more particulate C than in the cotton field. Soil bacteria and fungi in 0- to 15-cm depth were enhanced by 30%–68% and 72%–102%, respectively. Pecan orchards can improve soil health and soil profile C sequestration, particularly in the first 20 years of establishment.

Plain Language Summary

Climate change and variability have affected crop production and soil health more seriously in arid and semiarid regions than in other areas. Farmers have been planting crops with high market value and carbon (C) sequestration potential, like pecan in the

Abbreviations: AMF, arbuscular mycorrhizal fungi; MAOC, mineral-associated organic carbon; PMC, potentially mineralizable carbon; POC, particulate organic carbon; POXC, permanganate oxidizable carbon; SOC, soil organic carbon; SON, soil organic nitrogen; TLN, total labile nitrogen.

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southwestern United States, to cope with climate change. However, their soil health and C sequestration potential have not been quantified yet. We evaluated the response of selected soil health indicators and profile C storage in pecan orchards of different ages (20, 40, and 80 years) and a nearby cotton field as a control. We demonstrated that pecan orchards can enhance soil health and C sequestration compared to annual crops like cotton, particularly in the first 20 years of establishment.

1 | INTRODUCTION

Climate change poses significant risks to arid and semiarid regions that occupy more than one-third of the Earth's land surface (Ghimire et al., 2024). These areas are vulnerable to temperature increases and precipitation changes affecting agricultural sustainability (Ardö, 2015). Therefore, carbon (C) sequestration through sustainable land management practices can offer a potential mitigation strategy (Ghimire et al., 2024). Orchards and tree plantations store a large amount of soil C and maintain soil health in arid lands (Slade & Wells, 2022). These plantations are considered valuable in arid regions because they capture and store large amounts of atmospheric carbon dioxide (CO₂) in woody biomass and translocate biomass C to soil C through their extensive root systems (Gelaye & Getahun, 2024). Soil C accounts for over 70% of the total C sinks in orchard ecosystems (Z. Li et al., 2010). Sustainable orchard systems help to sequester atmospheric CO₂ at a greater rate than net greenhouse gas fluxes because of improved biological efficiency and reduced inputs (Montanaro et al., 2021). While orchards can significantly increase soil organic carbon (SOC) stocks and help mitigate greenhouse gas emissions, the relative impact varies by crop type and orchard age (De Feudis et al., 2022; Sharma et al., 2021). A limited number of studies have focused on orchard systems, including pecan [*Carya illinoensis* (Wangenh.) K. Koch] orchards, that cover significant acreage in the arid southwestern United States and contribute to soil health improvement. Understanding the long-term effects of orchards on soil health and SOC storage would provide insight into their potential for climate change mitigation in arid environments.

The United States is one of the world's leading pecan producers, and New Mexico is the second-largest producer in the country. With more than 19,000 ha of production, it accounts for nearly 35% of the total pecan production in the United States (USDA–NASS, 2022). Pecan production in New Mexico has been documented since 1920; by then, the state produced only 284 kg of nuts. During the 1960s, new orchards were established, and a significant increase in production was experienced (Herrera, 2000). Due to the pecan's high value and suitability to the climate of the desert southwest, many producers have converted their farmlands from traditional

cotton (*Gossypium hirsutum* L.) fields to pecan orchards (Heerema, 2021; Herrera, 2000). In 2017, New Mexico produced a record 92 million pounds of pecans, which became the state's leading agricultural commodity crop, resulting in a total market value of \$220 million (USDA–NASS, 2018). However, much focus is given to improve the pecan yield, and much less attention has been paid to the soil health and C storage in the orchards. Enhanced knowledge of soil health and C storage in orchards of varying ages could provide insights into how the conversion of row crop fields to pecan orchards has impacted soil health and design climate-smart management approaches as a part of nature-based solutions to climate change in arid and semiarid regions.

Converting croplands to orchards can lead to rapid improvements in soil health. Studies show positive responses of soil health indicators such as organic matter, microbial activity, and aggregate stability following conversion to orchards (Chamberlain et al., 2022; Lekberg et al., 2024). In the southern United States, pecan orchards enhanced soil health compared to conventional cotton fields, with microbial activity and soil organic matter improving as the orchard matures (Slade & Wells, 2022). However, on the Chinese Loess Plateau, transitioning croplands to pecan orchards resulted in reduced SOC and decreased microbial community complexity (Z. Wang et al., 2022). In subtropical China, older citrus orchards are associated with greater SOC and N contents and enhanced nitrification capacity (Zhang et al., 2015). In addition, soil microbial communities, including bacteria and actinobacteria abundance, are higher in mature orchards, serving as reliable bioindicators of soil health (Mingyan et al., 2011). Forty-year-old citrus orchards in southern China have been shown to support increased SOC storage, elevated enzyme activities, and distinct microbial communities, particularly in soil macroaggregates, compared to newly established orchards (Zheng et al., 2022). Discrepancies in responses of SOC and microbial indicators or soil health under these studies may be related to differences in ground cover, soil type, or management practices. For instance, drive rows in woody perennial systems often store more soil C than row crops, with cherry orchards having greater SOC accumulation and vineyards the lowest (Midwood et al., 2020). Tree canopies in woody grasslands also show microenvironment variation in SOC and soil microbial populations, highlighting

the importance of considering spatial and temporal variations in evaluating SOC and soil health in orchards.

Pecan orchards in New Mexico have been established since the early 1900s on lands used for row cropping systems (Herrera, 2000). Therefore, comparing soil health and soil C status in pecan orchards along with major crops grown in the region, including corn (*Zea mays* L.), sorghum (*Sorghum bicolor*), alfalfa (*Medicago sativa*), wheat (*Triticum aestivum*), and cotton (Sammis et al., 1985; Yadav & Geli, 2021), can help understand relative responses of various soil health indicators to orchard versus row crop management (variation in tillage, fertilizers, irrigation methods, etc.). Therefore, a thorough evaluation is needed to understand the soil health status under the row crop fields and those converted to pecan orchards. Additionally, most existing studies primarily examine soil C and N pools in surface soils, although previous research emphasizes the importance of examining soil health parameters in deeper soil profiles (Slade & Wells, 2022; Z. Wang et al., 2022).

The objectives of this study were to analyze and compare the soil health indicators in pecan orchards of different ages and nearby cotton fields. We aimed to understand how these soil health indicators respond to land-use shifts, enabling us to assess the impact of pecan orchards on soil health and SOC storage over time. We hypothesize that soil health improves and SOC storage increases after land conversion from cotton fields to pecan production.

2 | MATERIALS AND METHODS

2.1 | Study site and treatments

The experiment was conducted at mature pecan orchards and adjacent cotton fields in the Lower Rio Grande Valley, Las Cruces, NM. Soil sampling was conducted at the New Mexico State University's Leyendecker Plant Science Research Center (Site 1) near La Mesa, NM (32°11'54.7" N 106°44'25.9" W), at an elevation of 1175 m above sea level and Fabian Garcia Science Center (Site 2) in Las Cruces, NM (32.2799° N, 106.7725° W), with an elevation of 1186 m above sea level. The climate of the experimental areas is considered arid to semiarid, with low relative humidity and an average annual air temperature and precipitation of 17°C and 29 cm, respectively (Kellum et al., 2018). The pecan orchards were 20-, 40-, and 80-year old and established on land previously used for cotton production. The 20- and 40-year-old orchards were at Site 1, while the 80-year-old orchard was at Site 2 (Figure 1). An adjacent cotton field at Site 1 was also sampled and considered a typical row crop control. The 80-year-old orchard was 5.5 miles away from other fields, but all pecan orchards and cotton fields had similar parent materials with slopes of less than 0%–1%. The soils at both sites are primarily Glendale and Brazito series, well-suited for diverse crops (Deb et al.,

Core Ideas

- Soil organic carbon in 15- to 90-cm depth was 99%–190% greater at 20-year-old orchards than adjacent cotton fields.
- Potentially mineralizable carbon in 20-year-old orchards was 83%–103% greater than in cotton fields at 15- to 90-cm depth.
- Soil organic carbon stock in the 20-year-old orchards at 0- to 90-cm depth was 83.3% greater than in cotton fields.
- Mineral-associated and particulate carbon stocks at 0–90 cm were also 90.5% and 77.5% greater in 20-year-old orchards.
- The soil bacteria and fungal abundance were greater in pecan orchards at 0- to 15-cm depth than in cotton fields.

2011). Soil pH at the top 40-cm depth ranges from 7.8 to 9.1, and electrical conductivity ranges from 1.5 to 3.2 dS m⁻¹ (Othman, 2014).

The study spatially randomized four treatments and three replications (Figure 1). Cotton was planted on a 100-cm wide raised bed on the ridge in late April. The cotton planting distance within a row was 60 cm, and the plants between rows were 100 cm apart (Figure 1a). The pecan trees at both sites were 8 m within the rows and 9 m between the rows (Figure 1b). All the pecan orchards were irrigated every 3–4 weeks from May to December with flood irrigation using groundwater or canal water. The cotton field was irrigated every 2 weeks from April to November with furrow irrigation. The pecan orchard alleys were managed mechanically, with occasional disking, harrowing, and mowing. The tree rows were kept weed-free using herbicide mixtures (Ashigh et al., 2019). Preemergence herbicide pendimethalin (Prowl H₂O) 1.60 kg a.i. ha⁻¹ (3.52 L ha⁻¹) was used within 2 days after planting to control grasses and broadleaf weeds. Urea (225 kg ha⁻¹, 46% N) and zinc sulfate (foliar spray, 7 kg ha⁻¹) were applied to 20- and 40-year-old orchards, while urea (120 kg ha⁻¹) was applied to the 80-year-old orchard in May. Cotton was fertilized three times with N fertilizers, that is, dry application in April after planting at 112 kg ha⁻¹, then two liquid applications in May and June with 187 L ha⁻¹ (Omer et al., 2018). Pecan harvest occurs between October and December, while cotton is harvested in November.

2.2 | Soil sampling and laboratory analyses

Deepcore soil sampling was conducted from October 3–5, 2023. Samples were collected randomly from the middle of

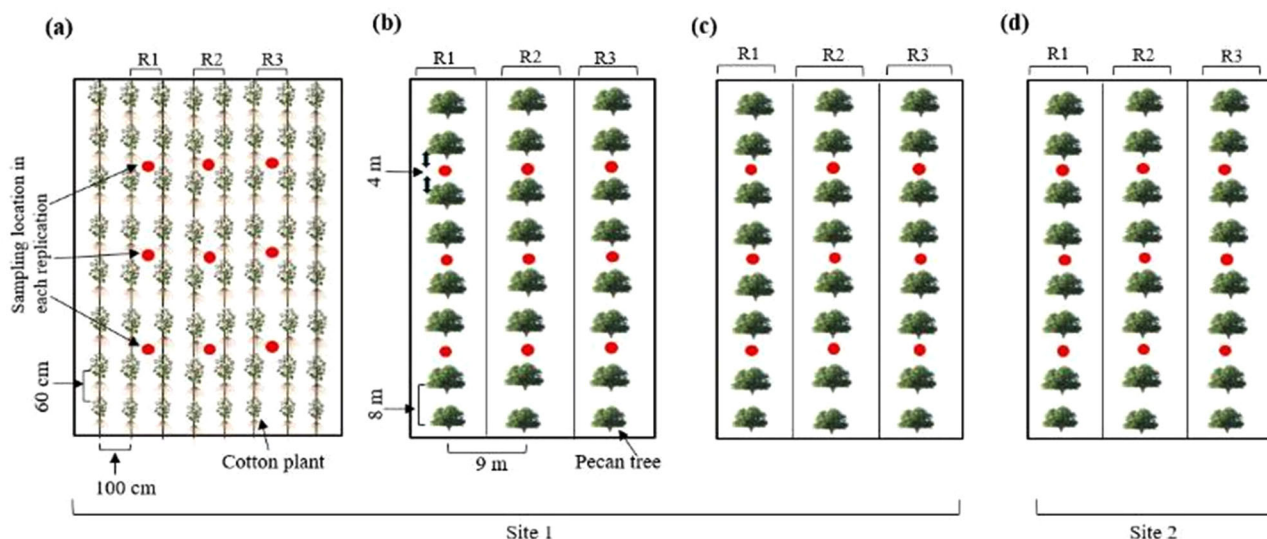


FIGURE 1 Field layout of cotton (a), 20-year-old orchard (b), 40-year-old orchard (c), and 80-year-old orchard (d), with replications in a randomized complete block design. Site 1 refers to the Leyendecker Plant Science Research Center, and Site 2 refers to the Fabian Garcia Science Center. R1, R2, and R3 denote Replication 1, Replication 2, and Replication 3, respectively. The red circle represents the soil sampling location.

rows in the orchards and cotton fields at 0- to 90-cm depth using a gas-operated earth drill auger (Honda GX 120, American Honda Motor Co., Inc.). The samples were taken at least 4 m from the pecan tree trunk. The samples were taken from the middle of the rows to ensure that soil health indicators, including SOC and N fractions, can reflect the broader orchard system rather than localized effects near tree trunks, where litter fall or root might affect the results. Inter-tree samples helped to avoid tree root damage during sampling. This area also represents the overall crop performance and tends to be less influenced by the edges and row boundary variability. As the treatments were not fully independent, the replications were pseudo-replications. Three replicated soil samples were collected from each orchard, and three soil cores were collected within each replication of a treatment. Then, the samples were divided into 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm-depth intervals, homogenized, and composited by depth. The soil samples were taken to the laboratory in a cooler with ice packs and stored at 4°C in a refrigerator until analysis was started. About 20 g of subsamples were used to estimate the soil moisture, and the remaining samples were used to estimate permanganate oxidizable carbon (POXC), potentially mineralizable carbon (PMC), total labile nitrogen (TLN), and SOC. Separate subsamples were taken for microbial community analysis and stored in a -20°C freezer until they were extracted for phospholipid fatty acid (PLFA) analysis.

Soil POXC was measured using the permanganate oxidation technique (Weil et al., 2003). It is a measure of labile C in the soil and has proven to be a valuable indicator of soil quality (Culman et al., 2012). Soil PMC was determined by placing 22 g of soil at field capacity (23% v/v) into a 1-L mason jar. The soil was then incubated aerobically (Zibilske,

1994), and CO₂ emissions were measured after 24 and 72 h using an infrared gas analyzer (LI-830, Licor Inc.). TLN concentration was determined by boiling 5 g of soil with 25 mL of 1 M KCl in a 50-mL plastic centrifuge tube for 4 h in a 100°C water bath. After boiling, the extract was filtered, and NO₃⁻ and NH₄⁺ ions were analyzed as inorganic N (Gianello & Bremner, 1986) using a Timberline automated flow injection analyzer (Timberline Instruments, LCC).

After labile C and N analysis, the soil samples were air-dried at room temperature, crushed, and sieved through a 2-mm mesh for particle size analysis using the hydrometer method (Gee & Bauder, 1986). Sand, silt, and clay percentages were calculated using hydrometer readings and suspension temperature data. The soil texture was then determined using the United States Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS) soil texture triangle. Air-dried soil samples were ground to pass through a <0.5-mm sieve and analyzed for total C concentration using dry combustion analysis (LECO Corporation). Soil inorganic C was estimated through acidification using a total inorganic C analyzer (UIC, Inc.). Then, SOC was calculated by subtracting the inorganic C from the total C. Soil bulk density was determined by oven-drying undisturbed soil core samples at 105°C for 24 h; then dividing the weight of oven-dried samples by the core volume. Particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) were estimated following the procedures outlined by Cambardella and Elliott (1992). Approximately 10 g of air-dried soil was mixed with 30 mL of 5 g L⁻¹ sodium hexametaphosphate and shaken for 16 h to disperse the soil particles. The resulting slurry was then passed through a 0.053-mm sieve and washed with deionized water three to four times. The fractions retained on the sieve (POC) and passed through (MAOC) were oven-dried at

50°C for 24 h and analyzed for total C and inorganic C content. The stocks of SOC (Mg ha^{-1}), MAOC (Mg ha^{-1}), POC (Mg ha^{-1}), soil organic nitrogen (SON) (Mg ha^{-1}), POXC (Mg ha^{-1}), PMC (kg ha^{-1}), and TLN (Mg ha^{-1}) were calculated as the sum of SOC content in individual depths. The SOC content in each depth is calculated by multiplying its concentration (mg kg^{-1}) by the bulk density (g cm^{-3}) and the thickness of each soil layer.

PLFA analysis was conducted for 0- to 15-cm soil depth to quantify the total microbial biomass and community composition on the surface soil. The PLFA was extracted from 5 g of field-moist soil using the chloroform-methanol extraction method outlined by Findlay (2004). PLFAs were separated from other lipid classes using solid-phase extraction through a four-step process, that is, extraction, fractionation, methylation, and chromatographic analysis of phospholipid components of soil. Qualitative and quantitative analyses of fatty acids (FAs) were conducted using gas chromatography (Agilent 6890, Agilent Technologies). Peaks were identified using the microbial identification software (MIDI) in the automated Microbial Identification System (Microbial ID, Inc.). The abundance of each FA was measured in nanomoles per gram of dry soil, using international standards (methyl ester C19:0, Matreya Inc.). The signature biomarker was carefully selected to avoid misinterpretation (Yao et al., 2016).

2.3 | Statistical analysis

The data for all the soil health indicators were analyzed using a linear mixed model procedure in R version 4.2.1. The treatment effects were considered fixed effects, and the experimental site and replications nested within the site were deemed random to account for pseudo-replications and spatial variability across the sites. Data for each soil depth were analyzed separately to assess the depth-wise treatment effects on each variable. Figure and table values for each treatment represent the average values observed at a soil depth. All the data were thoroughly examined, and the assumptions of homogeneity of variance and normality of residuals were satisfied. Treatment means were separated using Fisher's protected least significant difference test at a significance level of $p \leq 0.05$. A simple linear regression analysis was performed to explain the relationship between SOC and N fractions; significant relationships are presented in Section 3.

3 | RESULTS

3.1 | Soil carbon and nitrogen pools

Soil PMC content significantly differed among treatments at 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm soil depths

(Figure 2a). At 0–15 cm, PMC was 71% and 66% greater in 80- and 40-year-old orchards than in the cotton field, while it did not differ significantly between the cotton field and the 20-year-old orchard. However, the PMC was 105%, 118%, and 83% greater in the 20-year-old orchard than in the cotton field at 15- to 30-, 30- to 60-, and 60- to 90-cm soil depths, respectively. Soil POXC at all depths was similar among all the treatments (Figure 2b).

The SOC significantly differed among treatments at 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm depths (Figure 3a). At 0–15 cm, the SOC content was 45% greater in the 80-year-old orchard than in the cotton field and 116% greater in the 20-year-old orchard than in the cotton field at 15- to 30-cm depth. The SOC content at 30- to 60-cm depth was 99% greater in the 40-year-old orchard than in the cotton field. However, the SOC content at 60- to 90-cm depth was 190% greater in a 20-year-old orchard than in an 80-year-old one. Also, the results showed that SOC in 20- and 40-year-old orchards was higher at 30- to 60- and 60- to 90-cm depth compared to 0- to 30-cm depth. The MAOC content differed significantly among treatments at all depths (Figure 3b). The MAOC was 47%, 119%, 104%, and 89% greater in the 20-year-old orchard than in the cotton field at 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm depth, respectively. The POC content was 73% and 109% greater in 80- and 20-year-old orchards than in cotton fields at 0- to 15- and 15- to 30-cm depth (Figure 3c). At 30–60 and 60–90 cm, the POC was 118% and 101% greater in 40- and 20-year-old orchards than in the cotton field. Overall, the SOC, POC, and MAOC content followed the same pattern at all the depths, except at 0- to 15-cm depth (Figure 3).

The SON in the cotton field was 2.29, 4.17, and 4.45 Mg ha^{-1} , respectively, at 15- to 30-, 30- to 60-, and 60- to 90-cm depths, and were significantly greater than those of pecan orchards of all ages (Figure 4a). Also, the SON content in cotton fields at 0–30 cm was numerically lower than at 30- to 90-cm depth. Similarly, the cotton field had 58.3, 36.1, 58.6, and 80.1 kg ha^{-1} TLN content at 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm depth, respectively, and were significantly greater than those measured in 40- and 80-year-old pecan orchards at all the depths (Figure 4b). In contrast, the 20-year-old orchard did not significantly differ in the cotton field. However, the TLN content in the 20-year-old orchard increased with depth.

3.2 | Soil profile carbon and nitrogen stocks

The average SOC stock at 0- to 90-cm depth under 20-year old (139 Mg ha^{-1}) was 83% and 84% higher than the cotton field (75.8 Mg ha^{-1}) and 80-year-old (75.7 Mg ha^{-1}) orchard (Table 1). Like SOC, the MAOC and POC stocks were significantly greater in the 20-year-old orchard (96.8 and 42.6 Mg ha^{-1}) than in the cotton field. Soil PMC stock was

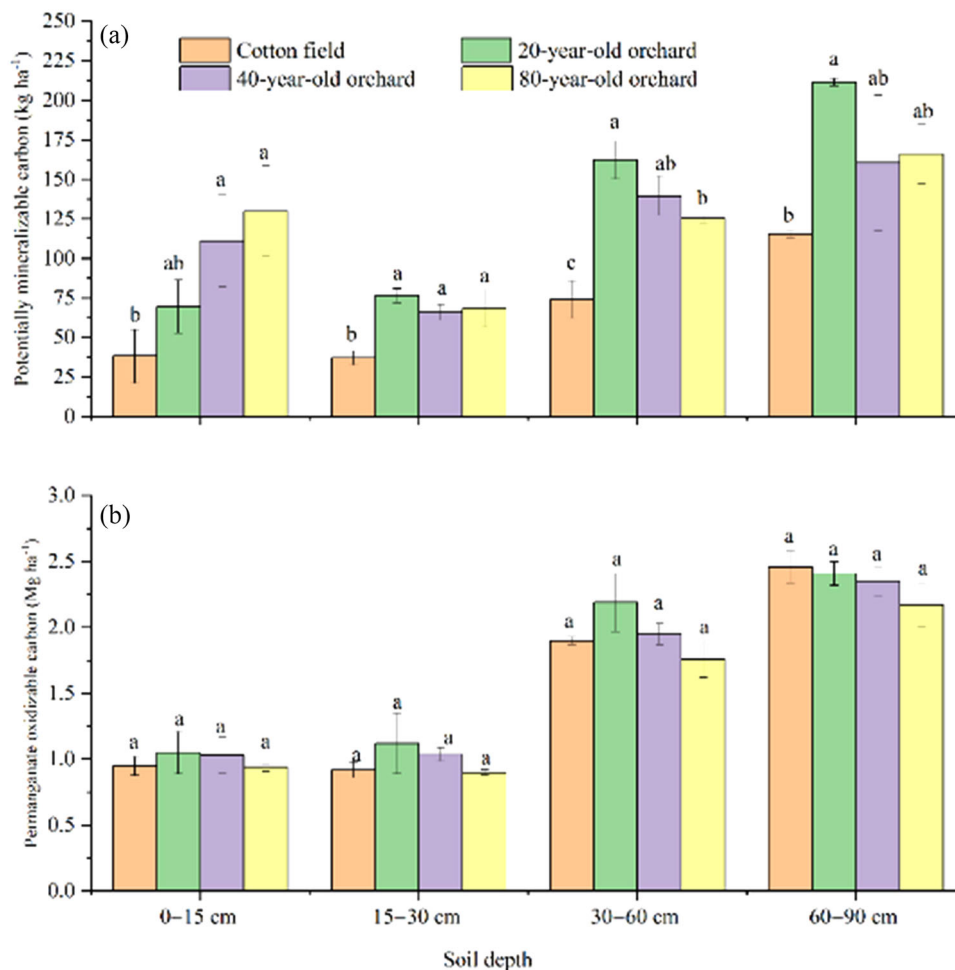


FIGURE 2 Potentially mineralizable carbon (a) and permanganate oxidizable carbon (b) under pecan orchards at different ages and a cotton field at different depths. Bars represent the mean values, and error bars represent the standard error of the means. Different lowercase letters within each depth represent significant differences among treatments at $p \leq 0.05$ (Fisher's protected least significant difference [LSD]).

TABLE 1 Soil profile (0–90 cm) stocks of carbon and nitrogen fractions under pecan orchards of different ages and a cotton field in southern New Mexico.

Treatment	SOC (Mg ha ⁻¹)	MAOC (Mg ha ⁻¹)	POC (Mg ha ⁻¹)	SON (Mg ha ⁻¹)	POXC (Mg ha ⁻¹)	PMC (kg ha ⁻¹)	TLN (kg ha ⁻¹)
Cotton field	75.8 ± 4.20c	50.8 ± 2.68c	24.0 ± 1.34b	13.2 ± 1.39a	6.43 ± 0.16a	296 ± 26.7b	233 ± 85.1a
20 years	139 ± 4.39a	96.8 ± 1.78a	42.6 ± 2.68a	6.15 ± 2.16b	6.78 ± 0.71a	489 ± 25.2a	54.8 ± 5.15b
40 years	115 ± 1.48b	75.2 ± 2.31b	40.1 ± 0.84a	7.72 ± 0.14b	6.39 ± 0.08a	477 ± 38.2a	123 ± 11.2ab
80 years	75.7 ± 1.80c	49.3 ± 1.12c	26.4 ± 0.90b	4.03 ± 0.33b	5.79 ± 0.24a	488 ± 36.8a	58.9 ± 3.17b

Note: Means ($\pm$ standard error) followed by different lowercase letters along the column represent significant differences among treatments ($p \leq 0.05$; Fisher's protected least significant difference).

Abbreviations: MAOC, mineral-associated organic carbon; PMC, potentially mineralizable carbon; POC, particulate organic carbon; POXC, permanganate oxidizable carbon; SOC, soil organic carbon; SON, soil organic nitrogen; TLN, total labile nitrogen.

significantly greater under the 20- (65%), 40- (61%), and 80-year-old (65%) orchards than in the cotton field. However, the PMC stock among orchard ages was not significantly different. The POXC stock did not differ significantly among the treatments, but the soil under the 20-year-old orchard had the largest stock of POXC. The SON stock at 0- to 90-cm

depth was significantly greater under cotton fields (13.2 Mg ha⁻¹) than under 20- (6.15 Mg ha⁻¹), 40- (7.72 Mg ha⁻¹), and 80-year-old (4.03 Mg ha⁻¹) orchards. Also, the TLN stock under the cotton field was significantly greater than the 20-year-old orchard by 425% and the 80-year-old orchard by 388%.

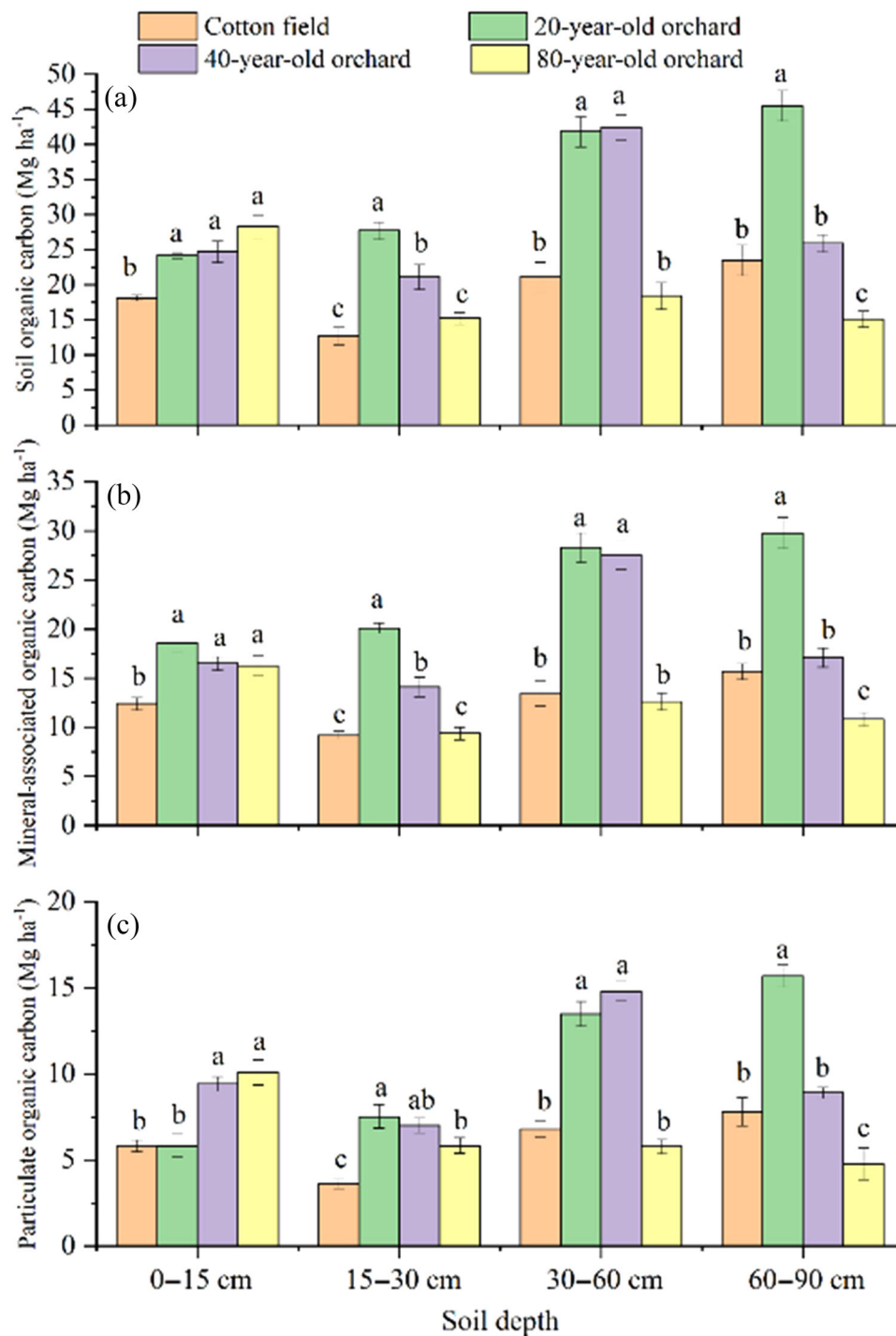


FIGURE 3 Soil organic carbon (a), mineral-associated organic carbon (b), and particulate organic carbon (c) under pecan orchards of different ages and a cotton field at various depths. Bars represent the mean values, and error bars represent the standard error of the means. Different lowercase letters within each depth represent significant differences among treatments at $p \leq 0.05$ (Fisher's protected least significant difference [LSD]).

3.3 | Soil microbial community structure

At 0- to 15-cm depth, Gram-positive and Gram-negative bacteria and actinomycetes differed significantly and were 19%, 141%, and 10% greater in 40-year-old orchards, respectively (Table 2). Also, the total bacteria sum was 30%–68% greater

in 20-, 40-, and 80-year-old orchards than in the cotton field. Arbuscular mycorrhizal fungi (AMF) in 40- and 80-year-old orchards was 91%–103% greater than in the cotton field. Saprophytic fungi differed significantly among treatments, with 63%–105% greater in 20-, 40-, and 80-year-old orchards than in the cotton field. Similarly, the total fungi sum was

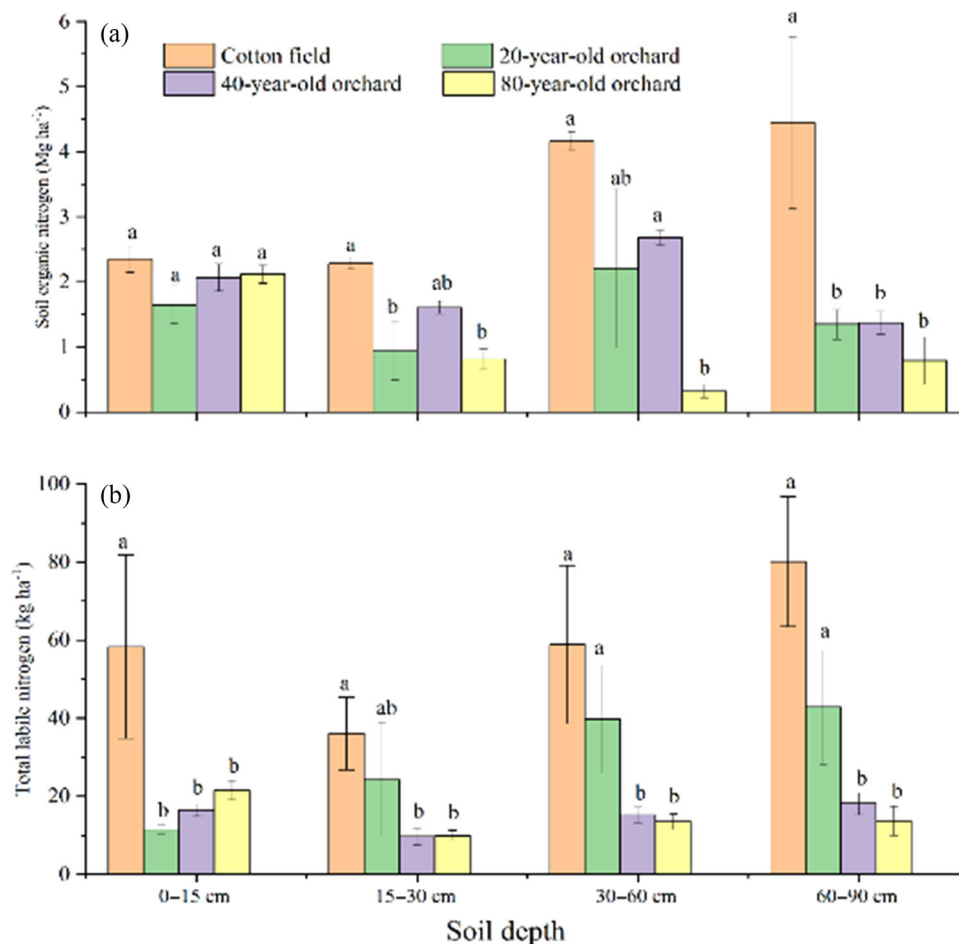


FIGURE 4 Soil organic nitrogen (a) and total labile nitrogen (b) under pecan orchards of different ages and a cotton field at various soil depths. Bars represent the mean values, and error bars represent the standard error of the means. Different lowercase letters within each depth represent significant differences among treatments at $p \leq 0.05$ (Fisher's protected least significant difference [LSD]).

72%–102% greater under 20-, 40-, and 80-year-old orchards than in the cotton field. The fungi-to-bacteria (F:B) ratio was similar among orchard treatments, but all orchard treatments had a 35%–41% greater ratio than in the cotton field. The ratio of Gram-positive to Gram-negative bacteria was significantly greater (50%–70%) in the cotton field than in pecan orchards. The regression analysis between SOC and MAOC (Figure 5a) and SON and POXC showed a strong positive relationship (Figure 5b).

4 | DISCUSSION

4.1 | Divergent response of soil carbon and nitrogen pools with increasing orchard age

Labile C and N responses to changes in pecan orchard age were assessed by monitoring PMC, POXC, and TLN. Our study showed that 20-year-old orchards had more PMC than the cotton field but not necessarily in 40- and 80-year-

old orchards. Root exudates, fertile soil, and decaying plant residues increase C sources for enhanced microbial activities and biologically driven organic matter (Sofi et al., 2012). Pecan trees are actively growing and may contribute to labile C accumulation in the first 20 years. In apple (*Malus pumila*) orchards, microbial activity was highest in middle-aged trees (10–25 years), nearly 1.4 times higher than in aged orchards. Likewise, soil microbial activities, plant root exudates, and biomass decreased in older citrus orchards due to a decline in plant vigor and soil fertility (Qiang et al., 2020). Microbial biomass was three times greater in young (0–10 years) and middle-aged apple orchards than in older (>25 years) orchards (Z. W. Li et al., 2011). Decreases in POXC with orchard age and soil depth may be associated with a decrease in oxidation stability of old orchards compared to cotton fields. The POXC in our study was only numerically higher in the 20-year-old orchard than in other treatments.

Our results showed that SOC stock was significantly higher in 20- and 40-year-old orchards compared to 80-year-old orchards. We attribute this trend to the change in root

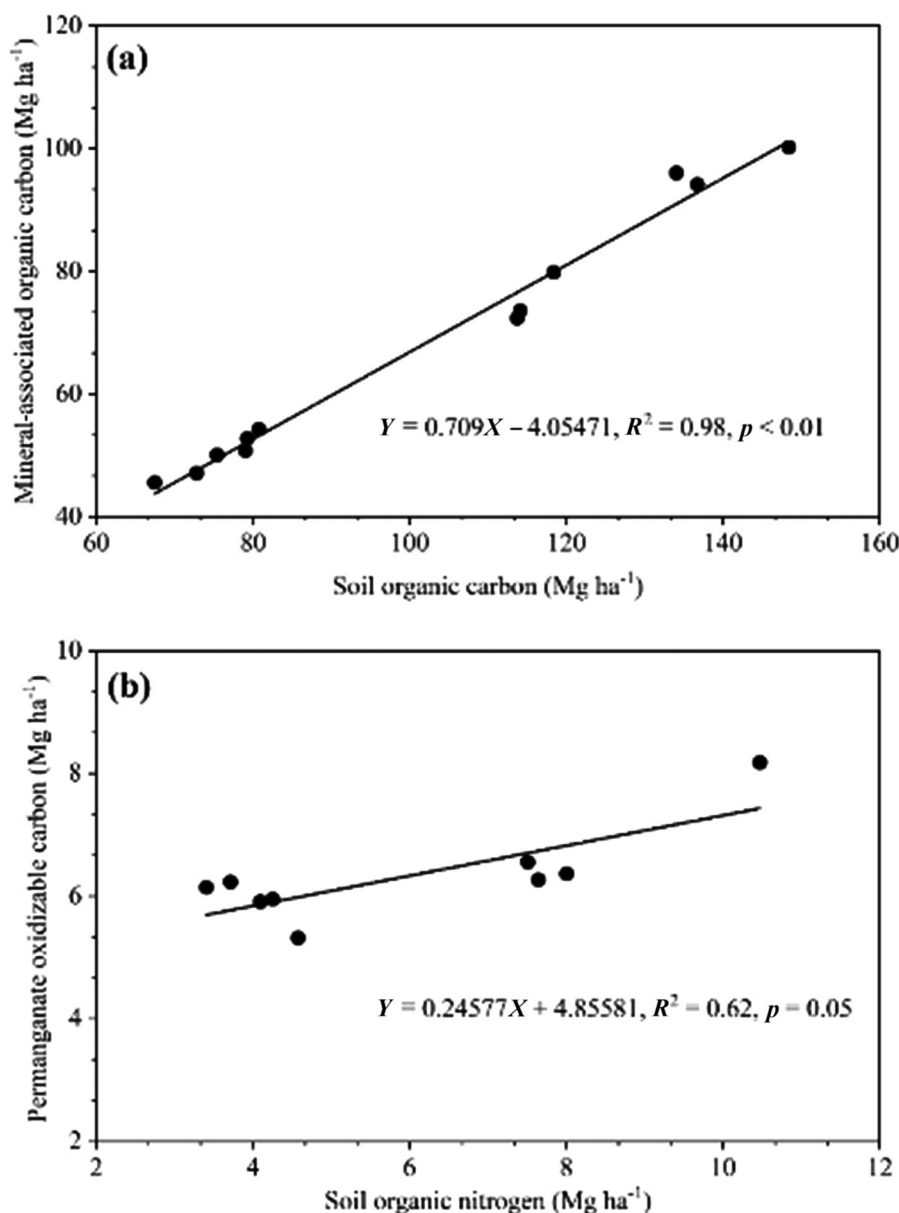


FIGURE 5 Relationship between mineral-associated organic carbon (MAOC) and soil organic carbon (SOC) (a), soil organic nitrogen (SON) and permanganate oxidizable carbon (POXC) (b).

dynamics, microbial activities, and organic matter input like leaf litter, root exudates, and pruning residues, which decrease in old-aged orchards. Studies suggest that microbial communities in the soil adapt to organic matter over time, leading to a change in SOC dynamics in older orchards. Zheng et al. (2022) and Sofi et al. (2012) reported that SOC stocks increase with orchard age, peaking around 40 years, mainly due to shifts in soil microbial dynamics, enzymatic functions, and quantity of organic matter inputs (Zheng et al., 2022). As leaf litter input declines and root growth slows down in the older orchards, microbial turnover of SOC components also slows down, leading to a decline in SOC in orchards older than 50 years (Sofi et al., 2012). Leaf litter inputs decline due to slower

vegetative growth and reduced canopy density in the 80-year-old trees, supporting lower biomass C input in older orchards. As mentioned in Section 2.1, the foliar application of N for 80-year-old orchard was reduced to half compared to 20- and 40-year-old orchards, which can also affect the litter quantity and quality and the efficiency of nutrient return to the soil. In addition, the 80-year-old orchard was in a slightly different soil than the 20- and 40-year-old orchards, which may have also affected the SOC storage.

In 20- and 40-year-old orchards, the SOC was also less at 0- to 30-cm depth than at 30- to 90-cm depth, possibly because the deep-rooted trees may have deposited root biomass in the deeper soil layers, contributing to SOC accumulation

TABLE 2 The abundance of selected soil microbial groups in pecan orchards of different ages and a cotton field at 0- to 15-cm soil depth.

Treatments	Bacteria		Fungi		Total (ng g ⁻¹ soil)	Saprophytic (ng g ⁻¹ soil)	Total (ng g ⁻¹ soil)	F:B ratio	Gram-positive: Gram-negative
	Gram-positive (ng g ⁻¹ soil)	Gram-negative (ng g ⁻¹ soil)	Actinobacteria (ng g ⁻¹ soil)	Total (ng g ⁻¹ soil)		AMF (ng g ⁻¹ soil)			
Cotton field	426 ± 22.2b	192 ± 13.9b	196 ± 7.49b	814 ± 41.2b	36.8 ± 3.26b	108 ± 3.97b	144 ± 6.41b	0.17 ± 0.01b	2.22 ± 0.04a
20 years	479 ± 23.1ab	323 ± 10.4ab	191 ± 6.02b	993 ± 31.3b	59.8 ± 5.62ab	188 ± 7.87a	248 ± 11.8a	0.24 ± 0.00a	1.48 ± 0.07b
40 years	578 ± 39.5a	463 ± 91.5a	216 ± 6.57a	1257 ± 123.1a	70.3 ± 7.62a	221 ± 40.7a	292 ± 48.2a	0.23 ± 0.01a	1.31 ± 0.16b
80 years	508 ± 56.7ab	390 ± 64.3a	201 ± 5.41b	1099 ± 119.3ab	74.7 ± 8.22a	176 ± 22.4a	251 ± 30.6a	0.23 ± 0.00a	1.33 ± 0.12b

Note: Means (± standard error) followed by different lowercase letters along the column represent significant differences among treatments ($p \leq 0.05$; Fisher's protected least significant difference). Abbreviations: AMF, arbuscular mycorrhizal fungi; F:B, fungi-to-bacteria ratio.

below 30-cm depth (Prescott & Grayston, 2013). In addition, regular flood irrigation may have leached organic C to the lower soil layers. Also, orchard weed management, including mowing, plowing, or herbicide spray, may have limited the aboveground leaf litter inputs to the topsoil. Several long-term studies on litter exclusion in forest trees demonstrate that reducing organic matter input can significantly lower SOC levels, mainly in the upper soil layers (Bowden et al., 2014; Lajtha et al., 2014). Interestingly, increasing litter inputs by two times did not lead to higher soil carbon storage in a study by Bowden et al. (2014) and Lajtha et al. (2014), suggesting a nonlinear relationship between organic matter inputs and soil carbon storage. Management practices and environmental factors also influence the SOC content. A study by R. Li et al. (2015) reported that 0- to 10-year-old apple orchards had lower water deficits, which could help to increase SOC in surface depths compared to farmland. However, older orchards (>25 years) showed a reduction in soil water storage and SOC depletion.

Like SOC, our study showed that MAOC and POC content were greater in 20- and 40-year-old orchards than in 80-year-old orchards and cotton fields. MAOC is generally more abundant and stable than POC due to interactions with clay minerals (Bayer et al., 2001; Schweizer et al., 2021). In our study, the soils in 20- and 40-year-old orchards had higher clay content at 0- to 90-cm depth than 80-year-old orchards (Table S1). These differences in the clay content could be due to inherent spatial variability, irrigation practices, or long-term management practices. The higher clay content forms a bond with the organic compounds, stabilizes organic matter, makes it less available for microbial decomposition, and helps in long-term SOC storage. However, Schweizer et al. (2021) stated that clay content and SOC storage are complex. In some cases, soils with lower clay content can exhibit high MAOC content. This suggests that factors beyond clay content, such as soil mineralogy, organic matter composition, and land management practices, may also influence SOC storage.

In contrast to C pools, our study demonstrated that SON and TLN content were greater in cotton fields than in pecan orchards of all ages at 0- to 90-cm depth (Figure 4). The cotton field management practices, specifically frequent tillage and fertilizer application, low root biomass, and rapid root turnover, could have contributed toward higher N content in cotton fields. The soil sampling was done in October when cotton was at the flowering and boll development stage. The sampled cotton field received three N fertilizer applications during the growing season. The SON in the 0- to 30-cm cotton field was numerically greater than the 30- to 90-cm depth. This could be due to reduced organic inputs at the top surface due to tillage operations and crop residue removal. In addition, regular furrow irrigation application after every 2 weeks may have leached down N into the deeper layers.

Franzluebbers (2021) reported a lower SON in the surface layers (0–30 cm) under cotton production in North Carolina due to continuous disk tillage and the absence of organic matter at the surface. Pecan orchards under commercial farming receive synthetic fertilizers and 12% chelated zinc applications only once a year in the spring to early summer (Omer et al., 2018). The higher N inputs and soil mixing from tillage in the cotton field could have stimulated microbial activity, which leads to greater mineralization of organic N into labile forms.

Our results showed that TLN content increased with depth in the 20-year-old orchard. The 20- and 40-year-old orchards receive higher doses of urea than the 80-year-old orchards. The frequent irrigation may have leached N to deeper layers over time. The root distribution of 20-year-old orchards may not have developed more than that of 40- and 80-year-old orchards. The lack of a deeper root system could have helped to accumulate more TLN in the deeper layers. Ji et al. (2024) reported increased TLN with depth in a 20-year-old apple orchard in clay loam under semiarid conditions due to asynchronous water depletion and N fertilizer accumulation in the soil profile. Zhang et al. (2015) stated that TLN content increases with depth due to increased turnover time of recalcitrant organic N and stimulated nitrification capacity in subtropical conditions. The older orchards have more stable conditions that limit N transformation into labile forms. Additionally, the flood irrigation applied to pecan orchards results in deep percolation of N (25%–37%) below the upper 100 cm profile (Deb et al., 2011). Khattak and Hussain (2007) reported that orchard (apple, peach, pear, and citrus) soils have lower N concentrations due to leaching and runoff with flood irrigation.

4.2 | Orchard age affected soil profile carbon and nitrogen stocks

The SOC stock calculated for 0- to 90-cm depth accounts for more than 83% in 20-year-old orchards than in the cotton field. Similarly, the MAOC and POC stocks under 20-year-old orchards were 91% and 78% greater than in cotton fields, respectively. Regular soil disturbance from tillage may have resulted in low SOC stocks in cotton fields, while reduced soil disturbance in orchards and other changes may have increased C storage. However, studies on SOC stocks in orchards have produced mixed results. For example, Y. Wang et al. (2024) found no significant difference in SOC between farmlands and young orchards, but 15- and 20-year-old apple orchards had greater SOC than 5-year-old orchards and farmlands. However, Shi et al. (2015) reported 10% greater SOC stocks in 10- and 15-year-old orchards than in farmlands. Our results showed that the age of pecan orchards appears to play a role in

SOC accumulation, with two-decade-old orchards generally showing increased SOC stocks. Gómez et al. (2022) stated that tree density might also play a role in SOC stock accumulation, as an olive orchard planted in 2000 at 1850 trees ha^{-1} showed a significant increase in SOC stocks over time compared to orchards planted in 1996 at 310 trees ha^{-1} in southern Spain. The SOC, MAOC, and POC stocks were significantly lower in an 80-year-old orchard in our experiment compared to a 20-year-old orchard. Phuong and Nguyen (2024) reported similar results in citrus orchards in the Vietnamese Mekong Delta, where SOC decreases with orchard age and other macronutrients at 0- to 50-cm depth. This shows that the biomass production in the 80-year-old orchard slows down, reducing roots and leaves deposited in the soil, causing diminished organic carbon levels.

Senescence of roots associated with increasing tree age decreased root biomass in the lower soil layers, causing lower SOC levels under old eucalyptus trees (Loumeto & Bernhard-Reversat, 2001). Organic matter in soil decomposes over time, releasing carbon dioxide into the atmosphere. If the rate of organic matter input declines and decomposition continues at the same rate or increases over time, the SOC stock gradually decreases (Kumari et al., 2020). The 40- and 80-year-old orchards in our study may have promoted microbial activity that accelerated the breakdown of organic matter (Table 2). Soil PMC stock under orchards was significantly greater than in the cotton field, suggesting a greater rate of SOC turnover in orchards. Previous studies also indicated that labile C is generally higher in orchards than in cotton fields. Conversion of farmland to orchards or agroforestry systems generally increases SOC and labile C fractions, mainly due to a greater amount of plant residues (Z. Wang et al., 2022). In the southeastern United States, pecan orchards exhibited higher levels of POXC and microbial activity than cotton fields (Slade & Wells, 2022). In the Jinyun Mountains in China, forested and abandoned lands had greater labile C content than orchards and farmland, but orchards still contained more labile C than cropland (R. Li et al.,). In addition, the apple orchards in Kashmir, India, demonstrated significant improvements in various SOC pools, including labile C pools, up to 40 years of age (Sofi et al., 2012). Overall, these studies indicate that orchard systems accumulate more labile C than crops, likely due to less soil disturbance and increased residue inputs.

Soil N fractions, specifically SON and TLN, were significantly greater in cotton fields than in pecan orchards, probably due to frequent soil disturbance and annual input of N in cotton. Slade and Wells (2022) reported that the total N was significantly greater in 11- to 20-year-old pecan orchards than in row crops in Georgia. Orchards typically show higher N uptake than cotton fields, and intensive N fertilization in orchards can increase net primary productivity (Khalsa et al., 2020).

4.3 | Microbial communities flourished under pecan orchards improved soil C stability

Microbial communities, including the abundance of Gram-positive and Gram-negative bacteria, and actinobacteria, were significantly greater in pecan orchards than in the cotton field (Table 2), which can be attributed to the improvement in soil conditions due to the presence of trees. Previous studies indicate that pecan orchards and other perennial vegetation systems can enhance soil health compared to cotton fields. For example, Slade and Wells (2022) found that pecan orchards exhibited higher microbial activity, soil respiration, and SOC, which increased with orchard age. Similarly, perennial vegetation treatments, including grass buffers, biomass crops, and agroforestry buffers, showed significantly higher soil microbial biomass and SOC across all microbial groups than continuous corn–soybean rotation at 0- to 10-cm depth on claypan soil in Missouri (Alagele et al., 2020). The microbial community in orchard soils showed 28% more bacteria, with 14% more Gram-negative and 13% more Gram-positive bacteria (Lee & Lee, 2011). However, the results suggested a reduced Gram-positive to Gram-negative bacteria ratio with an increase in orchard age. In our study, Gram-positive bacteria increased by up to 36% and Gram-negative bacteria increased by up to 141% in the 40-year-old orchard. There is no statistical difference between 40- and 80-year-old orchards, and in some instances, smaller microbial community size may be due to site differences or reduced residue cycling in older orchards. In addition, the greater abundance of Gram-negative bacteria may help in nutrient cycling and mineralization of labile carbon, urging the need for additional conservation measures to enhance C storage and soil health beyond 40 years in orchard systems. Our study also showed that pecan orchards have greater AMF and saprophytic fungi than cotton fields at 0- to 15-cm depth. Due to their permanent and complex architecture, orchards typically support more diverse fungal communities than cotton fields (Mills et al., 2003). Organic amendments and fertilization preserve diverse AMF communities, whereas high phosphorus levels decreased AMF diversity in apple orchards in central Belgium (van Geel et al., 2015). Our study reveals that pecan orchards have more F:B ratio than cotton fields, possibly due to the permanent nature of orchards that couple with diverse microhabitats. From 15 to 89 years old, in apple orchards in Stavropol territory, Northern Russia, the proportion of fungi and yeast increased with orchard age, while the bacterial proportions decreased (Zakharov et al., 2021). However, fungal and bacterial diversity was higher in wheat fields than in orchards along the Taige Canal in China at 0- to 10-cm depth (Cui et al., 2022). Soil properties, including pH, organic C, and N levels, significantly shape the microbial community structure (Cui et al., 2022; Siles et al., 2023). These findings highlight the complex relationships among land use, management practices, and soil

microbial communities and urge more research linking soil health, soil C storage, and climate change mitigation potential of arid lands under diverse management.

Climate and soil factors influence the relationship between SOC and MAOC. The MAOC is an important component of SOC that increases with improved management but may reach saturation in soils (Z. Li et al., 2024). An increase in MAOC is often associated with increased microbial necromass and exudates, so microbial activities may have influenced the strong positive relation between these two components, with microbial litter contributing to the MAOC accumulation. We also observed the positive relationship between SON and POXC, which can be attributed to their roles in nutrient cycling. The C and N fractions in labile organic matter help regulate N mineralization in soils (Sano et al., 2006). N inputs suppress the labile C mineralization more significantly than any other stable pools (Zang et al., 2024). These results highlight the complex relationship between SON and labile C in nutrient cycling. However, changes in both labile C and N fractions, along with MAOC, suggest overall improvements in agroecosystem performance under pecan orchards. We noted that pecan orchard age can significantly mitigate climate change through C sequestration and improving soil health. Mainly, the 20- and 40-year-old orchards helped to capture and store more C in soil and act as long-term C sinks. They also enhance microbial communities in the topsoil that help to break down organic matter and stabilize C in the soil. Adopting sustainable management practices can play a pivotal role in mitigating climate change and improving soil health and overall agroecosystem sustainability beyond 40 years in arid environments.

5 | CONCLUSIONS

The results from our study show that the increasing age of pecan orchards may influence soil C pools and soil microbial communities at various depths in southwestern New Mexico. Soil PMC was significantly higher in 20-year-old pecan orchards at 15- to 90-cm soil depth compared to cotton fields. Compared to cotton fields and 80-year-old orchards, the SOC, MAOC, and POC were significantly greater in 20-year-old orchards at 15- to 90-cm depth. Soil TLN and SON were significantly higher under the cotton field at 0- to 90-cm depth than in pecan orchards of 20, 40, and 80 years old. The soil microbial communities, including bacteria and fungi biomass, were significantly greater in pecan orchards than in the cotton field at 0- to 15-cm depth. Results from these selected soil health indicators suggest that the soil quality of land previously used for row cropping systems in southern New Mexico can be improved by establishing pecan orchards. However, this needs to be balanced with the availability of irrigation water threatening this region. Pecan is a high

water-demanding crop compared to many row crops grown in the region, which presents a critical challenge for sustainable orchard management in semiarid areas. Introducing orchard practices on farmlands can lead to significant carbon inputs in above- and belowground biomass and soil. These systems can provide an integrated approach to sustainable land use while contributing to the region's climate change adaptation and mitigation. However, the reduced soil health indicators in the older pecan orchards require further investigation and should be considered properly in land management decisions.

AUTHOR CONTRIBUTIONS

Atinderpal Singh: Data curation; formal analysis; investigation; validation; visualization; writing—original draft. **Rajan Ghimire:** Conceptualization; data curation; funding acquisition; methodology; project administration; resources; software; supervision; validation; writing—review and editing. **Deb Raj Aryal:** Data curation; investigation; validation; visualization; writing—original draft. **Mohammed Omer:** Formal analysis; investigation; validation; writing—original draft. **Amrit Dhoj Adhikari:** Data curation; formal analysis; investigation; writing—review and editing. **Omolulu John Idowu:** Conceptualization; funding acquisition; investigation; methodology; project administration; writing—review and editing. **Richard Heerema:** Investigation; methodology; resources; supervision; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

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