Soil management affects soil C and N stocks but not overall soil health[1,2]

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ABSTRACT

Soil health describes a soil's capacity to function as a vital ecosystem that sustains plants, animals, and humans. It can be assessed by measuring specific soil physical, chemical, and biological parameters combined into a soil health index (SHI). The objective of this study was to evaluate the effect of management, depth, and their interaction on soil health indicators. We evaluated long-term continuous tillage, horticultural crop rotation, which had an antecedent tropical pumpkin/bean rotation, and a no-till avocado orchard in a Cumulic Haplustolls at the Juana Díaz Agricultural Experiment Substation. Soil samples were taken at 0 to 15, 15 to 30, 30 to 50, 50 to 75, and 75 to 100 cm intervals using a hydraulic probe. Soil pH, electrical conductivity, bulk density, dry stable aggregates, mean weight diameter, tensile strength, carbon and nitrogen stocks, and water content were quantified. The data were analyzed in a multivariate ANOVA. Results were classified considering threshold values, and an SHI score was determined based on the simple additive method. Our findings show that the no-till avocado orchard had better soil physicochemical qualities, including higher C and N stocks, but this did not lead to an improved SHI score when compared with the continuous tillage crop rotation plot. Soil depth, management, and their interaction were significant effects in both management systems with a score of 0.55 on the SHI scale. These results imply that, although overall soil health is not affected, increased C concentration, no-till, and perennials have a favorable effect on SHI indicators in horticultural systems in the San Antón series.

Keywords: soil health, indicators, depth, management

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RESUMEN

El manejo del suelo afecta las reservas de C y N del suelo, pero no la salud general del suelo

La salud del suelo es la capacidad de un suelo para funcionar como un ecosistema vital que sostiene plantas, animales y humanos. Se puede evaluar midiendo parámetros físicos, químicos y biológicos específicos del suelo que se pueden combinar en un índice de salud del suelo (ISS). El objetivo de este estudio fue evaluar el efecto del manejo, la profundidad y su interacción sobre los indicadores de salud del suelo. Evaluamos una labranza continua a largo plazo, rotación de cultivos hortícolas, donde previamente hubo una rotación de calabaza tropical/habichuela, y una huerta de aguacate sin labranza en un Cumulic Haplustolls en la Estación Experimental Agrícola de Juana Díaz. Se tomaron muestras de suelo a intervalos de 0 a 15, 15 a 30, 30 a 50, 50 a 75 y 75 a 100 cm utilizando sonda hidráulica. Se cuantificó el pH del suelo, la conductividad eléctrica, la densidad aparente, los agregados secos estables, el diámetro de peso promedio, la resistencia a la tracción, las reservas de carbono y nitrógeno y el contenido de agua. Los datos se analizaron en un ANOVA multivariado. Los resultados se clasificaron teniendo en cuenta los valores de umbral dados y se determinó una puntuación ISS con base en el método aditivo simple. Nuestros hallazgos demuestran que el huerto de aguacate sin labranza tenía mejores cualidades fisicoquímicas del suelo, incluidas mayores reservas de C y N, pero esto no condujo a una mejor puntuación de ISS en comparación con la parcela de rotación de cultivos de labranza continua. La profundidad del suelo, el manejo y su interacción fueron efectos significativos en ambos sistemas de manejo con un puntaje de 0.55 en la escala ISS. Estos resultados implican que, aunque la salud general del suelo no se ve afectada, el aumento de la concentración de C, la labranza cero y las plantas perennes tienen un efecto favorable sobre los indicadores de ISS en los sistemas hortícolas de la serie San Antón.

Palabras clave: salud del suelo, indicadores, profundidad, manejo

INTRODUCTION

Soil health can be divided into inherent and dynamic components (Davis et al., 2023). Inherent soil properties are those associated with soil morphology with minimal temporal change, and dynamic properties are influenced by changes in temperature, soil moisture, and soil management (Larsen and Pierce, 1994). Soil health assessments are conducted by choosing specific soil properties that affect its functions, and thus, can serve as soil health indicators (Aparicio and Costa, 2007; Bagnall et al., 2023). A single soil health indicator usually cannot be used to assess soil health, but rather various indicators are measured and combined to form an index (De Laurentis et al., 2019). Some studies have demonstrated that soil carbon (C) stocks may be the best soil health indicator (Bagnall et al., 2023; Brandão and Milà I. Canals, 2013; Milà I. Canals et al., 2007), as many inherent and dynamic soil properties are dependent or associated with total or a fraction of soil organic C.

Despite current knowledge, there are still gaps regarding the interaction of soil management, soil depth, and soil properties, and their effects on soil health indicators (Key et al., 2016; Poesen, 2018; Smith et al., 2015). The need for a science-based tool to measure soil health led to the development of a soil health index (SHI), according to Cao et al. (2023) and Li et al. (2023), a value that combines various soil characteristics and scores its “fitness to function” (Armenise et al., 2012). The simple additive approach is a common and straightforward method for developing an SHI because it uses selected soil parameters and designates threshold values based on available research (Amacher et al., 2007). It is based on a scale of 0 to 1, where a score lower than 0.54 is considered low, 0.54 to 0.75 is moderate, and above 0.75 is high (Rangel-Peraza et al., 2017).

This study aimed to assess how soil health indicators differ between a long-term tillage tropical pumpkin/bean (*Cucurbita moschata* L./*Phaseolus vulgaris* L.) rotation plot (TPB) and a no-till Semil 34/Semil 34 (rootstock/scion) avocado (*Persea americana* L.) orchard (AVO) and to obtain an SHI score for each. We chose the simple additive method approach because of its simplicity and cost-effectiveness (Amacher et al., 2007), as well as its appeal to small and low-income farmers. There were two treatment levels: annuals/tillage (TPB) and perennials/no-tillage (AVO). We tested the hypothesis that no-tillage operations and perennial crops result in the AVO having a higher soil C content, thus better values for the soil health indicators and a higher SHI score than the TPB with frequent tillage.

MATERIALS AND METHODS

Site Description

The study was conducted at the Agricultural Experiment Substation in Juana Díaz (18° 01’ 47.17” N and 66° 31’ 13.19” W) with an elevation of 36 m above sea level. Annual precipitation fluctuates between 508 and 1,016 mm and mean annual temperature fluctuates between 26.1 and 27.2° C with December, January, and February as the driest months of the year (Muñoz et al., 2018). The AVO had been previously established by Ordóñez-Torres (2009) in May 2006 on a 0.41 ha plot using the Semil 34/Semil 34 (rootstock/scion) cultivar for reproductive purposes. The field was prepared through conventional methods (herbicide application and disc plow). An irrigation system consisting of four nozzles was installed in a square around each avocado tree, with approximately 2 m between them. Triple superphosphate fertilizer was applied to each tree at planting at a rate of 29 to 43 kg P_2O_5/ha. After planting, the plot had only been managed for mechanical weed control. Cover crops, consisting of *Arachis pintoi* Krapov. & W. C. Greg. ‘Porvenir’ and *Arachis glabrata* Benth. TARS 17095, were planted in the AVO in June 2006. The conservation cover was maintained by mowing. The dominant soil series of the AVO is San Antón (Fine-loamy, mixed, superactive, isohyperthermic Cumulic Haplustolls) (National Cooperative Soil Survey, n.d.-a).

The TPB has an area of 2.59 ha of which 72% is dominated by the San Antón soil series, and 28% of Jacaguas series (Loamy-skeletal, mixed, superactive isohyperthermic Fluventic Haplustolls) (National Cooperative Soil Survey, n.d.-b). Since 2006, the plot has been prepared for bean planting once every two years, and for tropical pumpkin once every three. In 2019, 15-15-15 (N-P_2O_5-K_2O) fertilizer at a rate of 449 kg/ha was added to the bean rotation. In previous years, 10-10-10 had been applied at a rate of 112 kg/ha. For the tropical pumpkin rotation, a sum of 112 to 135 kg/ha of N, $P_2O_{5,}$ and K_2O was applied in the pre-planting. During the growing cycle, the plot was supplemented with N, P_2O_5, and K_2O at a rate of 89 to 111 kg/ha, 2 kg/ha, and 45 kg/ha, respectively. During fallow, the soil was kept weed-free by tillage. During the summer 2020 cycle, the plot was initially tilled with the disk plow at 20 cm using a 105 horsepower (hp) tractor on June 22, and the planting banks were lifted with the disc harrow at 15 cm using a 105 hp tractor on July 6; the plastic groundcover was installed with a Kennco©[6] plastic mulch layer using a 105 hp tractor on July 9, and herbicide was applied manually with a backpack sprayer on July 10.

Soil Sampling

Sampling points in the TPB treatment were selected based on a random selection procedure using ArcGIS, and four management units within the San Antón series were selected. Sampling points in the AVO treatment were selected based on the available trees. Both treatments were sampled once in June 2020. In the AVO treatment, sampling points for each tree were selected at a 1-m, 2-m, 3-m, and 4-m distance from the avocado tree. Soil samples were collected using a 6.25 cm diameter hand auger for the following soil intervals:

[6] Company or trade names in this publication are used only to provide specific information. Mention of a company or trade name does not constitute an endorsement by the Agricultural Experiment Station of the University of Puerto Rico, nor is this mention a statement of preference over other equipment or materials.

0 to 15 cm, 15 to 30 cm, 30 to 50 cm, 50 to 75 cm, and 75 to 100 cm, for a total of 30 disturbed samples per plot. Three undisturbed 1-m soil core samples were collected from each plot using a Giddings hydraulic auger with a liner-fitted corer, 6.4 cm in width [USDA/NRCS SPSD/SSR03 X MLRA SSO (3-MAZ)]. Undisturbed soil samples were analyzed for bulk density and moisture content on the collection day. Disturbed soil samples were sieved through a 4.5 mm mesh and then through a 2-mm mesh.

Soil Analysis

Bulk density was determined with the core method (Grossman and Reinsch, 2002) in the Soil Fertility and Water Laboratory at UPRM. A 20 g subsample was obtained from each depth segment and dried at 105° C for 24 h to determine the gravimetric and volumetric moisture content (Topp and Ferre, 2002). Dry aggregate stability was determined using 20 g of aggregates placed onto nested sieves 4.75, 2, 1, 0.5, and 0.25 mm (Chepil, 1962) in the SENR Soil Physics Laboratory at OSU, the site of the other soil analyses. This procedure was selected given the semi-arid conditions of the research sites. The samples were shaken at a 1.75 Hz frequency for 15 min and the mean weight diameter calculated. The crushing test determined tensile strength (Dexter and Watts, 2000; Horn and Dexter, 1989). Available water capacity was obtained using pressure plate extractors with pressures ranging from 0.01 to 0.04 MPa and at 1.5 MPa (Dane and Hopmans, 2002). The same procedure was followed to evaluate moisture retention at 1.5 MPa pressure on soils passed through a 2-mm sieve. Soil pH was determined in a 2:1 water: soil mixture (Thomas, 1996) using a Thermo-Scientific Orion Star Series pH/conductivity meter. The samples were shaken for 15 min, and the pH of the mixture was read and recorded. Electrical conductivity (EC) was determined using the same 2:1 water: soil ratio mixture and equipment used in the pH test (Rhoades, 1996). The device was recalibrated after every 10 samples. Total carbon (C) concentration was determined using 15 mg of soil by the dry combustion method (Nelson and Sommers, 2002) and total nitrogen (N), using a Thermo Scientific FLASH 2000 organic elemental analyzer. The soil C and N concentrations were converted to stocks using equations 1 and 2 (Poeplau et al., 2015).

The SHI indicators were classified considering assigned threshold values based on the literature reviewed and the expert opinion of authors named in Table 1 and 2. Equations 3 and 4 were used to obtain the SHI scores for each horticultural system (Amacher et al., 2007).

$$\mathbf{C\ in\ \frac{Mg}{ha} = \left(\frac{10,000m^2}{ha}\right)(horizon\ depth\ in\ m)\left(BD\ in\ \frac{Mg}{m^3}\right)\left(\%\ \frac{C}{100}\right)} \quad \textbf{Eq. 1}$$

$$\mathbf{C\ concentration\ \left(\frac{g}{kg}C\right) = (\%C)(10)} \quad \textbf{Eq. 2}$$

$$\mathbf{Total\ SHI = \sum individual\ soil\ parameter\ index\ values} \quad \textbf{Eq. 3}$$

$$\mathbf{SHI = \left(\frac{Total\ SHI}{SHI\ max}\right)} \quad \textbf{Eq. 4}$$

where $SHI_{\max}$ is the maximum total SHI for properties measured and C is carbon.

Statistical Analysis

Soil depths were analyzed as repeated measures through a multivariate ANOVA in SAS version 9.4 (SAS Institute Inc.) to evaluate the effect of management and depth as individual factors, and the interaction between depth*management using the Wilks' Lambda test. Significant differences were determined by mean separation using LSD ($p<0.05$).

RESULTS AND DISCUSSION

Tillage and other soil management strategies significantly affected soil C stocks to 1-m depth with 121 and 49.8 Mg C/ha for the AVO and TPB, respectively. There were significant treatment effects for soil C and N stocks when comparing treatments within each depth interval. These findings coincide with those of Rodríguez-Rivera (2023) where significant differences in organic matter content were observed between depth intervals in the San Antón series. Soil C stocks at specific depths of 0 to 15, 15 to 30, 30 to 50, 50 to 75 cm, and 75 to 100 cm, were 29.9, 24.3, 29.5, 25.4, and 11.7 Mg/ha for the AVO treatment and 13.7, 11.5, 9.33, 10.7, and 4.59 Mg/ha for the TBP treatment, respectively (Figure 1). Similar findings were observed by Denvir et al. (2024) where deeper horizons had less C than topsoil horizons. In another study conducted by Ordóñez et al. (2008), avocado orchards in Mexico reported 156 Mg C/ha. The disparity between our results and theirs could be attributed to the geomorphological differences between countries. Soil N stocks at specific depths of 0 to 15, 15 to 30, 30 to 50, 50 to 75 cm, and 75 to 100 cm, were 2.58, 3.94, 5.84, 6.85, and 4.65 Mg/ha

TABLE 1.—*Soil health indicators (SHI), threshold values, interpretation, and scores for chemical indicators.*

SHI Chemical Indicators	Range	Interpretation	Score	Reference
pH	5.5.-7.2	Slightly acidic to neutral	2	Amacher et al., 2007
	>7.2 < 8.0	Slight to moderately alkaline	1	
Electrical conductivity (dS/M)	<0.2	Low salt level	0	Lal, 1994
	0.2-0.5	Optimum salt level for plants	1	
	>0.5	High salt level, adverse effect likely	0	
N-stocks (Mg/ha)	<5.0	N deficient	1	Mukherjee and Lal, 2014
	5-10	Moderate to optimum N level	2	
	>10.0	N-rich soil	3	
C-stocks (Mg/ha)	<50.0	C deficient	1	Mukherjee and Lal, 2014
	50-100	Moderate to optimum C level	2	
	>100	C-rich soil	3	
Bulk density (Mg/m^3)	<1.0	High organic soil, supports plant roots	2	Amacher et al., 2007; Walczak et al., 2002
	1.0-1.5	Adverse effects unlikely	1	Sokoowska et al., 2011
	>1.5	Adverse effects likely	0	Brzezinska et al., 2011

[1] Adapted from Mukherjee and Lal (2014)

TABLE 1.—*(Continued) Soil health indicators (SHI), threshold values, interpretation, and scores for chemical indicators.*

SHI Chemical Indicators	Range	Interpretation	Score	Reference
Dry stable aggregates (%)	<50	Infiltration and soil erosion problems are likely	0	Li et al., 2013
	50-70	Moderate constraints	1	Lal, 1994
	70-90	Good soil	2	
	>90	Excellent soil	3	
Mean weight diameter (mm)	<1.0	Infiltration and soil erosion problems are likely	0	Li et al., 2013
	1-2	Moderate limitations	1	Lal, 1994
	2-5	No limitation	2	
Tensile strength (MPa)	1-2	Adverse effect on plant root unlikely	2	Lal, 1994
	2-3	Moderate adverse effect on plant root	1	Carter, 2006
	>3	Severe adverse effect on plant root	0	
Water content (cm)	<5.0	Water stress to plants	0	Mukherjee and Lal, 2014
	5-10	Moderate water availability	1	

[1] Adapted from Mukherjee and Lal (2014)

TABLE 2.—*Soil health indicators (SHI), threshold values, interpretation, and scores for physical indicators.*

SHI Physical Indicators	Range	Interpretation	Score	Reference
Bulk density (Mg/m^3)	<1.0	High organic soil, supports plant roots	2	Amacher et al., 2007; Walczak et al., 2002
	1.0-1.5	Adverse effects unlikely	1	Sokoowska et al., 2011
	>1.5	Adverse effects likely	0	Brzezinska et al., 2011
Dry stable aggregates (%)	<50	Infiltration and soil erosion problems are likely	0	Li et al., 2013
	50-70	Moderate constraints	1	Lal, 1994
	70-90	Good soil	2	
	>90	Excellent soil	3	
Mean weight diameter (mm)	<1.0	Infiltration and soil erosion problems are likely	0	Li et al., 2013
	1-2	Moderate limitations	1	Lal, 1994
	2-5	No limitation	2	
Tensile strength (MPa)	1-2	Adverse effect on plant root unlikely	2	Lal, 1994
	2-3	Moderate adverse effect on plant root	1	Carter, 2006
	>3	Severe adverse effect on plant root	0	
Water content (cm)	<5.0	Water stress to plants	0	Mukherjee and Lal, 2014
	5-10	Moderate water availability	1	

[1] Adapted from Mukherjee and Lal (2014).

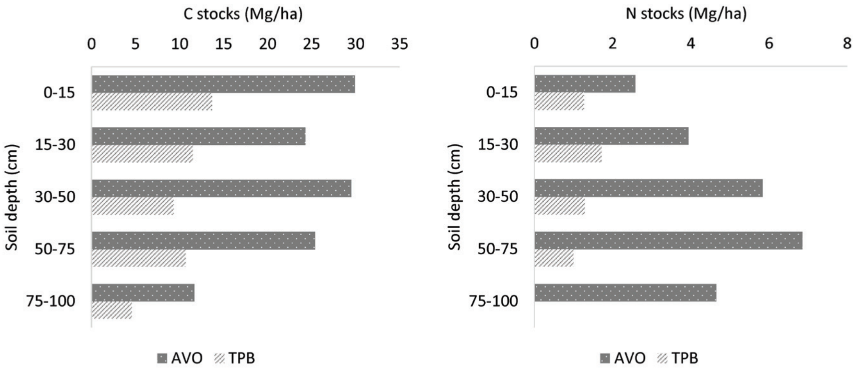

FIGURE 1. Soil C and N stocks (Mg/ha) in depth intervals for the AVO and TPB.

for the AVO treatment and 1.27, 1.72, 1.29, 1.00, and <0.5 Mg/ha in the TBP treatment, respectively (Figure 1). Soil N concentration at the 75 to 100 cm depth interval was below the detection limit. Soil C:N ratio based on soil C and N stocks at specific depths of 0 to 15, 15 to 30, 30 to 50, 50 to 75 cm, and 75 to 100 cm, were 11.7, 12.4, 12.7, 10.7, and 9.00 for the AVO treatment and 11.7, 12.3, 12.4, <0.5 from 50 to 100 cm in the TPB treatment, respectively.

Soil chemical (pH and electrical conductivity) and physical indicators (bulk density, dry stable aggregates, mean weight diameters, tensile strength, and water retention) were not affected by management treatment for each management and depth interval as shown in Tables 3 and 4. Soil pH was significantly higher for the AVO treatment at 15 to 30 cm, but not at other depths. The pH values for both treatments were neutral, ranging from 7.07 to 7.70, similar to the findings of Rodríguez-Rivera (2023). Soil electrical conductivity was higher in TPB at 15 to 30 cm and the opposite was observed at 75 to 100 cm. The AVO treatment had higher soil bulk density at 0 to 15 cm and the opposite was observed at 50 to 75 cm. Dry stable aggregates, mean weight diameter and water content were not affected by depth, management, or their interactions. This suggests that higher C stocks do not necessarily lead to improved aggregate stability as the findings of Liu et al. (2019) demonstrate. Distinctly, Rodríguez-Rivera (2023) observed statistically significant differences in aggregate stability within the 20 cm depth in the San Antón series, but he compared cultivated and non-cultivated plots, whereas in this study, both plots were cultivated. Tensile strength was significantly higher for the AVO treatment at 0 to 15 and 15 to 30 cm.

Despite both management systems having varying soil chemical and physical indicators, both systems scored 0.55 on the SHI, with no statistical difference (p>0.05) across management systems. Distinctly,

TABLE 3.—*Summary of soil health indicators (SHI): depth, management, and depth*management effects for chemical indicators.*

SHI Chemical Indicators	Treatment	0-15 cm	15-30 cm	30-50 cm	50-75 cm	75-100 cm
pH	AVO	7.27 (±0.38)	7.63 (±0.19)*	7.69 (±0.18)	7.70 (±0.18)	7.64 (±0.18)
	TPB	7.07 (±0.18)	7.27 (±0.19)*	7.54 (±0.24)	7.62 (±0.20)	7.60 (±0.16)
Electrical Conductivity (dS/M)	AVO	0.26 (±0.05)	0.16 (±0.03)*	0.16 (±0.03)	0.16 (±0.04)	0.12 (±0.07)*
	TPB	0.27 (±0.12)	0.23 (±0.10)*	0.16 (±0.07)	0.16 (±0.05)	0.10 (±0.03)*
N-stock (Mg/ha)	AVO	2.58 (±0.39)*	3.94 (±0.31)*	5.84 (±0.65)*	6.85 (±2.01)*	4.65 (±1.83)*
	TPB	1.27 (±0.28)*	1.72 (±1.36)*	1.29 (±2.03)*	1.00 (±2.45)*	0.00 (±0.00)*
C-stock (Mg/ha)	AVO	29.93 (±5.04)*	24.30 (±0.03)*	29.51 (±4.32)*	25.40 (±8.41)*	11.69 (±2.50)*
	TPB	13.70 (±3.28)*	11.52 (±4.04)*	9.33 (±4.98)*	10.70 (±5.02)*	4.59 (±1.16)*

[1] Standard errors are shown in parentheses.

[2] Means with an asterisk (*) indicate statistically significant effects of depth, management, and depth*management for each SHI at that specific depth as determined with Fisher's LSD test ($p<0.05$).

TABLE 4.—*Summary of soil health indicators (SHI): depth, management, and depth*management effects for physical indicators.*

SHI Physical Indicators	Treatment	0-15 cm	15-30 cm	30-50 cm	50-75 cm	75-100 cm
Bulk density (Mg/m^3)	AVO	0.93 (± 0.07)*	0.98 (±0.06)	0.95 (±0.10)	1.22 (±0.14)*	1.22 (±0.10)
	TPB	0.58 (±0.01)*	0.83 (±0.24)	1.01 (±0.02)	1.51 (±0.07)*	1.22 (±0.16)
Dry stable aggregates (%)	AVO	98.57 (±0.38)	98.44 (±0.19)	98.20 (±0.18)	98.09 (±0.18)	98.57 (±0.38)
	TPB	97.04 (±0.18)	97.52 (±0.19)	98.13 (±0.24)	97.41 (±0.20)	97.04 (±0.18)
Mean weight diameter (mm)	AVO	3.12 (±0.49)	2.99 (±0.31)	3.09 (±0.39)	3.07 (±0.38)	3.10 (±0.49)
	TPB	2.79 (±0.05)	2.84 (±0.06)	2.88 (±0.01)	2.88 (±0.03)	2.11 (±1.23)
Tensile strength (MPa)	AVO	22.6 (±4.35)*	22.5 (±5.27)*	—	—	—
	TPB	18.0 (±2.50)*	14.7 (±7.38)*	—	—	—
Water content (cm)	AVO	1.62 (±0.85)	1.78 (±0.05)	2.15 (±1.38)	3.38 (±1.20)	3.40 (±2.12)
	TPB	0.97 (±0.09)	1.23 (±0.27)	2.20 (±0.45)	4.33 (±1.90)	3.43 (±1.32)

[1] Standard errors are shown in parentheses.

[2] Means with an asterisk (*) indicate statistically significant effects of depth, management, and depth*management for each SHI at that specific depth as determined with Fisher's LSD test ($p<0.05$).

the findings of Rodríguez-Rivera (2023) suggest that cultivated plots with continuous tillage have higher SHI than plots managed with conservation tillage. However, a score of 0.55 is indicative of moderate soil health (Li et al., 2023; Moebius-Clune et al., 2017; Rangel-Peraza et al., 2017). Given that soil C was higher in the AVO, we expected it would have improved the SHI score, but our findings suggest the contrary. Nonetheless, the impact of tillage practices and crop residues on soil quality requires long-term studies to provide ample time for the decomposition of organic matter, and alongside it, the stabilization of physical parameters (Rodríguez-Rivera, 2023), such as the ones evaluated in this study.

Possibly, the greater soil C content in the soil under the AVO could be due to greater deposits of organic residue on the soil surface from tree leaf and litter deposition and the conservation cover mowing (Rodríguez-Rivera, 2023). The AVO had not been tilled for at least 13 years, thus the organic residue deposited is expected to decompose relatively slowly. It is possible that the AVO provided improved protective conditions for the mean residence time of soil C (Lal, 2016), and thus, soil C stocks were higher than in the TPB. Therefore, our data suggests that aboveground vegetation is an influential factor for increased belowground C storage in avocado orchards, as observed by Atucha et al. (2012) and Denvier et al. (2024). In contrast to the TPB, where the soil is tilled after each commercial crop, greater soil C oxidation and turnover are expected (Liu et al., 2018). Acosta-Martínez et al. (2008) evaluated soil C beneath mango (*Mangifera indica* L.) and quenepa (*Melicoccus bijugatus* L.) fruit orchards and tilled soil under vegetable production in a Cumulic Haplustoll in the same area and found greater soil C in untilled fruit orchards. The authors analyzed that the lower soil C content found at the vegetable production site could be attributed to the intensive tillage practices that promote soil C oxidation and alter the soil structure (Acosta-Martinez et al., 2008). Given that the TPB was exposed to more frequent tillage disturbance, such practice may have accelerated the loss of carbon through the rupture of soil aggregates along with the removal of native vegetation (Andrade et al., 2020; Kassa et al., 2017).

Mukherjee and Lal (2014) reported that soil health could be influenced more by soil type than management and sampling depth through the simple additive approach. This hypothesis is supported by the present study given that the AVO and the TPB belong to the same soil series: San Antón. Therefore, horticultural systems that are in the same soil type could have similar soil physicochemical attributes and soil health regardless of their management. Furthermore, the diversity of soil conditions affecting C storage on a landscape scale poses a challenge to determine soil health in horticultural systems (Denvir et al., 2024; Lal, 2016). Even though the simple additive procedure may lead to an oversimplification of the complex soil system (Yang et al., 2020) and is not sensitive enough to detect the effect of management, it is a relatively simple, quick, and user-friendly (Aravindh et al., 2020) method to conduct a soil health assessment, making it a viable alternative for farmers.

CONCLUSIONS

The data obtained in this study indicate that soil physicochemical properties were more favorable under perennials/no-tillage (AVO) than annuals/conventional tillage (TPB). Both systems scored 0.55 on the 0 to 1 SHI scale, thus rejecting the hypothesis that the AVO would have a higher SHI score than the TPB because of a higher C concentration. However, significant treatment effects were observed for C and N stocks within all depth intervals, but not for the rest of the SHI parameters. These findings suggest that higher C concentration, no-tillage, and perennials positively impact SHI indicators in horticultural systems located in the San Antón series, but not overall soil health. Therefore, landholders and managers are encouraged to adopt practices that minimize soil disturbance to improve soil properties even though this may not necessarily lead to improving soil health. Future long-term studies should address this concern.

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