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Evaluation of Soil Quality in a Composite Pecan Orchard Agroforestry System Based on the Smallest Data Set

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Abstract: Agroforestry not only takes into account the use of land for forestry and agriculture but can also improve the efficacy of utilized above- and belowground resources, which have always garnered widespread attention. The objective of this study is to evaluate the quality of pecan orchard soil following the implementation of agroforestry. Consequently, 15 indices were selected for a principal component analysis (PCA), which was then combined with the norm value of each index and the correlation coefficients between indices to establish a minimum data set (MDS). A comprehensive index model was used to calculate the soil quality index (SQI) of the total data set (TDS) and MDS (SQI-TDS and SQI-MDS, respectively), and a linear regression of the two was performed. The results revealed that the MDS indices for the evaluation of soil fertility included the pH, electrical conductivity value (EC), bulk density (BD), available potassium (AK), total nitrogen (TN), magnesium (Mg), and the index screening and filtering rates attained 60%. The Soil Quality Index (SQI-MDS) of the four planting patterns, sorted from largest to smallest, were: PPS (0.573) > PPH (0.519) > PPL (0.355) > CK (0.315). BD and AK were the main factors that affected the quality of hickory orchard soils. The agroforestry composite system improved the availability of nutrients and soil quality. Thus, the promotion of understory intercropping and appropriate increases in potassium fertilizers for plantations are recommended.

Keywords: pecan; soil quality evaluation; minimum data set; principal component analysis; environmental factors

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1. Introduction

Soil is a critical component of terrestrial ecosystems that operates at the intersection of the atmosphere, lithosphere, hydrosphere, and biosphere, which serves as an essential substrate for the regulation of nutrient absorption, material decomposition, and energy flows [1,2]. It plays an invaluable role in the maintenance of energy security and the protection of biodiversity [3]. The capacity to maintain crop production levels while improving environmental quality within specific boundaries is referred to as soil quality [4]. Soil quality is defined as the ability to ensure the sustainability of the soil environment and biosphere, which is a comprehensive reflection of soil characteristics based on its fertility [5,6].

As a tool for assessing the impacts of management measures and human activities such as land-use changes, soil quality assessments have attracted widespread attention [5,7,8]. They can assist with defining the status and dynamics of soil quality in a timely manner towards achieving the sustainable management of land resources [9]. Topsoil (0 to 20 cm) is a reliable indicator of the health of the soil as it is prone to disturbances. It is rich in important chemical elements such as C, N, P, and K, and is where soil microbes are most active [10,11]. Anthropogenic land management activities induce changes in physical and chemical soil properties, which ultimately impact its quality [12]. Poor soil quality is primarily manifested through decreased organic matter, lower permeability, reduced microbial diversity, increased bulk weight, the destruction of aggregate structures, and adverse pH changes [13,14]. Thus, the precise evaluation of soil quality is essential for guiding sustainable soil health [15].

Due to differences in the scale of soil quality evaluation parameters and the complexity of intense soil management, there is currently no unified standard for the evaluation of soil quality [16]. The Soil Quality Index (SQI) is the most common and widely accepted of the various available soil quality assessment tools [17,18]. The minimum data set (MDS) is a representative minimum set of soil parameters that can reflect most soil property data [8,19]. Studies have shown that MDS can accurately evaluate soil quality using minimal indicators, which can improve work efficiencies [5,16].

Agroforestry comprises an artificial ecosystem that makes full use of land for the development of multiple economies, primarily by planting crops beneath trees or large shrubs to maximize land utilization, while maintaining soil fertility [20]. It is generally believed that this management strategy can enhance soil structures, water holding capacities, and microenvironments to a certain extent, as well as reduce the loss of soil nutrients caused by soil erosion and leaching, and improve the activities of soil microorganisms [21]. Previous studies have reported that crop leaves or vines can maintain a relatively constant soil temperature while mitigating direct soil erosion by storms, can reduce water and nutrient loss, and provide a suitable environment for the reproduction and activities of microorganisms [22–24]; furthermore, increased soil microbial activities and the presence of fine roots within the surface soil improve nutrient turnover. Additional litter serves to augment soil carbon and nitrogen inputs, which are conducive to the improvement of soil quality [20,25].

Pecan (*Caray illinoensis*) is native to North America and is currently widely grown in more than 20 countries, including the United States, Mexico, South Africa, and China. In 2021, according to the U.S. Department of Agriculture, its 2020 production totaled 302 million pounds, covering an estimated 402,000 acres [26]. It was recently projected that by 2022 Mexico's total pecan production will reach ~330 million pounds [27]. As of 2021, 440,000 pecan trees were grown in South Africa, which produced 19,112 tons of fruit [28]. Introduced to China in the 19th century, pecans are now grown extensively countrywide, with Anhui Province covering the largest area at ~98,000 acres [29]. Since the growth of pecans is a long-term process, Chinese farmers typically select certain crops (e.g., *Paeonia suffruticosa*, *Hemerocallis citrina,* and *Glycine max*) for planting under young pecan trees to improve land efficiency and increase economic returns [30,31]. The accurate assessment of soil quality in the Pecan Agroforestry Complex system is required for the sustained management of thin-shelled pecans.

We hypothesized that the monocultivation of pecans reduces soil quality, whereas the agroforestry complex model has the capacity to improve soil quality. The objectives of this study were to: (1) Screen out the main factors that affected the soil quality of pecan fruit compound management; (2) Establish an MDS dataset to evaluate the soil quality of woodlands under the composite management model; (3) Compare the differences in SQI between MDS and the full data sets (TDS); (4) Select the optimal composite pecan fruit farming/forestry business model.

2. Materials and Methods

2.1. Study Area

This study took place at Xinfeng Agricultural Park, in the Yingquan District of Fuyang City, Anhui Province, China (115°33′44″ E, 32°57′25″ N). This area belongs to a warm semi-humid monsoon area with an average annual rainfall of 750–900 mm, an average annual temperature of 15 °C, and an average altitude of 33 m. The soil type is lime concretion black soil [20] (Table 1).

Table 1. Basic physiochemical soil properties of *Carya illinoinensis* plots.

Indicators	TN (g/kg)	TP (g/kg)	TK (g/kg)	AP (mg/kg)	AK (mg/kg)	PH	BD (g/cm^3)	MC (%)
Xinfeng Agricultural Park	0.89	1.27	3.12	8.79	178.7	8.12	1.61	18.73

The pecans were planted in 2016 followed by perennial herbs or small shrubs such as *Paeonia suffruticosa*, *Hemerocallis citrina*, and *Paeonia lactiflora* in 2017. In September 2019, an experimental randomized cluster design including three agroforestry composite models was adopted, and a single plantation of pecans was used as a control. The pecan row spacing was 4 m × 6 m and the agroforestry composite model included: (1) Pecans—*Paeonia lactiflora*—*Hemerocallis citrina* (PPH), with a peony row spacing of 0.2 m × 0.2 m, and yellow cauliflower row spacing of 0.4 m × 0.8 m; (2) Pecans—*Paeonia suffruticosa* (PPS), with a PPS row spacing of 0.2 m × 0.6 m; (3) Pecans—*Paeonia lactiflora* (PPL), with a PPL row spacing of 0.2 m × 0.6 m; (4) Single pecan plantation forest (CK) (Figure 1). The same cultivation and management measures were adopted for the different treatments. Organic fertilizer (6000 kg/acre) was applied in the winter after defoliation, whereas compound fertilizer and trace elements such as Zn and Mg were applied in summer.

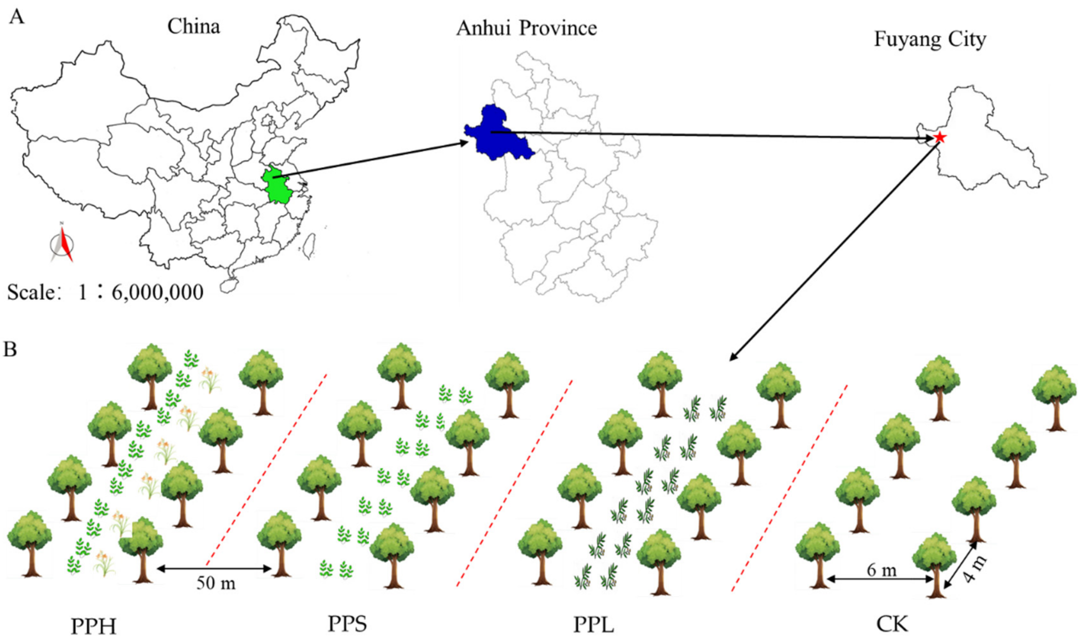

Figure 1. Location of the study area and experimental design: (**A**) The study site is located in the Yingquan District of Fuyang City of Anhui Province, China; (**B**) Experimental design of pecan plantation.

2.2. Sampling Design

We sampled nine plots from each of the four composite agroforestry models for a total of thirty-six plots, all of which were >50 m from any roadway. For each plot, a rectangle enclosed by eight pecan trees was randomly used as a cell. To reduce spatial autocorrelation, two drainage channels (~50 m) were spaced apart for each cell.

Soil samples were collected from the test site in early September 2019. Following the removal of plants and their litter on the plot surface, according to the "S" shape sampling method, the topsoil at 0 to 20 cm depth was extracted from each cell. After the removal of the roots and organic debris, the resulting sample was mixed and sampled using an Ø6 cm ring knife for a total of 36 mixed soil samples. The soil samples were then sealed and transferred to the laboratory at low temperatures to determine their physicochemical properties.

2.3. Laboratory Analysis

All sample processing and analyses were completed in a laboratory at Anhui Agricultural University. The fresh soil samples were divided into two parts in the laboratory, where the nitrate nitrogen (NO_3^--N), ammonium nitrogen (NH_4^+-N), available phosphorus (AP), and available potassium (AK) were quantified for one portion within 48 h. The ring knife method was used for the other portion to collect samples to determine the soil bulk density (BD), soil moisture content (MC), and Soil Porosity (SP) using the Specific Gravity Method [32]. After air drying, the soil pH, electrical conductivity (EC), total carbon (TC), total nitrogen (TN), total potassium (TK), calcium (Ca), and magnesium (Mg) were determined using 100 mesh sieves. The soil NO_3^--N, NH_4^+-N, AP, and AK were quantified using an automatic discontinuous chemical analyzer (CleverChem Anna, DeChem-Tech, Germany) [33]. The pH of the soil was determined using a pH meter (Mettler Toledo, Shanghai, China) in an aqueous solution of 1:2.5 (w/v), whereas the EC value was determined with an electrical conductivity meter (DDB-303A) using a 1:5 soil/water leaching solution at 25 °C [34]. The TC and TN of the soil were determined via an automatic element analyzer (Vario EL Cube, Elementar, Langenselbold, Germany) [33,35]. The TK, Ca, and Mg were determined using an inductively coupled plasma emission spectrometer (iCAP 6300 Series, Thermo Fisher Scientific, Waltham, MA, USA) [20].

2.4. Data Analysis

We selected 15 soil physicochemical properties (EC, SC, BD, pH, SP, AP, TP, NH_4^+-N, NO_3^--N, TK, AK, TN, TC, Ca, and Mg) as the total data set (TDS). The affiliation function method and the soil quality index were employed for comprehensive evaluation. First, an evaluation factor was selected to establish the minimum data set (MDS). To overcome autocorrelations between indicators, principal component analysis (PCA) was selected for grouping. The data for all indicators was standardized and the correlations between them were determined, after which the number of principal components was finally determined. Among the principal components of the eigenvalue ≥ 1 soil indicators with loads of ≥ 0.5 were designated into a group. For metrics that were likely to go into more than one group, those with low correlations were selected. The norm value was then calculated for the grouped indicator, where the larger the norm value the stronger its capacity to interpret the synthesis data. Indicators within the top 10% range of the norm values in each group were selected to further analyze the correlations between them. If the correlation was strong ($r > 0.5$) the indicator with the highest norm value was determined to enter the MDS, whereas if the correlation was low ($r < 0.5$) all entered and obtained the final MDS. The calculation method of the norm value of the evaluation index was as follows:

$$N_{\mathrm{ik}} = \sqrt{\sum\nolimits_i^k \left(\mu_{ik}^2 \beta_k\right)} \quad (1)$$

where N_{ik} is the combined load of the first k principal component of the i variable on the eigenvalue ≥ 1; μ_{ik} is the load of the i variable on the k-th principal component; β_k is the characteristic value of the k-th principal component.

Second, the membership and weight values of the indicators entering the MDS were obtained. According to the positive and negative effects of different indicators on soil quality, the MC, SP, AP, TP, NH_4^+-N, NO_3^--N, TK, AK, TN, TC, EC, Ca, and Mg were selected as S-type membership functions, while EC and BD were selected as anti-S membership functions. Pecans typically grow in soils at pH 6 to 8 as plantation soils are typically weakly alkaline; thus, the pH also selects for the inverse S-type membership function (Table 2). According to the norm value of each MDS indicator, the norm value ratio of each indicator to the sum of the norm values was calculated, and the weight W of each MDS indicator was obtained.

Table 2. Soil quality parameter membership function types.

Indicator	Membership Function Type	Membership Function
MC SP AP TP $NH_4{}^+$-N $NO_3{}^-$-N T AK TN TC Ca Mg	S-type membership function (Factor has a positive effect on soil quality)	$N = \frac{X_i - X_{imin}}{X_{imax} - X_{imin}}$
pH EC BD	Inverse S-type membership function (Factor has a negative effect on soil quality)	$N = 1 - \frac{X_i - X_{imin}}{X_{imax} - X_{imin}}$

Finally, the soil quality index (SQI) was calculated by weighting the membership values and weights of each evaluation index to be obtained. The calculation formula was:

$$\mathrm{SQI} = \sum\nolimits_{i=1}^{n} W_i N_i \quad (2)$$

where SQI represents the soil quality index; W_i represents the weight of the i-th evaluation index; N_i is the i-evaluation index membership value; n is the number of evaluation indicators.

All data analysis was performed with R 4.1.3, using Pearson correlation coefficients to quantify the correlations between soil indicators, whereas principal component analysis (PCA) was used to screen soil indicators into the MDS. To understand the capacity of MDS to interpret soil quality, we employed the 'basic trendline' package fitted linear regression to quantify the relationship between MDS and TDS [36,37].

3. Results

3.1. Soil Physicochemical Properties of Agroforestry Composite Systems

There were physical differences in the surface woodland soils following the implementation of the agroforestry composite (Table 3), and the EC of PPL in the four woodlands was significantly higher than that of the CK and the other two groups ($p < 0.05$). The MC of PPH was lowest among the four woodland soils, and significantly lower than PPS and CK ($p < 0.05$). The range of soil BD variations in all woodlands was 1.37 g/cm^3 to 1.56 g/cm^3, of which PPS and CK soil BD was significantly higher than those of PPH and PPL ($p < 0.05$). The SP of PPH was significantly higher than that of the other three groups ($p < 0.05$).

Compared with the agroforestry composite management model, the AP, TP, AK, TC, and TN content of the single model were significantly lower than those of the other three groups ($p < 0.05$); however, the TK content of PPH was significantly lower than that of CK and the other two compound planting modes. The $NH_4{}^+$-N and $NO_3{}^-$-N were enriched in the PPH and PPL groups, respectively. The content of Ca and Mg in PPS was significantly higher than that of PPH and PPL. The pH varied from 8.09 to 8.25 but showed no statistical difference.

Table 3. Soil physicochemical properties under different agroforestry patterns.

Indicators	Agroforestry Pattern				CV
	PPH	PPS	PPL	CK	
EC (ds/m)	1.34 ± 0.02 b	1.28 ± 0.01 a	1.50 ± 0.03 c	1.23 ± 0.0.02 a	8.84
MC (%)	18.32 ± 0.22 a	19.78 ± 0.22 c	18.60 ± 0.27 ab	19.42 ± 0.56 bc	6.14
BD (g/cm^3)	1.37 ± 0.03 a	1.56 ± 0.02 c	1.43 ± 0.02 b	1.56 ± 0.02 c	7.09
SP (%)	47.63 ± 0.91 c	40.63 ± 0.79 a	44.53 ± 1.25 b	41.15 ± 0.65 a	8.99
AP (mg/kg)	10.10 ± 0.40 c	9.70 ± 0.42 c	8.89 ± 0.38 b	7.18 ± 0.56 a	19.07
TP (g/kg)	1.69 ± 0.03 b	1.45 ± 0.15 b	1.50 ± 0.10 b	1.08 ± 0.07 a	20.02
NH_4^+-N (mg/kg)	0.73 ± 0.03 b	0.41 ± 0.15 a	0.38 ± 0.10 a	0.18 ± 0.07 a	70.08
NO_3^--N (mg/kg)	2.21 ± 0.29 ab	1.67 ± 0.14 a	7.42 ± 0.57 c	2.73 ± 0.20 b	71.85
TK (g/kg)	2.64 ± 0.19 a	3.84 ± 0.37 b	4.02 ± 0.23 b	3.80 ± 0.20 b	25.82
AK (mg/kg)	217.44 ± 11.68 c	220.65 ± 10.96 c	79.15 ± 4.96 b	54.55 ± 2.63 a	14.49
TN (g/kg)	0.81 ± 0.04 b	0.92 ± 0.02 c	0.86 ± 0.01 bc	0.52 ± 0.05 a	23.73
TC (g/kg)	15.78 ± 0.34 c	16.12 ± 0.19 c	14.67 ± 0.14 b	13.52 ± 0.20 a	4.54
pH	8.09 ± 0.11 a	8.23 ± 0.02 a	8.15 ± 0.02 a	8.25 ± 0.02 a	2.13
Ca (g/kg)	13.31 ± 0.31 a	15.16 ± 0.25 b	12.82 ± 0.16 a	15.25 ± 0.27 b	9.33
Mg (g/kg)	4.38 ± 0.10 a	5.44 ± 0.07 b	4.55 ± 0.05 a	4.57 ± 0.09 a	10.13

Note: There were significant differences in the one-way ANOVA of different compound patterns with different letters (LSD, $p < 0.05$).

3.2. Establishment of MDS

The smallest data set is a set of the fewest index parameters that can reflect soil quality. The MDS was established to select the indicators that were most suitable for evaluating soil quality in the study area, thereby reducing data redundancy. The results of the principal component analysis revealed that there were four principal components with eigenvalues of >1. The cumulative contribution rate of variance attained 76.328%, which implied that the four principal components had a strong capacity to interpret the overall variance (Table 4). Among them, BD, Ca, TP, SP, AP, NH_4^+-N, and MC all met the load ≥ 0.5 on PC1; all of which were classified as Group 1. AK, Mg, TC, and NO_3^--N satisfied the load ≥ 0.5 on PC2, whereas NO_3^--N satisfied the load ≥0.5 on PC2 and PC3. However, the correlation coefficient between NO_3^--N and EC (Group 3) was significantly positively correlated with 0.75 (Figure 2); thus, NO_3^--N was still classified in Group 2. TK met the load ≥ 0.5 on PC2; TN had an average load ≥0.5 on PC1, PC2, and PC3; EC met the load ≥ 0.5 on PC2 and PC3. However, as TN and EC had higher correlations with the indicators of Group 1 and Group 2, TK, TN, and EC were all included in Group 3. The pH satisfied the load ≥ 0.5 only on PC4, which was grouped into Group 4. Through the principal component analysis, the final Group 1 included BD, Ca, TP, SP, AP, NH_4^+-N, and MC, whereas Group 2 included AK, Mg, TC, and NO_3^--N, Group 3 included TK, TN, and EC, and Group 4 included the pH.

According to the principle of MDS index filtering, the norm values of each group were calculated and compared. The indicators with norm values within 10% of the maximum value in each group were selected, after which the correlations between the selected parameters in each group were compared (Table 4, Figure 2). Eventually, BD in Group 1 entered the MDS, and Group 2 had the highest norm values in AK. However, Mg had no significant correlation with AK, and all entered MDS. Group 3 had the highest norm values for TNs, but EC had no significant correlation with TNs, and all entered MDS, and Group 4 pH entered MDS. The final MDS metrics were BD, AK, Mg, TN, EC, and pH. In this study, a total of fifteen preliminary indicators were selected, a total of six indicators were entered into the minimum data set, and the index screening and filtering rate reached 60%. This simplified the soil quality evaluation system and better eliminated the impact of redundant data between indicators on soil quality evaluation.

Table 4. Explanatory power of total variance for the four selected principal components.

Indicators	Principal Component				Team	Norm	TDS
	1	2	3	4			
BD	−0.776	0.362	0.265	−0.340	1	1.907	Yes
Ca	−0.769	0.419	−0.256	0.041	1	1.897	
TP	0.747	0.288	0.036	−0.162	1	1.738	
SP	0.717	−0.322	−0.351	0.294	1	1.783	
AP	0.603	0.493	0.062	0.179	1	1.634	
NH_4^+-N	0.597	0.158	−0.260	−0.403	1	1.458	
MC	−0.528	0.322	0.116	0.414	1	1.395	
AK	0.464	0.813	−0.178	0.082	2	1.862	Yes
Mg	−0.339	0.765	0.384	0.004	2	1.709	Yes
TC	0.542	0.739	0.102	0.147	2	1.849	
NO_3^--N	0.224	−0.653	0.601	0.106	2	1.565	
TK	−0.296	−0.044	0.592	−0.217	3	1.065	
TN	0.526	0.544	0.549	0.035	3	1.717	Yes
EC	0.526	−0.434	0.544	0.257	3	1.623	Yes
pH	−0.486	0.093	−0.074	0.676	4	1.315	Yes
Eigenvalue	4.816	3.579	1.849	1.205			
Contribution of variance (%)	32.106	23.859	12.328	8.035			
Cumulative rate of accumulated variance (%)	32.106	55.965	68.293	76.328			

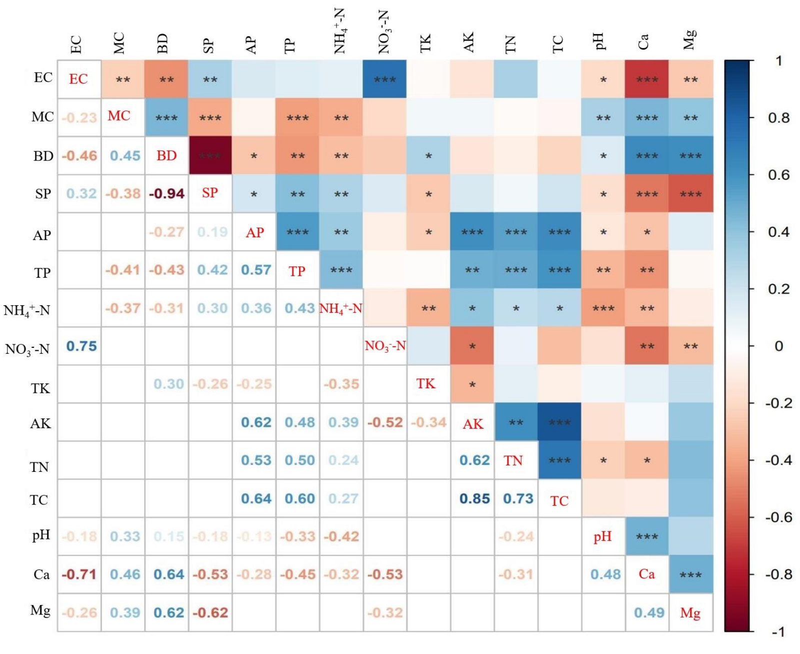

Figure 2. Correlation of soil indices. * Significance of $p < 0.05$. ** Significance of $p < 0.01$. *** Significance of $p < 0.001$.

3.3. Determination of the Weights of Comprehensive Evaluation Indicators for Soil Quality

Once the MDS index was determined, the weight value of each index was obtained by analyzing the TDS and MDS through the principal component analysis. The weight values W of EC, BD, AK, TN, pH, and Mg in MDS were 0.160, 0.188, 0.184, 0.169, 0.130, and 0.169, respectively. BD and AK contributed more to the evaluation of the quality of surface soil in the study area, followed by TN (Table 5).

Table 5. Weight values of soil fertility indexes in TDS and MDS.

Indicators	W (TDS)	W (MDS)
EC	0.072	0.16
MC	0.05	
BD	0.08	0.188
AP	0.056	
TP	0.058	
NH_4^+-N	0.053	
MC	0.074	
TK	0.043	
AK	0.08	0.184
TN	0.076	0.169
TC	0.076	
pH	0.062	0.13
Ca	0.073	
Mg	0.074	0.169
SP	0.072	

3.4. Evaluation of Soil Quality for Different Agroforestry Patterns Based on MDS

According to the membership function, the value of each index was calculated, while the average value of the soil quality index of pecan woodlands under the four agroforestry composite modes was plotted into stack and radar maps. To reflect the proportion of each index in the soil quality evaluation, a radar chart was employed for the comprehensive analysis of multiple indicators. The values of each point on the coordinate axis reflected the state of each indicator, where the closer to the origin the better the state of the indicator, and conversely, the worse the state of the indicator. The Soil Quality Index (SQI-MDS) of the four planting patterns, sorted from largest to smallest, were: PPS (0.573) > PPH (0.519) > PPL (0.355) > CK (0.315) (Figure 3).

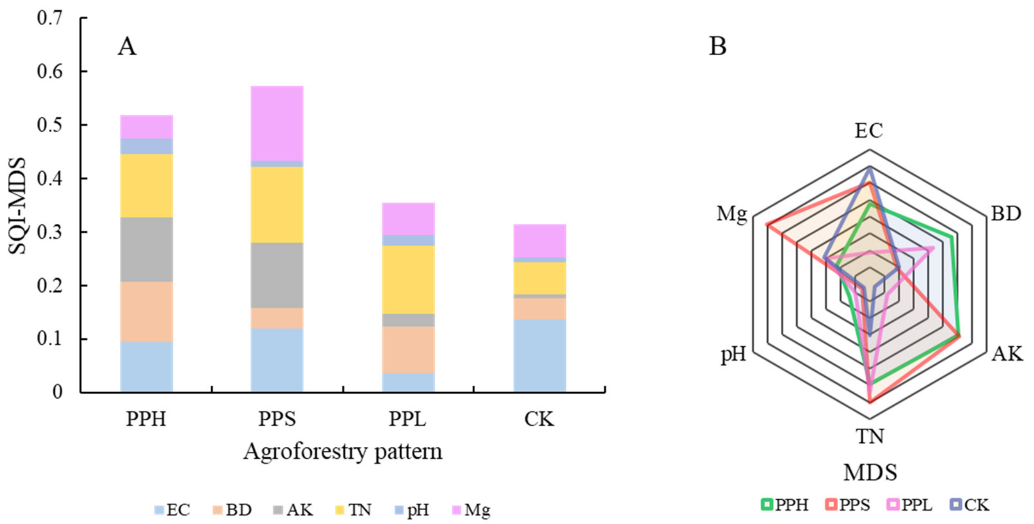

Figure 3. Correlation of soil indices. (**A**) Soil SQI accumulation map under different pecan agroforestry system; (**B**) Radar map of average membership degree of soil physical and chemical indexes.

3.5. SQI Construction and Evaluation

To verify the accuracy of the minimum data set SQI, this study linearly fitted the TDS-SQI with MDS-SQI (Figure 3), with the results revealing a significant correlation between the TDS-SQI and MDS-SQI ($p < 0.001$), where the R2 of the linear fit equation was 0.846. This indicated that the selected MDS index system for the evaluation of soil quality in the study area was highly representative and could be used to characterize it more accurately.

4. Discussion

4.1. Effects of Agroforestry System on Physicochemical Soil Properties

Compared with the monocultivation of pecans, the two composite management modes (PPH and PPL) reduced BD and increased SP, and the water retention capacity of the soil was also improved under agroforestry complex management (Table 2). These phenomena may be attributed to the fact that the root systems of herbs or shrubs such as *Paeonia suffruticosa*, *Hemerocallis citrina*, and *Paeonia lactiflora* were interspersed in the soil to improve its structure; making it loose and increasing its breathability [20]. Furthermore, increased intermediate crops can reduce the surface-water runoff, increase the filtration in soil moisture, and enhance the amount of soil storage, such that the soil moisture status can be improved [7,24]. Under the four intercropping models, the soil pH changed significantly, which may have been due to the short operation time and the pH changes not being obvious [20]. Compared with CK, the EC of the three agroforestry composite systems was improved, where the increase in intermediate crops led to greater litter and accelerated mineral decomposition, thereby increasing the mineral ion content of the soil [16]. However, the soil EC is generally considered to be positively correlated with the soluble salt content [38,39]. In contrast to the single cultivation of pecans, the agroforestry composite system requires increased operational and management inputs such as fertilizers, herbicides, etc. Furthermore, long-term operation is associated with the risk of soil salinization, which needs to be continuously observed.

Early research suggests that agroforestry management can increase the systematic nutrient cycling process and reduce systematic nutrient loss while increasing the total nutrient concentrations of plant-soil systems [40,41]. Our research results confirmed this conclusion, and that the content of TP, TN, and TC in the topsoil was increased following multiplex agroforestry operations. Previous studies found that the soil TN, TP, AP, and organic matter content increased by 10–25% subsequent to tea-michelia intercropping [21]. Udawatta's [42] study found that the soil TN content increased significantly after 12 years of *Dalbergia sissoo* and wheat intercropping, and suggested that the addition of intermediate crops improved the woodland microclimate, soil aggregate structure, and enhanced the binding capacity of soil nutrients to a certain extent. Furthermore, increased understory vegetation cover was observed to play an important role in reducing direct surface erosion by rainwater, which also reduced the loss of soil nutrients [24]. Compared with the mono-planting of pecans, the presence of more litter and dead roots in agroforestry composite systems enhanced organic matter inputs into the soil. We observed that the decomposition of soil microorganisms improved the availability of nutrients, whereas the AK, AP, and NH_4^+-N content of the soil was significantly higher than that of CK [10,20]. Overall, the physicochemical attributes of soil quality in agroforestry composite systems were superior to those of the monoculture pecan model, which was confirmed by the comparison of the soil quality index (Figures 3 and 4).

4.2. MDS Index Screening and Evaluation of Soil Quality

The efficient and accurate evaluation of soil quality in agroforestry composite systems is key to assessing their ecological benefits. Although the SQI calculated by TDS can accurately assess soil quality, the acquisition of all evaluation indicators is a time-consuming and laborious task [15,17]. MDS is able to screen for the fewest number of soil indicators, which reflects the true picture of soil quality [8,16]. The selection of evaluation indicators is usually not fixed, where MDS indicators are intimately related to the target to be evaluated. Influencing factors of soil quality (e.g., soil type, land use mode, soil layer thickness, etc.) can directly alter the selection of evaluation indicators [9,43]. Consequently, the scope of use of MDS is typically specific and cannot be applied to evaluate all soils [8]. Nevertheless, it is still universally applicable within a certain range of plantation types.

In this study, through principal component analysis and the norm values of each index, the MDS indicators including EC, BD, AK, TN, pH, and Mg were screened, including soil aeration, soil nutrient, and soil acid-base properties. Bunemann [16] collected statistics on the selection of soil evaluation indicators from the extensive literature and proposed that the soil organic carbon content (SOM), pH, AP, AK, TN, EC, and BD, as well as other indicators, were selected as high-frequency indicators of MDS, which was consistent with those selected by the Institute. The obtained SQI results for soil quality based on MDS and TDS methods were similar (y = 0.645x + 0.166, R^2 = 0.846, p < 0.001) (Figure 4), which objectively evaluated the soil quality of Pecan Farming and Forestry Complex Systems. From the results, the soil quality of a hickory agroforestry composite system was PPS > PPH > PPL > CK, which was consistent with previous research results. The outcome of another of our studies revealed that the soil enzyme activity of PPS was higher than that of PPH and PPL [20]. This may be attributed to the fact that the developed fleshy roots of *Paeonia suffruticosa* better improved the soil permeability and moisture, and enhanced the activities of soil microorganisms; thus, improving the status of soil nutrients [21,44]. The root systems of shrubs are quite extensive, which is conducive to the transformation of symbiotic nitrogen fixation and refractory nutrients, as it is easier to obtain nutrients from the deep soil and lift them to the topsoil [24]. The soil quality of PPH was superior to that of PPL and CK, which may have been affected by the complexity of agroforestry systems. This further illustrated that exclusive pecan management is not conducive to the maintenance of soil fertility. To a certain extent, intermediate crop species are positively correlated with soil quality [21]. However, the impacts of more complex agroforestry systems on soil quality will require further study.

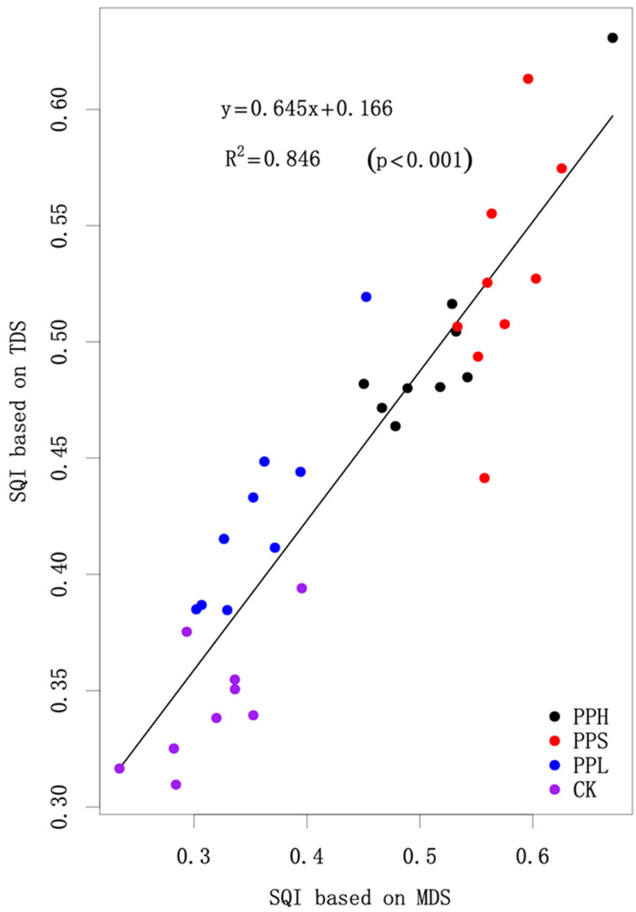

Figure 4. Linear relationship between SQI-TDS and SQI-MDS.

5. Conclusions

In this study, the soil quality of different composite pecan agroforestry patterns was evaluated by SQI using TDS and MDS methods. Overall, our study revealed that complex pecan agroforestry systems improved the availability of soil nutrients and enhanced soil quality. Among these treatments, pecans—*Paeonia suffruticosa* peony achieved improved ecological benefits over other treatments, while monocultured pecan plantation soils underwent degradation with the long-term operation. Crops such as *Paeonia suffruticosa*, *Hemerocallis citrina*, and *Paeonia lactiflora* for oil in pecan forests are a viable strategy for achieving the sustainable management of pecan orchards, which can provide a double harvest for further ecological and economic benefits.

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