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Establishing a Soil Health Assessment System for Quaternary Red Soils (Luvisols) under Different Land Use Patterns

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Abstract: The health status of Quaternary red soil is a comprehensive reflection of the production and ecological service functions, which directly affects agricultural productivity and ecosystem sustainability. Based on the Cornell Soil Health Assessment (CASH) system frame, a health evaluation system for Quaternary red soils was established including the soil's physical, chemical, and biological indicators. The soil's health status under different land use patterns (the buried Quaternary red soil, sparse forest and grassland, grassland, woodland, and arable land) was systematically diagnosed in the low hilly region of western Liaoning Province. The results showed significant differences in the soil health comprehensive index of the Quaternary red soils under different land use patterns (the whole soil), presenting a trend of woodland (0.64) > arable land (0.61) > grassland (0.49) > sparse forest and grassland (0.37) > buried Quaternary red soils (0.33). The woodland and arable land are at a healthy level, the grassland and sparse forest and grassland are at a sub-healthy level, and the buried Quaternary red soil is at an unhealthy level. The health status of the topsoil layer (A) under different land use patterns has a trend of woodland (0.86) > arable land (0.73) > grassland (0.70) > sparse forest and grassland (0.67). This is consistent with the overall health status of the profile, better than that of subsoil layer (B), which presents a trend of arable land (0.41) > grassland (0.40) > woodland (0.38) > sparse forest and grassland (0.34), with relatively poor soil health conditions. Overall, the soil health status of the four land use patterns is better than that of the buried Quaternary red soils, showing an evolution trend towards healthy soil. This indicates that at this stage, human land use activities have to some extent promoted the healthy development of Quaternary red soils. The Quaternary red soils of the woodland have a healthy status, and the land use pattern is suitable and can be scientifically recommended in low mountain and hilly areas.

Keywords: soil properties; soil health evolution; arable land

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1. Introduction

Quaternary red soils are mainly distributed in areas south of 30° N and are important soil resources in China [1,2]. Influenced by factors such as the parent material, topography, living organisms, time, climate, and human activities [3], especially climate changes, Quaternary red soils have undergone a certain degree of desilication, iron and aluminum accumulation, and clayification, with the presence of reddish, heavy-textured soils called "red clay" [4]. Due to the strong desilication, iron and aluminum accumulation in Quaternary red soils, and people's unreasonable utilization, they are more prone to issues such as acidification, hardpan formation, erosion, and low fertility, limiting the sustainable use of land resources [5]. Therefore, it is essential to carry out soil health assessments of Quaternary red soils under different land use patterns, systematically and comprehensively diagnose their health status, and provide a theoretical basis for the sustainable management and use of land resources.

Soil health refers to the ability of soil, as a living system, to maintain biological productivity and the environmental quality of air and water and to promote the health of plants, animals, and humans within the scope of ecosystems and land use [6]. Soil is a complex composite formed by the integration of soil physics, soil chemistry, and soil biology; so, a comprehensive selection of multiple indicators should be used to diagnose soil health [7]. Physical indicators include soil texture, bulk density, water content, and aggregate stability, etc. [8–10]. Chemical indicators include soil nitrogen, phosphorus, potassium, and organic carbon, etc. [8–10]. Biological indicators include microbial diversity, total biomass, biomass carbon, and microbial groups, etc. [8–10]. Due to the large quantity, variety, and rapid change of soil organisms, they show dynamic changes in time and space, and it is difficult to form a stable relationship with environments [9–11]. Therefore, there has been some difficulty in conducting quantitative research on them, and the biological indicators have not been widely used [11,12]. However, with the rapid development of bioinformation technology in recent years, scholars have gradually realized the importance of soil biodiversity, and more and more biological indicators have been used to assess soil health conditions [10,13,14]. Soil's physical, chemical, and biological indicators are independent from and related to each other [15]. Scholars rarely use one of the indicators alone in soil health evaluation but synthesize and analyze the evaluation results by combining a variety of evaluation indicators [8,15]. The Cornell Soil Health Assessment (CASH) method involves various forms of soil evaluation indicators and mathematical function models for the graded determination of soil [7], making it a more advanced soil health assessment method.

Based on the research background, the study aims to establish a soil health assessment system for Quaternary red soils under different land use patterns based on the CASH method frame. The results are expected to improve our understanding of the health of Quaternary red soils and provide a theoretical basis for maintaining the multifunctional ecosystem and promote the sustainable utilization and protection of soil resources.

2. Materials and Methods

2.1. The Study Area Descriptions

The northeastern Quaternary red soils are mainly distributed in the western part of Liaoning Province, China. The studied region is mountainous and hilly, located in places from the Inner Mongolia Plateau to the east coastal plain [3,16]. According to several field investigations, Quaternary red soils are mostly found in the middle and lower parts of low hills and gentle slopes, as well as in the high terraces [16]. The Quaternary red soil is classified as Argosols in the Chinese Soil Taxonomy [17], corresponding to Alfisols in the Soil Taxonomy [18] and Luvisols in the World Reference Base for Soil Resources [19]. Combining these and referring to soil survey data, such as the Soil Series of China—Liaoning Volume, along with field investigations, Wujianfang Town in Chaoyang City was selected as the typical research area. The region belongs to the North Temperate Continental Monsoon climate zone, with an average annual temperature of 5.4–8.7 °C and an average annual precipitation of 450–580 mm [20,21].

2.2. Sample Collection

Following several field investigations in the area, a relatively stable region was found to contain an evolution sequence of Quaternary red soils, derived from the same Quaternary red soil stratum, under different land use patterns such as sparse forest and grassland, grassland, woodland, and arable land, and a nearby buried Quaternary red soil underground. The investigated Quaternary red soils were basically consistent in the parent material, topography, climate, and time of soil formation (derived from a stratum), except for the land use pattern. The effects of different land use patterns on the soil under the same soil forming factors could be then discussed. Typical samples of sparse forest and grassland, grassland, wood land, and arable land were collected within the same stratum [3], and a Quaternary red soil profile buried underground was collected as the reference baseline (Figure 1).

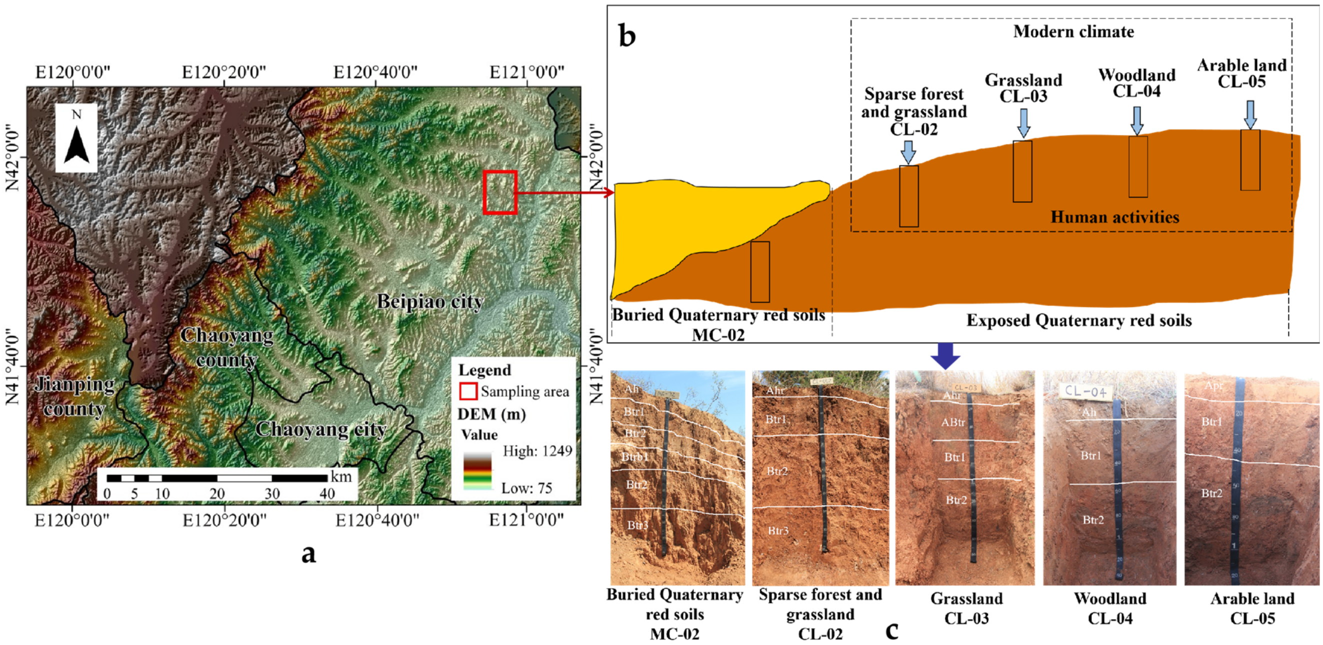

Figure 1. (**a**) The sampling area location of Chaoyang City, Liaoning Province, China; (**b**) the schematic distribution map of the sampling points; (**c**) the profile photos of the Quaternary red soils under different land use patterns. The schematic map was plotted based on the base map of the World Topographic Map (2016) using Arc GIS 10.2.2.

CL-02 represents the sparse forest and grassland. The main herbaceous type of CL-02 is *Themeda triandra Forssk*, and the forest types are *Vitex negundo*, *Ulmus pumila* L., and *Pinus massoniana Lamb.*, with a vegetation coverage of 30%. CL-03 represents the grassland. The main herbaceous type of CL-03 is *Themeda triandra Forssk*, with a vegetation coverage of 30%. CL-04 represents the woodland. The forest types of CL-04 are *Vitex negundo*, *Ulmus pumila*, and shrubbery, with a vegetation coverage of 35%. CL-05 represents the arable land. The main vegetation type of CL-05 in the growing season is maize (*Zea mays* L.). MC-02 represents the buried Quaternary red soil, which is buried under the ground.

Before sowing, around 10,000 kg of organic manure (sheep manure) and 1200 kg of maize fertilizer (the ratio of N-P_2O_5-K_2O was 18-10-12, and the total nutrient content was 40%) were applied per hectare on the arable land. No irrigation was conducted throughout the year. No additional management was given to the other land use patterns during vegetation growth. A typical soil profile was collected for each different land use pattern as the research object. Detailed descriptions of the profiles were conducted according to the Manual of Soil Description and Sampling [22]. The pedogenic horizon samples were collected from bottom to top in the profile. At the same time, the surface samples (0–30 cm) affected by human activities were collected at 10 cm intervals. The collected samples were air-dried indoors and stored for the following analysis.

Soil samples (0–20 cm) under different land use patterns were collected to analyze the microbial diversity. Each sample was collected at 5 random points along the "S" curve using a soil auger (with an inner diameter of 5 cm) and a cutting ring (100 cm^3). The root residues and litter on the soil surface were carefully removed with sterile gloves. The five soil samples under the same land use pattern were thoroughly mixed into a mixed sample. The above sampling process was repeated three times in each land use pattern and packed into sterile polyethylene sealed bags, respectively. The samples were transported in dry ice and stored in the refrigerator at −80 °C immediately upon arrival at the laboratory. The widely used Shannon index was used to show the bacteria diversity, which does not have any units. The higher the Shannon index, the greater the bacteria diversity.

2.3. Laboratory Methods

2.3.1. Basic Soil Physicochemical Properties

Basic physical and chemical properties were determined using conventional laboratory methods. The soil bulk density was determined using the cylindrical core method [23]. For the soil pH, the 10.00 g 10-mesh soil sample was placed in a small beaker. Then, 25 mL of distilled water without CO_2 was added and stirred for 1 min. Then, the beaker stood for 30 min, and the sample was measured using a pH meter (PHSJ-3F, Shanghai, China).

2.3.2. Soil Organic Carbon (SOC) and Soil Total Nitrogen

The 0.04–0.05 g 100-mesh soil sample was placed in a tint boat. After being packed and compacted, the sample was measured by an elemental analyzer produced by the Elementar Analysensysteme (GmbH, Vrrio E1 III) to obtain the contents of SOC and soil total nitrogen [24]:

$$\text{Soil organic matter (SOM)} = \text{SOC} \times 1.724,$$

where 1.724 is the conversion coefficient of soil organic carbon to soil organic matter.

2.3.3. Soil Total Phosphorus and Soil Total Potassium

The 0.25 g 0.149-mesh soil sample was placed in a nickel crucible. Then, 2 g sodium hydroxide was added to the nickel crucible and mixed with the soil sample thoroughly. The nickel crucible was put into a high-temperature electric furnace and melted at 720 °C for 15 min. After cooling, the sample was removed and dissolved and then filled into a 100 mL volumetric bottle for the determination of the total phosphorus [25] and total potassium content [26].

2.3.4. Microbial Diversity

The total DNA in soil was extracted by an Omega M 5635-02 kit. After DNA quantification, the Illumina sequencing library was established with a nucleic acid purifier. MiSeq Reagent Kit V3 (600 cycles) was used to determine 2 × 250 bp double-ended sequencing (Perseno Bio, Shanghai, China, http://www.personalbio.cn, accessed on 1 July 2023). According to the selection of the sequencing region, PCR amplification was performed using specific primers with Barcode. The 338F (5′-barcode + ACTCCTACGGGAGGCAGCA-3′) and 806R (5′-GGACTACHVGGGTWTCTAAT-3′) amplified the V3V4 region of the bacterial 16SrRNA gene. In addition, ITS5 (5′-GGAAGTAAAAGTCGTAACAAGG-3′) and ITS2 (5′-GCTGCGTTCTTCATCGATGC-3′) amplified the ITS1 gene region of the fungus. The Vsearch method was used to remove the low-quality sequences from the sequencing results. According to the sequence structure and primer sequence at both ends of the sequence, the effective sequence was obtained, and the direction of the sequence was corrected. Vsearch software classified the sequences with a similarity threshold above 97% into an OTU (Operation Taxonomic Unit) and generated an OTU table. QIIME2 (April 2019) was used to comparatively analyze the representative sequences of the OTU, the database of 16S rRNA Greengenes, and the UNITE database, and to obtain the species classification information of each OTU. The Alpha diversity index calculated based on the OTU clustering results can reflect the richness and diversity of the microbes [27]. Among them, the Shannon index was used to show the bacteria diversity in the study.

2.4. The CASH System Frame

2.4.1. The Selection of Evaluation Indicators

In the Cornell Soil Health Assessment system, thirty-nine physical, chemical, and biological indicators were selected as the potential evaluation indicators [7]. According to the minimum dataset theory [28], the selected soil health evaluation indicator should be sensitive, dominant, independent, and practical. Indicators that do not have the above characteristics should be removed from the soil health evaluation system. Therefore, the indicators in Table 1 were preliminarily selected to establish the soil health evaluation indicators. In addition, the soil texture has a significant effect on other soil properties and soil functions [7], and a texture indicator can indicate different soil health conditions in soils. Therefore, the soil texture also should be included in the evaluation indicator data set [7].

Table 1. Soil characteristics and functions corresponding to the evaluation indexes in the CASH frame.

Evaluation Indexes	Soil Health Indicators	Soil Function and Properties
Physical Indicators	Soil texture	All functions and properties of soil
	Soil aggregates' stability (0.25–2 mm)	Aeration, infiltration, root growth of superficial layer, soil hardening
	Available water content of soil	Soil water retention
	Soil surface hardness	Root growth of plough layer
	Subsurface hardness of soil	Root growth of deep layer, soil leaching
Biological Indicators	Soil organic matter content	Soil carbon storage, soil water, and fertility conservation
	Soil active carbon content	Soil organic matter provides biological growth ability
	Soil protein content	Nitrogen supply capacity
	Soil respiration	Pressure of soil-borne pests
Chemical Indicators	pH	Toxicity and nutrient availability
	Soil available phosphorus	Phosphorus availability
	Soil available potassium	Potassium availability
	Trace elements	Availability of trace elements, element imbalance, and toxicity

2.4.2. The CASH Level Division

The CASH soil health index (SHI) was calculated based on the scores of the determined indicators. A total score of soil health less than 20% means the level of soil health is very low. A total score of soil health between 20 and 40% means the level of soil health is low. A total score of soil health between 40 and 60% means the level of soil health is medium. A total score of soil health between 60 and 80% means the level of soil health is high. A total score of soil health more than 80% means the level of soil health is very high [7].

2.5. The Selection Method of Soil Health Evaluation Indicators

A preliminary selection of soil health evaluation indicators was conducted using database retrieval and literature analysis. The China National Knowledge Infrastructure (CNKI) database was used as the literature analysis retrieval database, searching for materials related to soil health evaluation from 1 January 2000 to 31 March 2023. In total, 116 soil health evaluation indicators were compiled by reading 132 articles. The indicators were classified into three categories: soil physical evaluation indicators, soil chemical evaluation indicators, and soil biological evaluation indicators.

2.6. Data Processing

We constructed a minimum dataset (MDS) [29] by selecting soil health evaluation indicators through principal component analysis (PCA) [30] and combining normal values (Norm) with correlation analysis to analyze the correlation between the indicators in the MDS. Indicators with smaller main body correlation degrees were retained, and redundant ones were eliminated to the greatest extent. To study the relationship between the soil health indicators and evaluation objects within a certain range, i.e., the relationship between soil indicators and soil health, the fuzzy mathematical membership function was used [30,31]. Based on the CASH method frame, the soil health indicator membership functions were divided into three function types, including the increasing type, decreasing type, and intermediate optimal type [7] (Table 2).

Then, the Bartlett spherical test was used to determine whether the final soil health evaluation indicators selected in the MDS conformed to the normal distribution trend of the initially selected soil indicators [30].

Table 2. Types and calculation formulas of fuzzy mathematics membership functions.

Types of Membership Functions	Computing Formula	Parameter Description
Membership function of incremental type	$y(x) = \begin{cases} 1, & x \geq b \\ \frac{x-a}{b-a}, & a < x < b \\ 0, & x \leq a \end{cases}$	Y(x): membership function; x: the measured value of the index; a: lower limit of the threshold; b: upper limit of the threshold.
Membership function of decreasing type	$y(x) = \begin{cases} 1, & x \leq a \\ \frac{x-b}{a-b}, & a < x < b \\ 0, & x \geq b \end{cases}$	
Membership function of the intermediate optimal form	$y(x) = \begin{cases} 1, & b_2 \geq x \geq b_1 \\ \frac{x-a_1}{b_1-a_1}, & a_1 < x < b_1 \\ \frac{x-a_2}{b_2-a_2}, & a_2 > x > b_2 \\ 0, & x \leq a_1 \text{ or } x \geq a_2 \end{cases}$	Y(x): membership function; X: the measured value of the index; a1: lower limit of the threshold; a2: upper limit of the threshold; b1: lower limit of the optimal value; b2: upper limit of the optimal value.

The CASH method does not take into account the weight of soil attribute indicators, resulting in relatively low accuracy at the regional scale. To further optimize, the weighted comprehensive method was used to determine the comprehensive SHI. Referring to the soil quality index calculation method and according to the weights and membership obtained from PCA, the cumulative method was used to calculate the comprehensive SHI. The formula is as follows [7,32]:

$$SHI = \sum_{i=1}^{n} (H_i \times C_i) \tag{1}$$

where SHI is the comprehensive soil health index, Hi is the membership of the i-th evaluation indicator, Ci is the weight of the i-th evaluation indicator, and n is the number of evaluation indicators [32].

2.7. The Graphic Outline of the Indicator Selection and Soil Health Index Calculation

The graphic outline of the indicator selection and soil health index calculation was showed in the Figure 2.

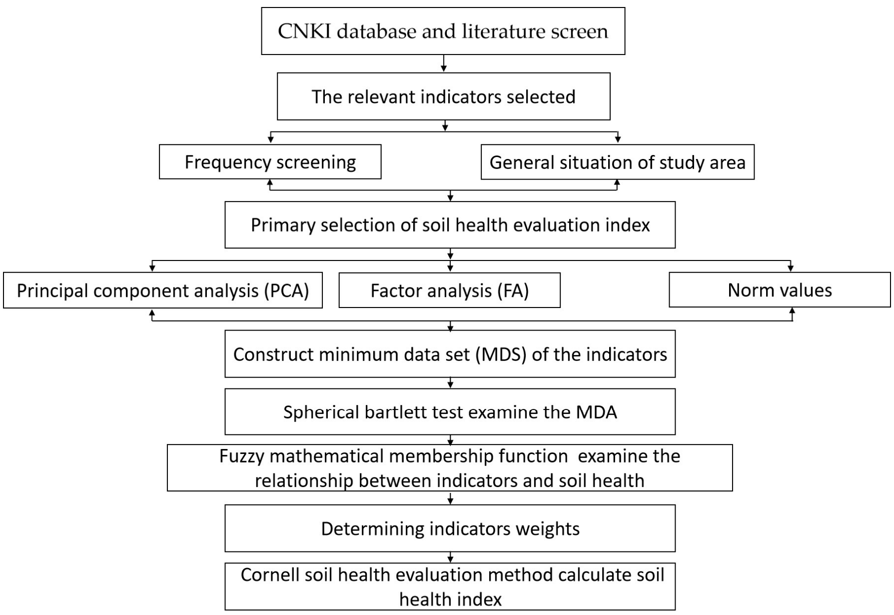

Figure 2. The graphic outline of the indicator selection and soil health index calculation.

3. Results

3.1. Screening Soil Health Evaluation Indicators for Quaternary Red Soils under Different Land Use Patterns

In total, 31 soil physical evaluation indicators were screened (Figure 3). Among them, the usage frequency of soil bulk density was the highest at 41.70%; followed by the soil clay content, the soil layer thickness, and the soil texture, with usage frequencies higher than 20.00%; aggregate stability and soil porosity, as indicators of soil mechanical stability and permeability, had usage frequencies of 16.70% and 15.20%, respectively, in the literature. Considering that soil health evaluation indicators should have simple measurement, strong operability, and a strong correlation with soil while being representative, the infiltration rate, soil saturation, and litter thickness were rarely selected.

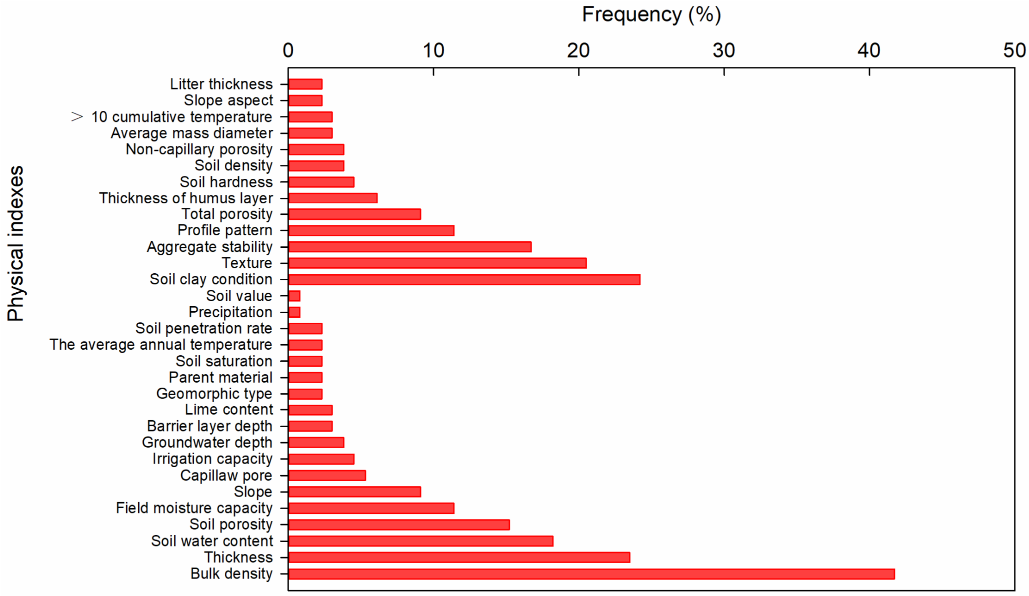

Figure 3. The selection frequencies of soil physical indicators in the literature.

A total of 35 soil chemical indicators were screened (Figure 4). Among them, the usage frequency of organic matter content was the highest at 87.10%; the soil pH value was second at 72.00%; total nitrogen, total phosphorus, and total potassium were the main soil nutrient elements supporting the growth of aboveground crops, participating in crop photosynthesis and other physiological functions, with usage frequencies of 50.00%, 48.50%, and 34.10%, respectively; cation exchange capacity, reflecting the soil buffering performance, had a usage frequency of 19.70%, slightly higher than the conductivity usage frequency of 12.90%; since the measurement methods of soil trace elements were complicated and costly, they were rarely used by researchers.

A total of 29 soil biological indicators were screened (Figure 5). Among them, the usage frequency of soil urease was the highest at 19.00%; phosphatase and catalase, reflecting the soil enzyme activity, had usage frequencies of 16.70% and 11.40%, respectively. With the development of science and technology, the accuracy of soil health evaluation has also increased, and soil microbial diversity can directly reflect the soil fertility status, with a usage frequency of 14.40% through the application of scientific and technological means. However, microbial diversity was rarely selected due to its dynamic changes in time and space; thus, it is difficult to form a stable relationship with environments.

According to the principles that soil health indicators should have representativeness, universality, sensitivity, repeatability, and operability [7], combined with the characteristics of Quaternary red soils [1,2], this study preliminarily selected 12 indicators including the soil layer thickness, the soil bulk density, the soil texture, the clay content, the aggregate stability, the profile configuration, the soil pH value, the organic matter content, the soil nutrient element content (total nitrogen, total phosphorus, and total potassium), and the microbial diversity.

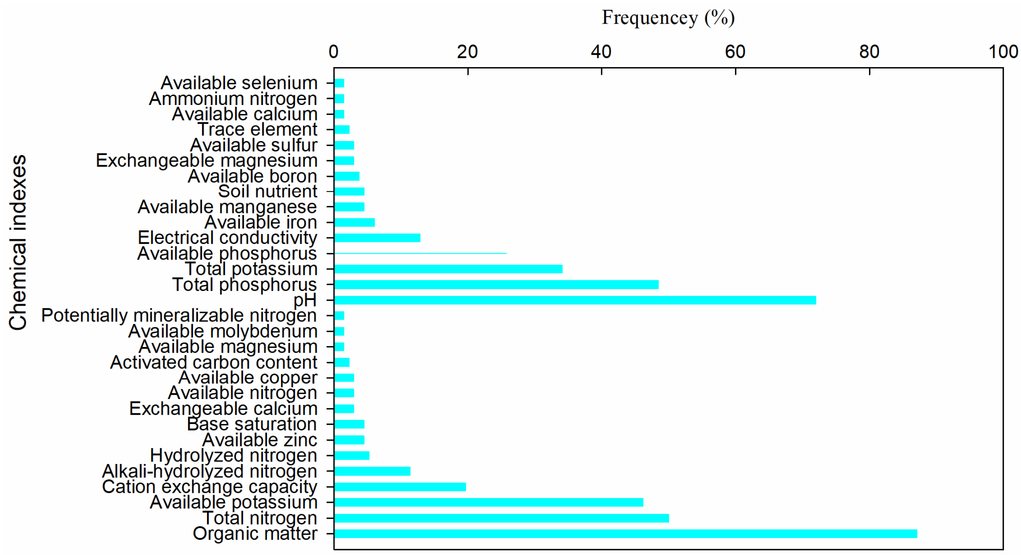

Figure 4. The selection frequencies of soil chemical indicators in the literature.

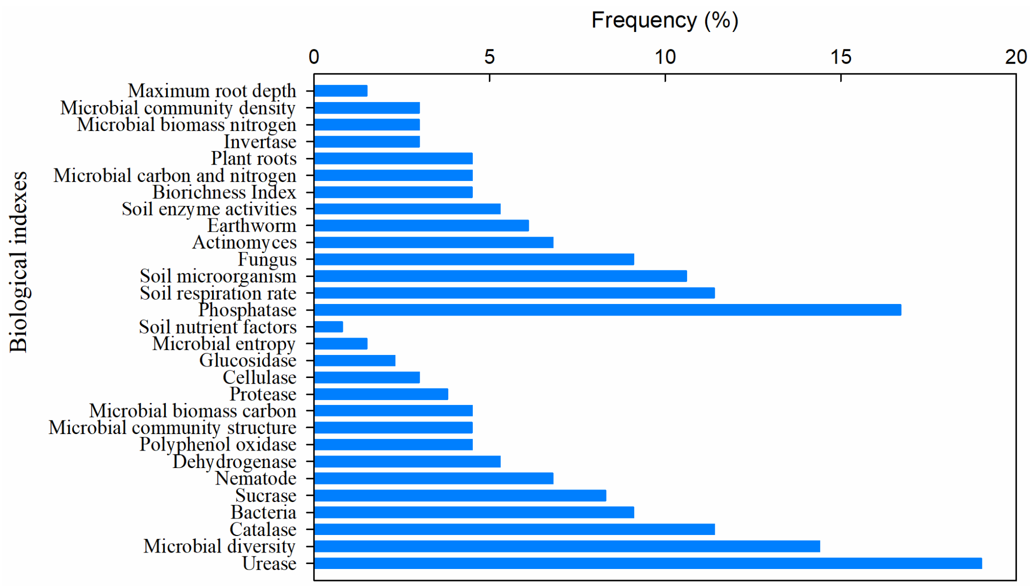

Figure 5. The selection frequencies of soil biological indicators in the literature.

3.2. Final Evaluation Indicator Confirmation

An MDS was constructed, and PCA, Norm values, and correlation analysis were used to screen suitable soil evaluation indicators for the study.

After using SPSSAU for data collation and analysis, the test statistic value for PCA was 0.75, and the eigenvalue was greater than 1. The value after the Bartlett spherical test was lower than the 0.05 significance level, indicating that there were connections between variables and meeting the requirements for PCA [31].

From the loadings of the initially selected 12 soil evaluation indicators on each principal component, the indicators were divided into four key components. The first component matrix included four indicators: profile configuration, soil layer thickness, pH value, and total phosphorus content; the second component matrix contained clay content and organic matter content; the third component matrix contained total potassium content and aggregate stability; the fourth component matrix contained total nitrogen content and microbial diversity. Six soil health evaluation indicators had Norm values greater than 1. The total nitrogen had the highest value for 1.68. The remaining evaluation indicators were ranked by Norm value size in the following order: pH (1.46), organic matter (1.36), bulk density (1.24), total phosphorus (1.23), and total potassium (1.20). One indicator was selected from each of the four component matrices, and three additional indicators were added based on the Norm values. The indicator screening rate reached 41.70%, effectively eliminating the impact of redundant information between the indicators on soil health evaluation and optimizing the soil health evaluation index system. Finally, the MDS included the pH value, the organic matter content, the total potassium content, the microbial diversity, the total nitrogen content, the bulk density, and the total phosphorus content.

3.3. Comparison of the Soil Health Evaluation Indicators of Quaternary Red Soils under Different Land Use Patterns

The soil bulk density of the Quaternary red soils under different land use patterns was in the following order (Table 3): sparse forest and grassland (1.57 g·cm^{-3}) > woodland (1.53 g·cm^{-3}) > arable land (1.49 g·cm^{-3}) > grassland (1.23 g·cm^{-3}) > buried Quaternary red soils (1.12 g·cm^{-3}) (Table 3). The sparse forest and grassland had the greatest bulk density compared to the buried Quaternary red soils. Studies have shown that when the soil pH is between 6.50 and 7.00, crops generally have a better nutrient absorption effect. The pH values of the Quaternary red soils under different land use patterns showed a trend of buried Quaternary red soils (6.09) > arable land (5.91) > woodland (5.84) > grassland (5.81) > sparse forest and grassland (5.76), with no significant difference and overall weak acidity. The organic matter content showed a trend of woodland (12.65 g·kg^{-1}) > arable land (6.26 g·kg^{-1}) > sparse forest and grassland (4.00 g·kg^{-1}) > grassland (3.17 g·kg^{-1}) > buried Quaternary red soils (1.93 g·kg^{-1}), with the woodland having the highest organic matter content. The total nitrogen content showed a trend of woodland (0.70 g·kg^{-1}) > arable land (0.35 g·kg^{-1}) > grassland (0.34 g·kg^{-1}) > sparse forest and grassland (0.30 g·kg^{-1}) > buried Quaternary red soils (0.19 g·kg^{-1}), with the overall soil total nitrogen content being low. The total phosphorus content showed a trend of woodland (0.05%) = arable land (0.05%) = buried Quaternary red soils (0.05%) > grassland (0.04%) = sparse forest and grassland (0.04%), with no significant difference and overall low content. The total potassium content showed a trend of arable land (2.75%) > buried Quaternary red soils (2.72%) > sparse forest and grassland (2.71%) > grassland (2.68%) > woodland (2.64%). The microbial diversity showed a trend of woodland (10.72 mg·g^{-1}) > arable land (10.40 mg·g^{-1}) > sparse forest and grassland (10.15 mg·g^{-1}) > grassland (9.82 mg·g^{-1}) > buried Quaternary red soils (5.96 mg·g^{-1}). Among them, the woodland had a rich microbial content when compared to other Quaternary red soils under different land use patterns, indicating the soil was relatively barren.

Table 3. Comparisons of the Quaternary red soil health evaluation indicators (the whole soil) between different land use patterns.

Index	The Measured Value of the Index				
	Buried Quaternary Red Soil	Sparse Forest and Grassland	Grassland	Woodland	Arable Land
pH	6.09	5.76	5.81	5.84	5.91
Bulk density (g·cm^{-3})	1.12	1.57	1.23	1.53	1.49
Organic matter (g·kg^{-1})	1.93	4.00	3.17	12.65	6.26
Total nitrogen (g·kg^{-1})	0.19	0.30	0.34	0.70	0.35
Total phosphorus (%)	0.05	0.04	0.04	0.05	0.05

Table 3. *Cont.*

Index	The Measured Value of the Index				
	Buried Quaternary Red Soil	Sparse Forest and Grassland	Grassland	Woodland	Arable Land
Total potassium (%)	2.72	2.71	2.68	2.64	2.75
Microbial diversity (bacteria)	5.96	10.15	9.82	10.40	10.72

Notes: the numbers are the average of three samples. The microbial diversity does not have any units.

3.4. Soil Health Evaluation

3.4.1. Determining the Weights

Soil health indicators refer to indicators that can reflect a certain health attribute of soil [7]. The weights of the indicators are different due to their different impacts on the soil health status [33]. The PCA method can comprehensively balance the related influence of various soil evaluation indicators and is often chosen by researchers [30].

The weight values of various soil health indicators for Quaternary red soils under different land use patterns are shown in Table 4. In the buried Quaternary red soils, the weight proportion of the organic matter was the highest at 16.16%, and the weight proportion of the soil bulk density was the lowest at 11.21%; in the sparse forest and grassland red soils, the weight proportion of the total phosphorus content was the highest at 15.26%, and the weight proportion of the pH value was the lowest at 12.11%; in the grassland red soils, the weight proportion of the total potassium content was the highest at 15.49%, and the weight proportion of the soil bulk density was the lowest at 9.19%; in the woodland red soils, the weight proportion of the organic matter content was the highest at 14.50%, and the weight proportion of the soil bulk density was the lowest at 13.79%; in the arable land red soils, the weight proportion of the pH value was the highest at 16.02%, and the weight proportion of the total phosphorus content was the lowest at 8.46%.

Table 4. Weight values of the Quaternary red soil health evaluation indicators on the MDS under different land use patterns.

Index	Weight Value of Different Land Use Patterns (%)				
	Buried Quaternary Red Soil	Sparse Forest and Grassland	Grassland	Woodland	Arable Land
pH	13.33	12.11	14.90	14.46	16.02
Bulk density	11.21	14.81	9.19	13.79	15.18
Organic matter	16.16	14.24	15.35	14.50	14.86
Total nitrogen	16.13	14.01	15.46	14.47	14.75
Total phosphorus	14.16	15.26	14.97	14.01	8.46
Total potassium	15.85	15.25	15.49	14.48	15.36
Microbial diversity	13.16	14.32	14.63	14.30	15.36

3.4.2. The Coefficient of Variation of the Soil Health Indicators

The smaller the coefficient of variation, the smaller the deviation, the smaller the fluctuation of the measured indicators, and the more stable the indicator. Combined with Pearson correlation analysis, the comparison of the coefficient of variation of various indicators found (Table 5) that the coefficient of variation of the total phosphorus was the highest at 74%, which is a highly sensitive indicator; the coefficient of variation of the soil microbial diversity was between 20% and 50%, which is a moderately sensitive indicator; the coefficients of variation of the pH, bulk density, organic matter, total nitrogen, and total potassium were between 0% and 20%, which are low sensitivity indicators.

Table 5. Coefficients of variation for the seven Quaternary red soil health evaluation indicators under different land use patterns.

Index	pH	Bulk Density	Organic Matter	Total Phosphorus	Total Nitrogen	Total Potassium	Microbial Diversity
Standard deviation (SD)	0.26	0.16	0.44	0.31	0.08	0.01	2.90
Mean	5.94	1.45	6.23	0.42	2.72	0.05	9.51
Coefficient of variation (%)	4.40	11.20	7.00	74.00	2.90	18.80	30.50

3.4.3. The SHI and Its Classification

By running the fuzzy membership function formula, each indicator was calculated separately to obtain the membership of the soil health indicators. Then, combined with the weight values of each indicator obtained from the PCA [30], the SHI values were calculated based on the SHI formula. The soil health index of the minimum dataset (MDS-SHI) (seven final soil indicators) ranged from 0.22 to 0.81, with an average of 0.40.

Referring to the CASH method frame for the soil health level divisions, three scoring functions (increasing, decreasing, and optimal) were used [7,34], combined with the classification standards of the soil nutrient indicators. The upper critical value in the classification standard was set as a score of 10, and the lower critical value was set as a score of 1 [7,34]. Subsequently, the measured values of the selected indicators under different land use patterns were sorted in ascending order, and the score comparison curve was drawn to obtain the scores of each soil health indicator. Finally, the sum of the scores corresponding to the measured values of each indicator was compared with the sum of the scores corresponding to the upper critical value of the overall indicator. In this study, seven soil health evaluation indicators were selected, and the sum of the scores corresponding to the upper critical value of the overall indicators was 70. Finally, three evaluation levels of Quaternary red soils under different land use patterns were determined. According to the results of the SHI calculation, the range of levels was [0–1.00]. The evaluation index SHI $\geq$ 0.6 was classified as healthy soil, the evaluation index 0.4 $\leq$ SHI < 0.6 indicated sub-healthy soil, and the evaluation index SHI < 0.4 indicated unhealthy soil [7,34].

The comprehensive health indexes of the Quaternary red soils under different land use patterns, such as the buried Quaternary red soil, sparse forest and grassland, grassland, woodland, and arable land, were 0.33, 0.37, 0.49, 0.64, and 0.61 (Figure 6), respectively. The health status of the Quaternary red soils under different land use patterns tested showed significant differences with a sequence for woodland > arable land > grassland > sparse forest and grassland > buried Quaternary red soils. The comparison results showed that the soil health value of the woodland was highest, and the buried Quaternary red soils was the lowest.

The MDS-SHIs of the buried Quaternary red soils and sparse forest and grassland soils were 0.33 and 0.37, respectively, less than 0.40, belonging to the unhealthy level; the grassland SHI was 0.49, between 0.40 and 0.60, belonging to the sub-healthy level. The SHI of arable land and woodland was 0.61 and 0.64, respectively, belonging to the healthy soil types. Therefore, the Quaternary red soils of woodland and arable land belong to the healthy level.

In order to further explore the impact of different land use patterns on the health status of Quaternary red soils, the topsoil layer (A) and subsoil layer (B) of each profile were compared.

The pH values of the topsoil layers were not significantly different (Table 6), all samples showed weak acidity. The soil bulk density of the topsoil layer of grassland was the lowest at 1.23g·cm^{-3}, and the arable land soil was the highest (1.54 g·cm^{-3}). The organic matter and total nitrogen contents of woodland were the highest (30.53g·kg^{-1} and 1.58g·kg^{-1}, respectively), providing sufficient nitrogen nutrients for plant growth. The total phosphorus content was similar in soils under different land use patterns, all presented low content. The maximum Shannon microbial diversity in arable land was 10.72. The topsoil layers' health status was woodland (0.86) > arable land (0.73) > grassland (0.70) > sparse forest and grassland (0.67) (Figure 6), consistent with the profile soil health evaluation results. Among them, the soil health status of woodland was the best, and that of the sparse forest and grassland was the worst. According to the soil health grading standard, the SHI of the Quaternary red soils under the four land use patterns was greater than 0.60, all belonging to healthy soil types. Overall, the topsoil layers' health status of Quaternary red soils under different land use patterns was relatively good.

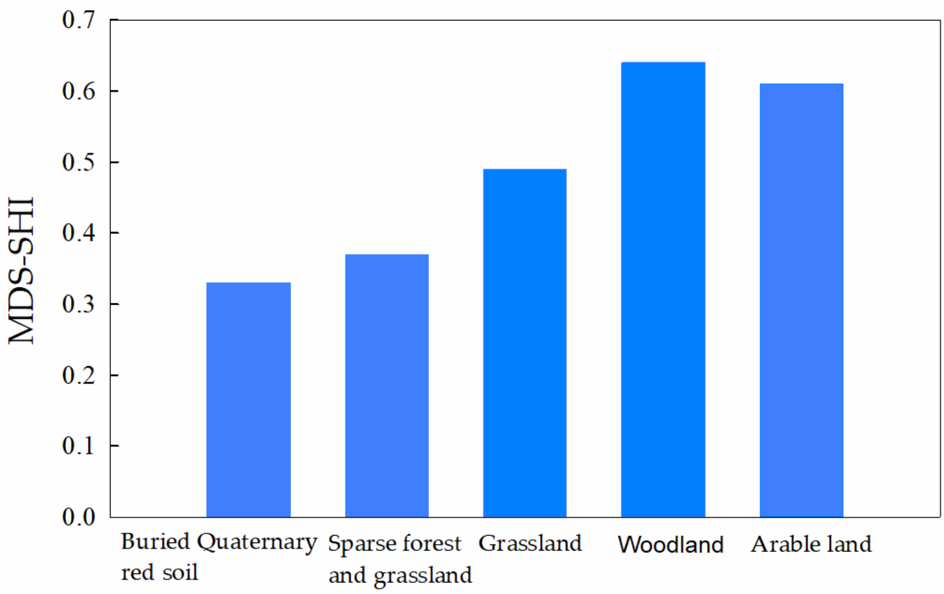

Figure 6. Comparisons of the Quaternary red soil health evaluation indexes under different land use patterns.

Table 6. Contents of the soil health evaluation indexes for A and B horizons of the Quaternary red soils under different land use patterns.

Index	Sparse Forest and Grassland		Grassland		Woodland		Arable Land	
	A	B	A	B	A	B	A	B
pH	5.63	5.8	5.62	5.91	5.67	5.92	5.75	5.99
Bulk density ($g{\cdot}cm^{-3}$)	1.35	1.64	1.23	1.33	1.38	1.61	1.54	1.46
Organic matter ($g{\cdot}kg^{-1}$)	9.33	2.21	7.46	1.36	30.53	3.71	12.93	2.93
Total nitrogen ($g{\cdot}kg^{-1}$)	0.55	0.21	0.78	0.18	1.58	0.27	0.57	0.24
Total phosphorus (%)	0.05	0.04	0.06	0.04	0.07	0.04	0.06	0.05
Total potassium (%)	2.62	2.74	2.61	2.75	2.71	2.60	2.76	2.75
Microbial diversity	10.15	10.15	9.82	9.82	10.4	10.4	10.72	10.72

The differences in the pH values of the subsoil layers in the Quaternary red soil profiles were not significant (Table 6), all showing weak acidity. The grassland had the lowest bulk density (1.23 $g{\cdot}cm^{-3}$), and the sparse forest and grassland had the highest bulk density (1.64 $g{\cdot}cm^{-3}$). Like the topsoil layer analysis results, the woodland had a higher organic matter and total nitrogen content (3.71 $g{\cdot}kg^{-1}$ and 0.27 $g{\cdot}kg^{-1}$, respectively). The differences in the total phosphorus content were not significant, all showing a poor state, but the total potassium content was higher. The microbial diversity of the arable land was the highest.

The soil health status of the subsoil layer showed the trend of arable land (0.41) > grassland (0.40) >woodland (0.38) > sparse forest and grassland (0.34) (Figure 7). According to the soil health grading standards, the SHI of the sparse forest and grassland and woodland was less than 0.40, belonging to the unhealthy level; the SHI of the grassland and arable land was between 0.40 and 0.60, belonging to the sub-healthy level; overall, the health status of the subsoil layers under different land use patterns was relatively poor.

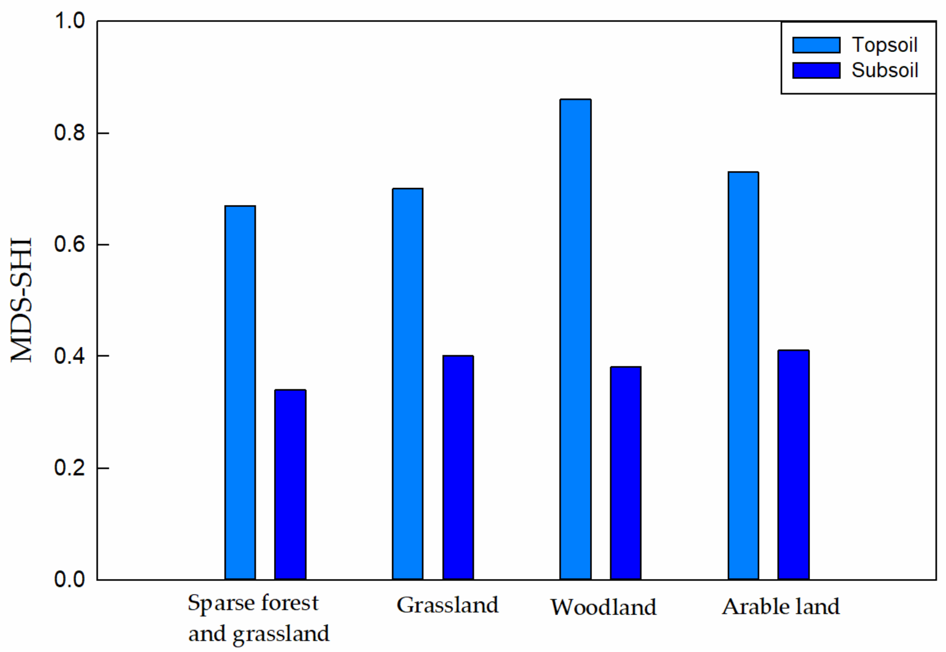

Figure 7. Comparisons of the Quaternary red soil health evaluations for topsoils and subsoils under different land use patterns.

It can be seen that topsoil layers were directly affected by frequent human land use activities, resulting in significant differences in the health status of the topsoil layers and subsoil layers (Figure 7). The health status of the Quaternary red soil topsoil layers (A) under different land use patterns was consistent with the overall profile health status trend, better than the health status of the subsoil layer (B), with the subsoil layer health status showing a trend of arable land > grassland > woodland > sparse forest and grassland. Overall, the health indexes of the sparse forest and grassland, grassland, woodland, and arable land were higher than that of the buried Quaternary red soils (0.33), indicating that certain human land use activities have improved the soil health status, with the woodland having the best health status, making it a suitable land use pattern in low mountain and hilly areas.

3.5. Soil Health Evaluation Result Verifications

In order to evaluate the accuracy of the MDS-SHI, the soil health index of the total dataset (TDS-SHI) (12 initially selected soil indicators) was calculated. The TDS-SHI ranged from 0.20 to 0.71, with an average of 0.31 and a coefficient of variation of 21.30%.

The soil health evaluation results were verified using linear regression, in the case of undetermined independence, to ensure the accuracy of soil health evaluation results. Linear regression analysis was performed based on the relative deviation coefficient. There was a highly significant positive correlation ($p < 0.01$) between the soil health comprehensive index of the TDS-SHI and the MDS-SHI, proving that the MDS-SHI under PCA was reasonable and correct (Figure 8). This indicated that the results of the established health evaluation system of Quaternary red soils under different land use patterns was representative.

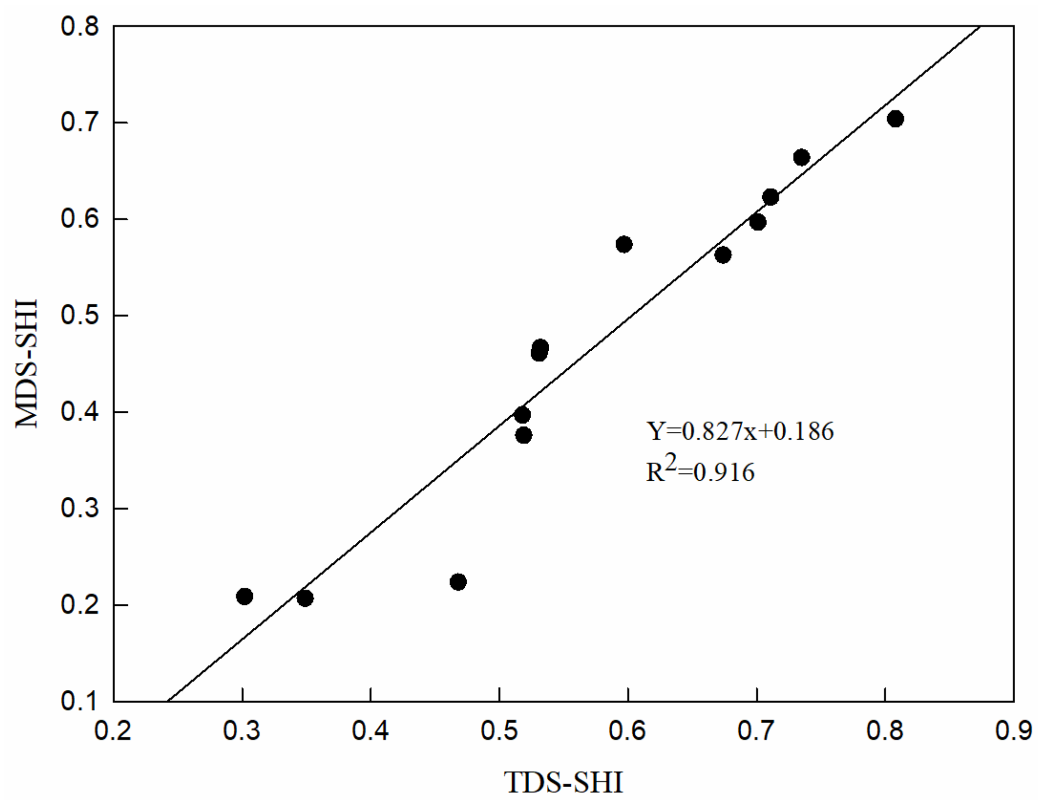

Figure 8. The correlation of the Quaternary red soil health evaluation between the results using the minimum dataset (MDS-SHI) and the total dataset (TDS-SHI).

4. Discussion

Soil health is affected by many factors [33,34]. The established health evaluation system is a preliminary exploration of the study on Quaternary red soils. In order to continuously improve the health evaluation system, more detailed and comprehensive analysis and investigation are needed, such as index optimization, membership function selection, weight value determination, and soil health classification.

4.1. The Selection of the Health Evaluation Indicators for the Quaternary Red Soils under Different Land Use Patterns

The advantage of the SHI method is that it can fully consider the influence of the measured value, weight, and interaction of evaluation indicators on the evaluation results [7,34]. In the selection of the soil health indicator (Figure 2), the representativeness, universality, sensitivity, reproducibility, and the measurement cost, as well as its appropriate range and threshold should be considered [7,35,36]. In the study, 116 potential indicators were firstly selected according to the CNKI. Through frequency screening and combining with factors such as the topography, climate, hydrological conditions, and soil properties, 12 evaluation indexes were further selected. Based on the frame of the Cornell Soil Health Evaluation system [7], seven evaluation indicators including the bulk density, pH, organic matter content, total potassium content, total nitrogen content, total phosphorus content, and microbial diversity were determined using the MDS, PCA, and Norm values. Theoretically, the more evaluation indicators, the closer the evaluation results are to the real condition of the soil health [35,36]. However, the indicators that can be used in the actual operation process are limited. Thus, it is necessary to use limited data to obtain the results closest to reality. Therefore, indicators can be flexibly selected for health evaluation according to the local conditions [34–37]. The significant correlation between the SHI-MDS and SHI-TDS further indicates that the MDS can replace the TDS to accurately evaluate the health status of Quaternary red soils under different land use patterns (Figure 8).

4.2. Changes in the Health Status of Quaternary Red Soils under Different Land Use Patterns

The health index of the Quaternary red soils under different land use patterns was obtained by calculating the SHI-MDS. The reference base of the buried Quaternary red soils was not affected by human activities, maintaining the original characteristics. Long-term compaction resulted in a soil structure that was compact, sticky, and poorly permeable. In addition, with the low precipitation and dry climate, the rate of organic matter mineralization was far higher than the rate of humus. Therefore, the organic matter content, soil nutrient content, and soil microbial diversity were low. The SHI was 0.33, which is in an unhealthy state.

When the buried Quaternary red soils were exposed to the surface, the health status of the Quaternary red soils varied under different human land use activities, showing the trend of woodland (0.64) > arable land (0.61) > grassland (0.49) > sparse forest and grassland (0.37) > buried Quaternary red soils (0.33). According to the classification criteria of soil health [7,34], soils with an index below 0.4 are unhealthy, those between 0.4 and 0.6 are sub-healthy, and those above 0.6 are healthy. Among them, the Quaternary red soils under woodland and arable land use patterns showed a relatively healthy state. Woodland has a larger amount of biomass returned from trees and shrubs each year, and plant residues covering the surface help to conserve soil and water [38]. At the same time, the decomposition of fallen leaves participates in the soil humification process, increasing the soil nutrient content and creating a suitable environment for microbes [38–40]. Higher microbial diversity promotes the accumulation of organic matter and nutrient cycling [39], significantly improving the health status of the red soils. Therefore, the health index of woodland was the highest at 0.64, reaching the standard of healthy soils. The arable land ranked second, with a health index of 0.61. Human activities, such as applying organic fertilizers and chemical fertilizers, increase and maintain soil nutrient content in the arable land [41]. In addition, machine plowing loosens the topsoil layers, improving the structure and permeability of the red soils, making it suitable for microbial survival and enhancing soil health [35]. In the study area, with a semiarid climate and scarce precipitation, plant growth in woodland is greatly restricted due to extensive management. However, the relatively fine management of arable land brings their health status close to that of woodland under the influence of human land use activities. For the grassland (0.49) and sparse forest and grassland (0.37), the aboveground biomass is mainly annual herbaceous plants, and the organic matter returned to the soil through plant residues is limited. Compared to woodland and arable land, these areas have lower economic value and are under extensive management. Their external conditions are insufficient, and their internal conditions are scarce, making their health status lower than that of arable land and woodland and showing a sub-healthy soil state. Overall, the soil health status of the four land use patterns, woodland, arable land, grassland, and sparse forest and grassland, are better than that of the reference base buried red soils (0.33). This indicates that current human land use activities promote the development of red soils towards a better health status.

In order to further explore the impact of different land use patterns on the health status of Quaternary red soils, the topsoil layer (A) and subsoil layer (B) of the red soils were analyzed and studied under different land use patterns. The health index of the topsoil layer ranged from 0.67 to 0.86, showing a trend of woodland (0.86) > arable land (0.73) > grassland (0.70) > sparse forest and grassland (0.67), which was consistent with the overall trend of the soil health status in the profile. The health indexes of the red soils under different land use patterns in the study were greater than 0.6, belonging to the healthy level. In woodland, grasslands, and sparse forest and grasslands, the surface is covered with fallen leaves and branches all year round, which helps to maintain moisture and a suitable temperature [39,40]. At the same time, the decomposition of plant residues returns nutrients to the soil, improving the organic matter content and promoting microbial survival [40]. The increase in microbial diversity also promotes nutrient cycling in the soil, leading to healthier soil development [39]. However, for grasslands and sparse forest and grasslands dominated by annual herbaceous plants, the ground cover is not as high as that of woodland, and the aboveground biomass and coverage rate are lower than those of woodland. These conditions result in a lower humification process and microbial diversity than woodland, leading to a less healthy soil status for the grasslands and sparse forest and grasslands. For arable land, the topsoil layer is directly affected by human plowing and farmyard manure and chemical fertilizers, which improves the fertility status, making it comparable to woodland. Compared to the buried Quaternary red soils (0.33), the health status under different land use patterns has developed to varying degrees towards healthier soil conditions. Human land use activities directly affect the topsoil layer, having the greatest impact on its characteristics [35,41].

As the soil depth changes, the influence of human activities is limited [40], resulting in a weaker impact on the subsoil layer (B). Affected by the continental monsoon climate in the northern temperate zone, the study area has low precipitation and a dry climate [20,21]. Compared to the topsoil layer, which becomes looser and has a higher organic matter content under the influence of human land use activities, the subsoil layer is more compact, with poorer water permeability, and lower nutrient content, which affects the microbial activity, thus influencing the accumulation of humus and the transformation and formation of soil nutrient elements [35,42]. Therefore, the soil health level of the subsoil layer was lower than that of the topsoil layer, and the difference was significant. The SHI ranged from 0.34 to 0.41, presenting a trend of arable land (0.41) > grassland (0.40) > woodland (0.38) > sparse forest and grassland (0.34). Arable land and grasslands exhibited a sub-healthy soil state, while woodland and sparse forest and grasslands exhibited an unhealthy soil state. The reason for the relatively high health status of the arable land is that humans pursue a higher crop yield, applying large amounts of organic and chemical fertilizers [33,43]. Mechanical plowing allows some fertilizers to enter the subsoil layer directly [43]. After plowing, the topsoil layers become loose, and nutrients can easily move to the subsoil layer, making its soil health status better than other land use patterns [43]. Compared with the SHI of the paleosol profile, the soil health status has declined, but compared with the reference buried red soils (0.33), the soil health status has also improved, albeit with a weak degree of change towards a healthy soil state.

Combining the above analysis, it is clear that when buried Quaternary red soils are exposed and used by humans, factors such as topographic features, climatic characteristics, hydrological features, different human land use activities, soil properties, and external environmental characteristics can lead to changes in the soil health. Compared with buried Quaternary red soils, the health status under other land use patterns has improved to varying degrees and is developing towards healthier soil. At this stage, soil health has become an important limiting factor in regional land use in agricultural production practices. It is necessary to plan, manage, and use land scientifically and rationally according to the local conditions. While obtaining crop yields, it is also essential to improve the soil health and gradually achieve the sustainable use of paleosol resources.

5. Conclusions

The buried red soils have not been affected by human land use activities, main-taining their original state. Due to their long-term compacted state, their permeability and aeration are poor, with low organic matter content and low soil microbial diversity. The SHI was 0.33, indicating an unhealthy state. As the buried red soils are exposed to the surface due to erosion and other factors and affected by different land use activities, the soil health improves, transitioning to various degrees of healthier states. This suggests that to a certain extent, land use activities positively impact the health of the Quaternary red soils.

Compared with the buried Quaternary red soils, the health index of soils under different land use patterns showed a trend of woodland (0.64) > arable land (0.61) > grassland (0.49) > sparse forest and grassland (0.37) > buried Quaternary red soils (0.33). Among them, buried Quaternary red soils were classified as unhealthy, grasslands and sparse forest and grass-lands were sub-healthy, while woodlands and arable lands were healthy.

The soil health trend in the topsoil layer (A) of the Quaternary red soils under different land use patterns was consistent with the profile health status, namely woodland (0.86) > arable land (0.73) > grassland (0.70) > sparse forest and grassland (0.67) > buried Quaternary red soils (0.33). Except for buried the Quaternary red soils, the topsoil layer under other land use patterns was in a healthy state.

The health status of the subsoil layer (B) showed a trend of arable land (0.41) > grassland (0.40) > woodland (0.38) > sparse forest and grassland (0.34) > buried Quaternary red soils (0.33) and was in a sub-healthy state.

The soil health conditions under the four types of land use were better than those of the buried Quaternary red soils, showing a trend towards soil health. This suggests that human land use activities in the low mountain and hilly areas have to some extent promoted the healthy development of the Quaternary red soils.

The woodland red soil is in a healthy status and is suitable land use pattern for low mountain and hilly areas. The research results are expected to provide a scientific basis for adjusting the land use structure and a reference for scientific management and use in similar regions, to promote the sustainable use of the Quaternary red soils.

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References

1. Duan, S.Y.; Sun, Z.X.; Wang, Q.B.; Jiang, Y.Y.; Han, C.L.; Zhang, Y.W.; Lv, M.F.; Sun, F.J.; Chen, L.M. Characteristics of soil organic carbon distribution of quaternary red soils under different land use patterns. *Chin. J. Soil Sci.* **2021**, *52*, 1078–1084.
2. Sun, Z.X.; Owens, R.P.; Han, C.L.; Chen, H.; Wang, X.L.; Wang, Q.B. A quantitative reconstruction of a loess–paleosol sequence focused on paleosol genesis: An example from a section at Chaoyang, China. *Geoderma* **2016**, *266*, 25–39. [CrossRef]
3. Duan, S.Y.; Sun, Z.X.; Wang, Q.B.; Jiang, Y.Y.; Sun, F.J. Comparison of aggregate composition in quaternary red soil under different land use pattens. *Chin. J. Soil Sci.* **2020**, *51*, 587–596.
4. Liu, L.W.; Gong, Z.T. Development and evolution of red paleosols. *Mar. Geol. Quat. Geol.* **2000**, *20*, 37–42.
5. Kang, L.F.; Rui, L.F.; Hua, W.; Tan, J.A.; Yang, F.W.; Long, H.W. The effects of different land-use types on quality of urban soils. *Ecol. Sci.* **2006**, *25*, 59–63.
6. Doran, J.W.; Sarrantonio, M.; Liebig, M.A. Soil health and sustainability. *Adv. Agron.* **1996**, *56*, 1–54.
7. Moebius-Clune, B.N.; Moebius-Clune, B.K.; Gugino, B.K.; Idowu, O.J.; Schindelbeck, R.R.; Ristow, A.J.; Van Es, H.M.; Thies, J.E.; Shayler, H.A.; McBride, M.B.; et al. *Comprehensive Assessment of Soil Health-The Cornell Framework Manual*; Edition 3.1; Cornell University: Geneva, Switzerland; New York, NY, USA, 2016.
8. Lehmann, J.; Bossio, D.A.; Kögel-Knabner, I.; Rillig, C.M. The concept and future prospects of soil health. *Nat. Rev. Earth Environ.* **2020**, *1*, 544–553. [CrossRef]
9. Fine, A.K.; van Es, H.M.; Schindelbeck, R.R. Statistics, scoring functions, and regional analysis of a comprehensive soil health database. *Soil Sci. Soc. Am. J.* **2017**, *81*, 589–601. [CrossRef]
10. Rinot, O.; Levy, G.J.; Steinberger, Y.; Svoray, T.; Eshel, G. Soil health assessment: A critical review of current methodologies and a proposed new approach. *Sci. Total Environ.* **2019**, *648*, 1484–1491. [CrossRef]
11. Zhu, Y.G.; Peng, J.J.; Wei, Z.; Shen, Q.R.; Zhang, F.S. Linking the soil microbiome to soil health. *Sci. Sin. Vitae* **2021**, *51*, 1–11.
12. Zhang, J.Z.; LI, Y.Z.; Li, Y.; Zhang, J.L.; Zhang, F.S. Advances in the Indicator System and Evaluation Approaches of Soil Health. *Acta Pedol. Sin.* **2022**, *59*, 603–616.

13. Zhu, Y.G.; Shen, R.F.; He, J.Z.; Wang, Y.F.; Han, X.G.; Jia, Z.J. Soil Microflora in China: Progress and Prospect. *Agric. Sci. Eng. China* **2018**, *3*, 6–13.
14. Wall, D.H.; Nielsen, U.N.; Six, J. Soil biodiversity and human health. *Nature* **2015**, *528*, 69–76. [CrossRef] [PubMed]
15. Bünemann, E.K.; Bongiorno, G.; Bai, Z.G. Soil quality-A critical review. *Soil Biol. Biochem.* **2018**, *120*, 105125. [CrossRef]
16. Han, C.L.; Liu, S.H.; Wang, Q.B.; Wang, H.Q. Basic properties and genetic characteristic research of Quaternary paleosol in Chaoyang city of Liaoning. *Chin. J. Soil Sci.* **2009**, *6*, 1233–1239.
17. Chinese Soil Taxonomy Research Group; Institute of Soil Science Chinese Academy of Sciences; Cooperative Research Group on Chinese Soil Taxonomy. *Keys to Chinese Soil Taxonomy*, 3rd ed.; University of Science and Technology of China Press: Hefei, China, 2001. (In Chinese)
18. Soil Survey Staff. *Keys to Soil Taxonomy*, 12th ed.; USDA, NRCS Publications: Washington, DC, USA, 2014.
19. IUSS Working Group WRB. *World Reference Base for Soil Resources 2014, Update 2015 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; World Soil Resources Reports No. 106; FAO: Rome, Italy, 2015.
20. Sui, J.Y. Analysis on precipitation features during the flood season of Chaoyang in Liaoning Province in recent 58 Years. *J. Anhui Agric. Sci.* **2011**, *39*, 14931–14932.
21. Zhang, F.M.; Zong, Y.F. The characteristics of temperature change in Chaoyang area of Liaoning Province. *Anhui Agric. Sci. Bull.* **2015**, *21*, 150–160.
22. Zhang, G.L.; Li, D.C. *Manual of Soil Description and Sampling*; Science Press: Beijing, China, 2017. (In Chinese)
23. Grossman, R.B.; Reinsch, T.G. Bulk Density and Linear Extensibility. In *Methods of Soil Analysis: Part 4 Physical Methods*; Dane, J.H., Topp, G.C., Eds.; ASA and SSSA: Madison, WI, USA, 2002; pp. 201–228.
24. Li, J.W.; Jiao, X.G.; Sui, Y.Y.; Cheng, S.J. The Belonging of Dark Brown Soil in the East of Jilin Province in Chinese Soil Taxonomy. *Chin. Agric. Sci. Bull.* **2011**, *27*, 74–79.
25. *GB/T9837-88*; Determination of Soil Total Phosphorus. Standards Press of China: Beijing, China, 1988.
26. *GB/T9836-88*; Determination of Soil Total Potassium. Standards Press of China: Beijing, China, 1988.
27. Frank, S.; Tebbe, C. A new approach to utilize PCR-Single-Strand-Conformation polymorphism for 16S rRNA gene-based. *Appl. Environ. Microbiol.* **1998**, *64*, 4870–4876.
28. Larson, W.E.; Pierce, F.J. *Conservation and Enhancement of Soil Quality: Evaluation for Sustainable Land Management in the Developing Word*; International Board for Soil Research and Management Lnc.: Bangkok, Thailand, 1991; pp. 175–203.
29. Doran, J.W.; Parkin, T.B. *Quantitative Indicators of Soil Quality: A Minimum Data Set*; Soil Science Society of America Special Publication 49; American Society of Agronomy: Madison, WI, USA, 1996; pp. 25–37.
30. Du, Z.F. *Multivariate Statistical Analysis*; Tsinghua University Publishing House Co., ltd.: Beijing, China, 2016.
31. Wang, X.; Jin, L.; Fu, M. Research on Fuzzy Plastic Constitutive Model Based on Membership Function. *Math. Probl. Eng.* **2021**, *2021*, 9901948. [CrossRef]
32. Andrews, S.S.; Karlen, D.L.; Cambardella, C.A. The Soil Management Assessment Framework: A Quantitative Soil Quality Evaluation Method. *Soil Sci. Soc. Am. J.* **2004**, *68*, 1945–1962. [CrossRef]
33. Andrews, S.S.; Karlen, D.L.; Mitchell, J.P. A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agric. Ecosyst. Environ.* **2002**, *90*, 25–45. [CrossRef]
34. Sheng, F. Introduction and application of Cornell Soil Health Assessment. *Chines J. Soil Sci.* **2014**, *45*, 1289–1296.
35. Wu, K.N.; Yang, Q.J.; Zhao, R. A Discussion on Soil Health Assessment of Arable Land in China. *Acta Pedol. Sin.* **2021**, *58*, 537–544.
36. *NY/T 1634-2008*; Ministry of Agriculture of the People's Republic of China. Rules for Soil Quality Survey and Assessment. Chinese Agriculture Press: Beijing, China, 2008.
37. Raiesi, F. A minimum data set and soil quality index to quantify the effect of land use conversion on soil quality and degradation in native range lands of upland arid and semiarid regions. *Ecol. Indic.* **2017**, *75*, 307–320. [CrossRef]
38. Li, L.; Zhang, Y.; Wang, L.B.; Wang, L.M. Vertical changes of the soil microbial biomass and the correlation analysis in different forests. *J. Cent. South Univ. For. Technol.* **2007**, *2*, 52–60.
39. Wang, Y.; Ding, G.D.; Liu, M.J.; Gao, G.L.; Yu, M.H.; Li, X. Influence of different vegetation types on soil microbial characteristics of typical forest land in Yulin Sandy Area. *Chin. J. Soil Sci.* **2022**, *4*, 97–918.
40. Lauber, C.L.; Ramirez, K.S.; Aanderud, Z.; Lennon, J.; Fierer, N. Temporal variability in soil microbial communities across land use types. *ISME J. Multidiscip. J. Microb. Ecol.* **2013**, *7*, 1641–1650. [CrossRef]
41. Sharma, K.L.; Sharma, S.C.; Bawa, S.; Singh, S.; Chandrika, D.S.; Sharam, V. Combined effect of tillage and organic fertilization on soil quality key indicators and indices in alluvial soils of Indo-Gangetic Plains under rainfed maize-wheat system. *Arch. Agron. Soil Sci.* **2015**, *61*, 313–327. [CrossRef]
42. Yang, Q.J.; Wu, K.N.; Feng, Z.; Zhao, R.; Zhang, X.; Li, X.L.; Ma, N. Soil quality assessment on large spatial scales: Advancement and revelation. *Acta Pedol. Sin.* **2020**, *57*, 565–578.
43. Qi, Y.B.; Darilek, J.L.; Huang, B.; Zhao, Y.; Sun, W.; Gu, Z. Evaluating soil quality indices in an agricultural region of Jiangsu Province, China. *Geoderma* **2009**, *149*, 325–334. [CrossRef]