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Croplands Quality Evaluation of Whole Tillage Layer Based on the Minimum Data Set in Jilin Province, China

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Abstract: The aim of this study is to accurately evaluate the quality characteristics of whole tillage cropland and deepen the knowledge of sub-tillage soil quality evaluation in Jilin Province, China. In this study, top-tillage and sub-tillage soil samples were collected from 185 maize continuous cropping areas in Jilin Province, and 12 physicochemical indexes (pH, cation exchange capacity (CEC), soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), available nitrogen (AN), available phosphorus (AP), available potassium (AK), sand, silt, and clay) were used to evaluate the whole tillage layer soil quality index (SQI). The results showed that the whole tillage soil physicochemical indexes in Jilin Province were generally above the moderate level, and nutrient contents increased from West to East among the regions. The minimum data set SQI (SQI-MDS) of the top-tillage and sub-tillage layers were 0.22–0.98 (0.46) and 0.23–0.93 (0.55), respectively. The suitable ranges of MDS parameters for reasonable tillage layers were as follows: top-tillage layer SOM $\geq$ 34.5 g kg^{-1}, 31.5% $\leq$ sand $\leq$ 53.5%, AP $\geq$ 32.1 mg kg^{-1}, and TK $\geq$ 15.18 g kg^{-1}; sub-tillage layer 31.3% $\leq$ sand $\leq$ 51.2%, TN $\geq$ 1.48 g kg^{-1}, 6.4 $\leq$ pH $\leq$ 7.1, and AK $\geq$ 157.6 mg kg^{-1}. In summary, the SQI and evaluation indexes of the top-tillage and sub-tillage layers in different ecological zones are varied. It is necessary to adjust the evaluation index thresholds in combination with the actual conditions to establish a more accurate evaluation index system of the whole tillage soil quality.

Keywords: Jilin Province; whole tillage layer; spatial distribution; minimum data set; cropland quality

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1. Introduction

As the main maize-producing area in China, Jilin Province occupies a critical strategic position in China's food security due to its high soil fertility, suitable for farming with high production potential [1]. The main soil type in this planting area is black soil, and these croplands are viewed as an essential strategic resource for safeguarding national food security. Despite China's implementation of the most stringent cropland protection policies, the unique geographic and climatic conditions of the northeast region, combined with irrational farming measures and excessive fertilization in recent years, have led to cropland quality degradation and maize yield reduction, and other obstacles are becoming more serious [2]. It is urgent to rationally utilize the cropland soil and ensure black soil health. Soil quality reflects the ability to maintain crop growth, and accurate evaluation of the whole tillage layer soil quality characteristics is the basis for constructing a reasonable tillage layer [3]. With the deepening of our understanding of black soil protection and utilization, the research on black soil cropland quality has been emphasized.

Current research usually relies on the organic matter concentration layer and the length of crop root growth to determine the tillage layer depth; generally, the top-tillage layer is determined as 0–20 cm. Agricultural production-process farming activities are mainly concentrated in the top-tillage layer, and black soil "heavy use and light maintenance" management mode has reduced the top-tillage layer soil quality [4]. The black soil cropland quality has been effectively improved in recent years through the straw-return, microbial fertilizer, and green manure use [5]. The cropland quality grade (2019 national bulletin on cultivated land quality grades) has been improved by an average of 1.17 grades [6], of which 0.77 grades have been increased in Jilin Province [7]. The top-tillage soil quality of typical black soil regions in central Jilin Province is in the middle to upper level, indicating that cropland protection has achieved some specific results in recent years but still has more space for restoration and development than in the 1980s [8]. The sub-tillage layer, the important tillage layer connecting the topsoil layer and subsoil layer, is generally extended to 20–40 cm on the basis of the top-tillage layer. In response to the degradation of the sub-tillage layer caused by predatory utilization, the application and promotion of straw deep returning significantly affects the sub-tillage layer's fertilization [9]. Sub-tillage soil fertility levels have become a key determinant of high maize yields, and "vertically extended" root system configuration is an adaptive response characteristic of high-yielding maize populations [10]. Sub-tillage soil fertilization is compatible with the concept of crop root growth to deeper soils and fertile tillage construction [11]. Previous researchers have conducted extensive work on physical, chemical, and biological aspects of soil fertility enhancement and cropland quality evaluation, but most of them have focused on exploring the top-tillage layer, and little research has been reported on the sub-tillage layer. Given the nutrient storage and buffering role of the sub-tillage layer soil, the current research on the construction of the fertility tillage layer gradually tended to favor the whole tillage layer (0–40 cm) from the top-tillage layer.

Out of the 17 Sustainable Development Goals set by the United Nations, 13 goals are directly or indirectly related to soil [12]. Understanding the current status of soil health, conducting a systematic diagnosis and establishing a forecasting system, is the basis for safeguarding soil health and an important component of sustainable soil management [13]. The soil quality index (SQI) is a comprehensive indicator for evaluating soil quality, taking into account the physical, chemical, and biological characteristics of the soil. It comprehensively reflects the soil condition. Accurately evaluating cropland's whole tillage soil quality and overcoming its obstacles is highly relevant to rational tillage construction and sustainable agricultural development [1,14]. As soil quality is affected by many factors and a unified evaluation system has not yet been formed, soil quality is difficult to measure directly. Soil physicochemical indicators can all reflect soil quality [15], but evaluating all indicators involved in soil quality simultaneously is computationally complex and may have data redundancy problems. The minimum data set (MDS) method is used to optimize and simplify large amounts of data by using principal components and correlation analyses and to comprehensively characterize a research object by collecting the least amount of data. Using the MDS method for soil quality evaluation can effectively eliminate redundant indicators and optimize the soil evaluation model [16]. The SQI-MDS method specific steps include the following: selecting appropriate variables, converting variables into scores, determining variable weights, and integrating variable scores into the SQI [17]. In the indicator-scoring process, soil variables are usually scored using standardized functions, and the measured variable values are normalized and then integrated into the SQI [18]. An accurate assessment of the standardization function scoring thresholds is critical for SQI assessment using scoring functions. Unfortunately, the determination of indicator thresholds is difficult for specific study areas, especially for sub-tillage soils. In most cases, critical values are based on published results that are directly generalized to similar large soil areas [19,20], and existing models perform differently in different regions. In comparison, the better models are mostly site-specific. Given the complexity of soil health to critical values, the best approach is to establish these key soil indicator values based on local soil health objectives [21,22].

Soil quality evaluation studies in the northeast black soil zone of China have mostly screened indicators such as bulk density, pH, cation exchange capacity, organic matter, and total potassium into the MDS [3,23,24], and climate, topography, land use type, and management have all been considered [25]. However, the great spatial heterogeneity of soil characteristics and environmental composition has led to extensive uncertainties in the pattern and relative importance of environmental factors on agricultural soils in different regions and scales [26]. For the black soil zone, the lack of sampling data has resulted in fewer large-scale studies on soil quality evaluation and related environmental factors, and the studies have been mainly focused on the top-tillage layer. This study took the maize continuous cropping area in Jilin Province as the research object, combined with Global Positioning Systems (GIS) technology to study the soil properties and spatial distribution of the top-tillage and sub-tillage layers. The MDS method was used to construct the whole tillage soil quality evaluation index system based on soil physicochemical properties and explored the suitable range of the regional cropland quality index parameters to provide a theoretical basis for the cropland quality evaluation and the fertile tillage construction in Jilin Province.

2. Materials and Methods

2.1. Overview of the Study Area

Jilin Province is located in the central part of northeast China (121°38′ E–131°19′ E, 40°52′ N–46°18′ N). The region has a temperate continental monsoon climate, with high relief in the southeast and low relief in the northwest, with an average annual precipitation of 400–600 mm, a frost-free period of 100–160 days, and an average annual sunshine of 2260–3000 h. According to topography and climate, Jilin Province is divided into three ecological zones, i.e., the western semi-arid plains zone (Baicheng and Songyuan), the central semi-moist plains zone (Changchun, Siping, Liaoyuan, and Jilin), and the eastern moist mountainous zone (Tonghua, Baishan, and Yanbian).

2.2. Soil Sampling and Laboratory Analysis

Selecting the national farmland quality monitoring sites in 2020, farmland soils with typical farming systems of maize continuous cropping were collected from different villages in the region, with 44 sites in the western semi-arid plains (8 in Baicheng and 36 in Songyuan), 93 sites in the central semi-moist plains (31 in Changchun, 28 in Siping, 15 in Liaoyuan, and 19 in Jilin), and 48 sites in the eastern moist mountainous regions (28 in Tonghua, 9 in Baishan, and 11 in Yanbian), totaling 185 sampling points. Five soil cores (5 cm diameter covering 0–40 cm depth) were randomly collected from each plot and divided into two parts (0–20 cm and 20–40 cm), and then mixed independently to make two composite samples. The soil cores were gently broken apart along the natural break points and sieved (<5 mm) to remove visible plant matter and organic debris [27]. The samples were air-dried, ground, and stored for backup. GPS positioning was performed at the center of each cropland after sampling (Figure 1).

Soil samples were analyzed for pH, cation exchange capacity (CEC), organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), available nitrogen (AN), available phosphorus (AP), available potassium (AK), and soil mechanical composition (sand, silt, and clay), totaling 12 items. The standard methods were used to measure soil samples [28]: soil pH was determined using a 1:2.5 soil–water suspension, CEC was estimated using the ammonium acetate saturation method, SOM by the potassium dichromate volumetric method–external heating method, TN by the semi-micro-volume Kjeldahl method, TP by the sodium hydroxide melt-molybdenum antimony colorimetric method, TK by the sodium hydroxide melting-flame photometric method, AN by the alkaline diffusion method, AP by the 0.5 mol L^{-1} $NaHCO_3$ extraction–molybdenum antimony colorimetric method, AK by the 1 mol L^{-1} NH_4OAc leaching-flame photometric method, and soil mechanical composition was determined by the gravimetric method.

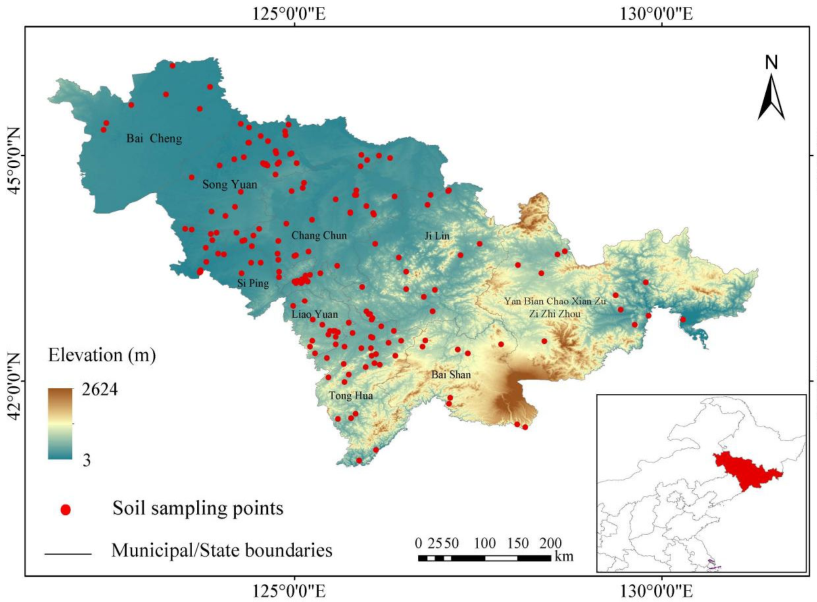

Figure 1. Schematic diagram of soil sampling distribution.

2.3. Soil Quality Evaluation

2.3.1. Indicator Selection

The 12 indicators that reflect soil physicochemical properties were comprehensively selected to establish a soil quality total data set (TDS). The selection of representative and mutually independent evaluation indicators was performed through correlation analysis (Pearson) and principal component analysis (PCA) in combination with Norm values to construct a minimum data set (MDS). The principal components with eigenvalues ≥1 were extracted, and the indicators with loading values ≥0.5 in the same group of principal components were classified into a group [1,29]. If the loading value of an indicator on multiple principal components was ≥0.5, it was classified into a group with less correlation with other indicators in its principal components. If the loading value of an indicator on each principal component is <0.5, it was classified into a group of indicators with a higher loading value. The indicators within 90% of the highest loading values in each group were selected, and the correlation between the indicators was analyzed. If the correlation coefficient was >0.3, then the indicators with higher loading values were included in the minimum data set. If the correlation coefficient was <0.3, then all indicators were included in the MDS [30]. The Norm value of the evaluation indicators is calculated as follows:

$$N_{ik} = \sqrt{\sum_{i=1}^{k} u_{ik}^2 \lambda_k}$$

where N_{ik} denotes the Norm value of the ith indicator for the first kth principal components with eigenvalue ≥1, u_{ik} denotes the loading of the ith indicator for the kth principal component, and λ_k is the eigenvalue of the kth principal component.

2.3.2. Soil Quality Evaluation Methods

The soil quality index (SQI) integrates the evaluation indexes of soil physical, chemical, and other characteristics, and the higher the value, the better the cropland quality. The common factor variance obtained from the PCA reflects the degree of the contribution of an indicator to the overall variance [31]. This study used PCA to calculate the weight value of each indicator. The weights are equal to the ratio of the value of the common factor variance of each indicator to the sum of the common factor variance of all indicators [21]. Indicator scores were derived from the normalization function (Table 1). Then, the soil quality index for the total data set (SQI-TDS) and the soil quality index for the minimum data set (SQI-MDS) were calculated using the SQI formula. The calculation formula is as follows:

$$SQI = \sum_{i=1}^{k} W_i \times S_i$$

where SQI is the soil quality index, W_i is the weight of the ith soil indicator derived from the PCA, S_i is the standardized score of the ith soil indicator, and k is the number of participating indicators.

Table 1. Membership function of soil quality evaluation index.

Function Type	Indicator	Affiliation Function	Parametric Expression	Subordinate Function Meaning
Type S	CEC SOM TN TP TK AN AP AK	$u(x) = \begin{cases} 1.0,\ x \geq b \\ 0.9\left(\frac{x-a}{b-a}\right) + 0.1,\ a < x < b \\ 0.1,\ x \leq a \end{cases}$	a: minimum value; b: maximum value	Evaluation indicators are positively correlated with soil quality within a certain range
Type parabola	pH	$u(x) = \begin{cases} 1.0,\ b1 < x \leq b2 \\ 1 - 0.9\left(\frac{x-b2}{b-b2}\right),\ b2 < x \leq b \\ 0.1 + 0.9\left(\frac{x-a}{b1-a}\right),\ a < x \leq b1 \end{cases}$	a: minimum value; b: maximum value; b1: lower bound of the appropriate value; b2: upper bound of the appropriate value	Evaluate the optimal range of the indicator and soil function; the greater the deviation, the lower the impact on soil function.

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK represent cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively.

2.4. Statistical Analysis

The soil fertility index grading was developed using as a reference the Second National Soil Survey [32], and qualitative evaluation was performed based on the quantitative data of each index (Table 2). Data statistical analysis was performed in Microsoft Excel 2017 and SPSS 22.0. SPSS 22.0 software was used for normal distribution tests, ANOVA, PCA analysis, and Pearson correlation analysis. Correlation coefficient matrix heatmaps were generated using the corrplot package of R software (version 4.0.3), and ArcGIS 10.8 software was applied for spatial distribution mapping.

Table 2. Soil physical and chemical properties grading standards.

Level	pH	CEC (cmol kg^{-1})	SOM (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
I Extremely rich	>8.5	>20.0	>40	>2.0	>1.0	>25	>150	>40	>200
II Rich	7.5~8.5	15.4~20.0	30~40	1.5~2.0	0.8~1.0	20~25	120~150	20~40	150~200
III Relatively rich	6.5~7.5	10.5~15.4	20~30	1.0~1.5	0.6~0.8	15~20	90~120	10~20	100~150
IV Moderate	5.5~6.5	6.2~10.5	10~20	0.75~1.0	0.4~0.6	10~15	60~90	5~10	50~100
V Poor	4.5~5.5	<6.2	6~10	0.5~0.75	0.2~0.4	5~10	30~60	3~5	30~50
VI Extremely poor	<4.5	-	<6	<0.5	<0.2	<5	<30	<3	<30

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK denote cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively.

3. Results

3.1. Top-Tillage Soil Properties

The descriptive statistical analysis of the top-tillage soil quality characteristics (Table 3) showed that the average soil pH was 6.06, which was weakly acidic overall. The cation exchange capacity (CEC) was 31.26 cmol kg^{-1}, the organic matter (SOM) was 26.87 g kg^{-1}, total nitrogen (TN) was 2.19 g N kg^{-1}, total phosphorus (TP) was 0.86 g P kg^{-1}, total potassium (TK) was 12.58 g K kg^{-1}, available nitrogen (AN) was 151.16 mg N kg^{-1}, available phosphorus (AP) was w21.92 mg P kg^{-1}, available potassium (AK) was 176.59 mg K kg^{-1}, sand was 48.28%, silt was 23.66%, and clay was 28.07%. Only AP has a coefficient of variation more significant than 50%, meaning that it is a moderately sensitive indicator [8], and the coefficient of variation of the other indicators was less than 50%, meaning that they are low-sensitive indicators, showing that black soil is able to maintain more stable farmland productivity.

Table 3. Soil physicochemical characteristics of top-tillage layer (0–20 cm) in Jilin Province, China.

Indicator	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation (%)	Skewness	Kurtosis
pH	4.06	8.34	6.06	1.16	19.14	0.49	−1.04
CEC (cmol kg^{-1})	6.51	76.74	31.26	13.23	42.32	0.29	−0.40
SOM (g kg^{-1})	9.03	75.97	26.87	9.90	36.85	1.53	4.52
TN (g kg^{-1})	0.92	5.93	2.19	0.85	38.74	1.42	3.36
TP (g kg^{-1})	0.21	1.58	0.86	0.37	43.19	0.51	−0.83
TK (g kg^{-1})	6.54	24.20	12.58	4.82	38.30	1.05	−0.44
AN (mg kg^{-1})	51.45	403.20	151.16	59.17	39.15	1.20	1.95
AP (mg kg^{-1})	5.43	95.16	21.92	14.55	66.40	1.92	5.28
AK (mg kg^{-1})	50.00	404.00	176.59	82.30	46.60	0.85	0.02
Sand (%)	16.49	89.95	48.28	16.89	34.99	0.49	−0.48
Silt (%)	1.01	48.96	23.66	10.92	46.16	−0.17	−0.83
Clay (%)	5.04	48.94	28.07	8.71	31.04	−0.24	−0.27

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK represent cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively.

According to the distribution frequency of soil physicochemical indexes in Jilin Province and the grading standards of the Second National Soil Survey (Tables 2 and 4), the proportion of top-tillage soil pH between 5.5 and 7.5 was 35.1%. The soil in 21.6% and 43.3% of the areas was slightly alkaline and acidic, respectively. The CEC, SOM, TN, TP, AN, AP, and AK contents were mainly at the appropriate level or above. The distribution frequency was higher than 93%, and the soil had a strong fertilizer retention capacity. The distribution area with TK in a deficient state reached 40.5%. The spatial distribution results (Figure 2 and Table 5) showed that the spatial variability of top-tillage layer soil quality indicators differed significantly. The pH value decreased from West to East, and the soil nutrient indicators were higher in the central semi-moist and eastern moist areas than in the western semi-arid area. Soil sand content was high in the west, which was low in silt and clay content, while the central and eastern regions showed the opposite trend to the west, with higher silt and clay content.

Table 4. Status of physicochemical indicators of top-tillage soils in Jilin Province, China.

Level	Frequency (%)								
	pH	CEC	SOM	TN	TP	TK	AN	AP	AK
I Extremely rich	-	75.7	9.7	51.9	31.4	-	42.7	9.7	31.4
II Rich	21.6	7.6	20.6	29.2	16.2	15.7	20.5	34.1	22.2
III Relatively rich	8.1	11.9	43.8	16.2	20.5	9.2	23.8	38.9	25.9

Table 4. *Cont.*

Level	Frequency (%)								
	pH	**CEC**	**SOM**	**TN**	**TP**	**TK**	**AN**	**AP**	**AK**
IV Moderate	27.0	4.8	25.4	2.7	24.9	34.6	10.8	17.3	20.5
V Poor	37.9	-	0.5	-	7.0	40.5	2.2	-	-
VI Extremely poor	5.4	-	-	-	-	-	-	-	-

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK denote cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively.

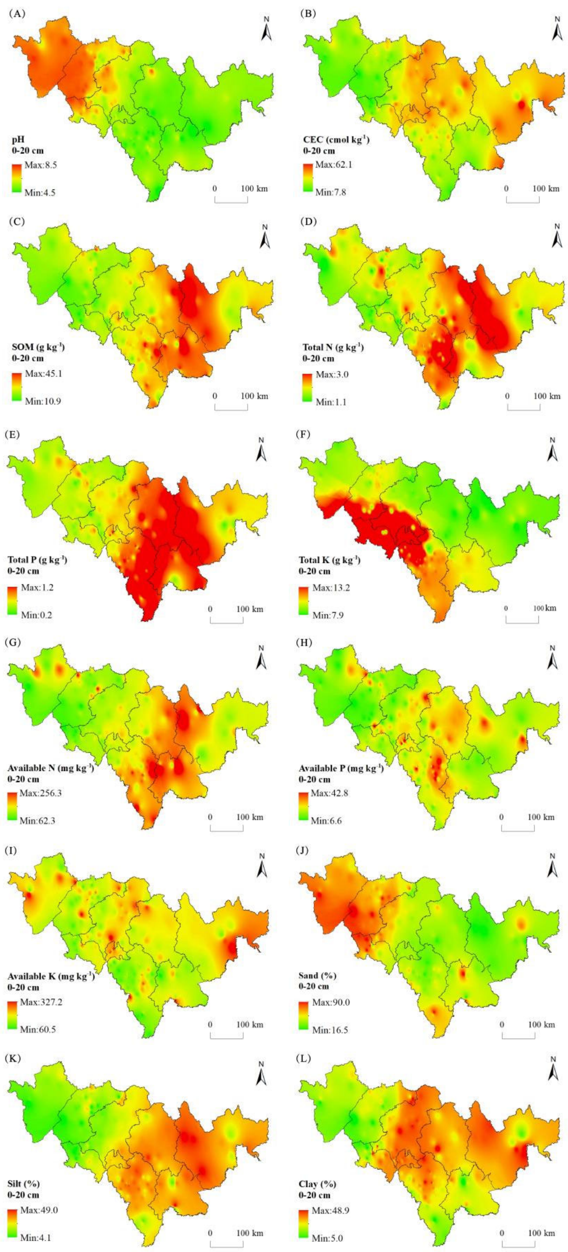

Figure 2. Spatial distribution of soil physicochemical properties of the top-tillage layer (0–20 cm) in Jilin Province, China. (**A**) pH, (**B**) cation exchange capacity, (**C**) soil organic matter, (**D**) total nitrogen, (**E**) total phosphorus, (**F**) total potassium, (**G**) available nitrogen, (**H**) available phosphorus, (**I**) available potassium, (**J**) sand, (**K**) silt, and (**L**) clay.

Table 5. Regional distribution characteristics of top-tillage soil fertility in Jilin Province, China.

Region	City	pH	CEC (cmol kg^{-1})	SOM (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	Sand (%)	Silt (%)	Clay (%)
Western	Baicheng	7.6 ± 0.7 a	21.0 ± 9.3 d	21.9 ± 4.1 d	1.8 ± 0.6 c	0.6 ± 0.2 d	9.3 ± 0.5 de	129.9 ± 68.8 cd	19.6 ± 13.6 ab	218.9 ± 116.2 ab	64.0 ± 11.8 a	14.8 ± 7.0 b	21.2 ± 5.7 d
	Songyuan	7.3 ± 1.0 a	25.1 ± 12.2 cd	22.2 ± 7.6 d	2.0 ± 0.7 bc	0.6 ± 0.2 d	10.1 ± 1.0 de	119.9 ± 53.0 d	14.9 ± 10.0 b	175.5 ± 96.3 abc	60.1 ± 16.1 ab	16.7 ± 10.6 b	23.2 ± 7.4 cd
	Average	7.3 ± 1.0 A	24.4 ± 11.8 B	22.1 ± 7 B	2.0 ± 0.7 B	0.6 ± 0.2 C	10.0 ± 1.0 B	121.7 ± 55.4 B	15.8 ± 10.7 B	183.4 ± 100.2 A	60.9 ± 15.3 A	16.3 ± 10.0 C	22.8 ± 7.1 B
Central	Changchun	6.1 ± 0.9 b	35.9 ± 12.9 ab	23.4 ± 6.8 d	1.8 ± 0.5 c	0.7 ± 0.2 cd	14.3 ± 6.0 b	129.5 ± 29.7 cd	22.0 ± 11.4 ab	197.2 ± 64.9 abc	49.2 ± 12.3 bcd	18.1 ± 6.4 b	32.8 ± 7.9 ab
	Siping	6.4 ± 1.2 b	31.1 ± 15.5 bc	22.7 ± 8.1 d	1.8 ± 0.6 c	0.7 ± 0.3 cd	19.5 ± 3.5 a	120.1 ± 37.2 d	21.5 ± 17.7 ab	181.4 ± 80.1 abc	53.4 ± 20.0 abc	18.4 ± 9.9 b	28.2 ± 10.8 abc
	Liaoyuan	5.1 ± 0.6 c	31.2 ± 10.1 bc	27.5 ± 4.4 cd	2.3 ± 0.5 bc	1.0 ± 0.3 b	13.8 ± 4.3 bc	167.2 ± 35.6 bc	24.8 ± 13.1 ab	108.7 ± 41.3 d	40.4 ± 12.1 def	31.8 ± 7.6 a	27.8 ± 5.6 abc
	Jilin	5.3 ± 0.7 c	41.4 ± 10.0 a	30.4 ± 7.1 bc	2.5 ± 0.7 ab	1.1 ± 0.3 b	9.3 ± 2.8 de	168.6 ± 38.1 abc	24.6 ± 12.6 ab	177.1 ± 51.4 abc	33.4 ± 9.4 ef	33.8 ± 6.5 a	32.9 ± 5.9 ab
	Average	5.9 ± 1.1 B	34.8 ± 13.2 A	25.3 ± 7.5 B	2.0 ± 0.6 B	0.8 ± 0.3 B	14.8 ± 5.7 A	140.7 ± 40.2 B	22.8 ± 13.9 A	174.0 ± 70.2 A	45.8 ± 16.3 B	23.6 ± 10.5 B	30.6 ± 8.5 A
Eastern	Tonghua	5.1 ± 0.6 c	27.0 ± 10.3 bcd	32.4 ± 11.4 abc	3.0 ± 1.2 a	1.3 ± 0.3 a	11.7 ± 0.5 cd	205.3 ± 58.1 ab	30.6 ± 18.2 a	162.4 ± 92.9 bcd	44.9 ± 14.7 cde	28.6 ± 8.4 a	26.5 ± 8.2 bcd
	Baishan	5.3 ± 0.9 c	27.7 ± 16.6 bcd	37.9 ± 16.9 a	2.1 ± 0.9 bc	1.1 ± 0.4 b	10.5 ± 0.7 de	208.4 ± 96.7 a	15.9 ± 7.1 b	148.9 ± 86.8 cd	45.2 ± 22.1 cde	30.7 ± 12.8 a	24.0 ± 9.8 cd
	Yanbian	5.4 ± 0.5 c	42.1 ± 16.3 a	36.0 ± 16.5 ab	2.4 ± 0.9 bc	0.9 ± 0.4 bc	8.5 ± 1.1 e	172.6 ± 82.4 ab	21.6 ± 11.8 ab	229.9 ± 82.5 a	31.1 ± 15.8 f	34.6 ± 10.0 a	34.4 ± 10.0 a
	Average	5.2 ± 0.6 C	30.6 ± 14.3 A	34.3 ± 13.7 A	2.7 ± 1.1 A	1.2 ± 0.4 A	10.8 ± 1.5 B	198.4 ± 72.0 A	25.8 ± 16.4 A	175.3 ± 92.8 A	41.8 ± 17.2 B	30.3 ± 9.8 A	27.8 ± 9.5 A
Province	Average	6.1 ± 1.2	31.3 ± 13.2	26.9 ± 9.9	2.2 ± 0.9	0.9 ± 0.4	12.6 ± 4.8	151.2 ± 59.2	21.9 ± 14.6	176.6 ± 82.3	48.3 ± 16.9	23.7 ± 10.9	28.1 ± 8.7

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK denote cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively. Different capital letters in the same column mean significant differences between regions at $p < 0.05$, and different lowercase letters mean significant differences between cities at $p < 0.05$.

3.2. Sub-Tillage Soil Properties

The average soil pH of the sub-tillage in Jilin Province was 6.36, with a range of 4.44–9.25, slightly higher than that of the top-tillage layer (Table 6). The CEC was 33.75 cmol kg^{-1}, the SOM was 19.38 g kg^{-1}, TN was 1.44 g N kg^{-1}, TP was 0.55 g P kg^{-1}, TK was 8.85 g K kg^{-1}, AN was 127.35 mg N kg^{-1}, AP was 12.53 mg P kg^{-1}, AK was 144.65 mg K kg^{-1}, sand was 40.11%, silt was 33.04%, and clay was 26.85%. The coefficients of variation for the SOM, TP, and AP were greater than 50%, meaning they are moderately sensitive indicators, and the coefficients of variation of the other indicators were less than 50%, meaning they are low sensitive indicators, indicating that the stability of soil productivity in the sub-tillage layer was weaker than that in the top-tillage layer. The sub-tillage soil fertility conservation capacity (CEC) was higher than that of the top-tillage layer, and the soil nutrient levels were significantly lower than those of the top-tillage layer. Compared with the top-tillage layer, the soil sand content of the sub-tillage layer was lower, and the silt content was higher.

Table 6. Soil physicochemical characteristics of sub-tillage layer (20–40 cm) in Jilin Province, China.

Indicator	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation (%)	Skewness	Kurtosis
pH	4.44	9.25	6.36	1.03	16.24	0.43	−0.73
CEC (cmol kg^{-1})	5.22	86.30	33.75	14.05	41.62	0.63	0.24
SOM (g kg^{-1})	3.01	55.72	19.38	10.54	54.37	1.26	2.27
TN (g kg^{-1})	0.14	3.65	1.44	0.61	42.18	0.98	1.39
TP (g kg^{-1})	0.01	1.45	0.55	0.28	51.42	0.96	0.74
TK (g kg^{-1})	5.85	16.30	8.85	2.68	30.30	0.98	−0.37
AN (mg kg^{-1})	28.70	316.40	127.35	63.45	49.83	1.01	0.64
AP (mg kg^{-1})	4.31	80.42	12.53	10.90	86.99	3.44	15.39
AK (mg kg^{-1})	36.50	407.50	144.65	71.34	49.32	1.29	2.01
Sand (%)	11.25	91.98	40.11	19.59	48.83	0.51	−0.75
Silt (%)	4.07	54.64	33.04	12.43	37.62	−0.28	−1.05
Clay (%)	2.00	55.44	26.85	8.99	33.48	−0.09	−0.10

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK represent cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively.

The proportion of sub-tillage soil pH between 5.5 and 7.5 was 55.7%, and 23.8% and 20.5% of the area soil was in a slightly alkaline and acidic state, respectively (Tables 2 and 7). The CEC, TN, AP, and AK contents were mainly at an appropriate level or above, and the distribution frequency was higher than 90%. The distribution areas where the SOM, TP, TK, and AN contents were in the deficient status amounted to 20.5%, 40.5%, 72.4%, and 15.7%, respectively. The spatial variability of soil quality indicators in the sub-tillage layer was significantly different and consistent with the spatial distribution trend of the top-tillage layer (Figure 3 and Table 8).

Table 7. Status of physicochemical indicators of sub-tillage soils in Jilin Province, China.

Level	Frequency (%)								
	pH	CEC	SOM	TN	TP	TK	AN	AP	AK
I Extremely rich	4.3	82.7	3.8	13.5	7.6	-	25.9	2.7	14.1
II Rich	19.5	9.2	7.6	25.4	8.1	-	15.7	9.7	25.4
III Relatively rich	20.6	6.5	28.6	35.7	18.4	0.6	22.7	26.5	33.5
IV Moderate	35.1	0.5	39.5	15.7	25.4	27.0	20.0	53.5	22.7

Table 7. *Cont.*

Level	Frequency (%)								
	pH	CEC	SOM	TN	TP	TK	AN	AP	AK
V Poor	20.0	1.1	14.6	9.2	32.4	72.4	14.1	7.6	4.3
VI Extremely poor	0.5	-	5.9	0.5	8.1	-	1.6	-	-

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK denote cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively.

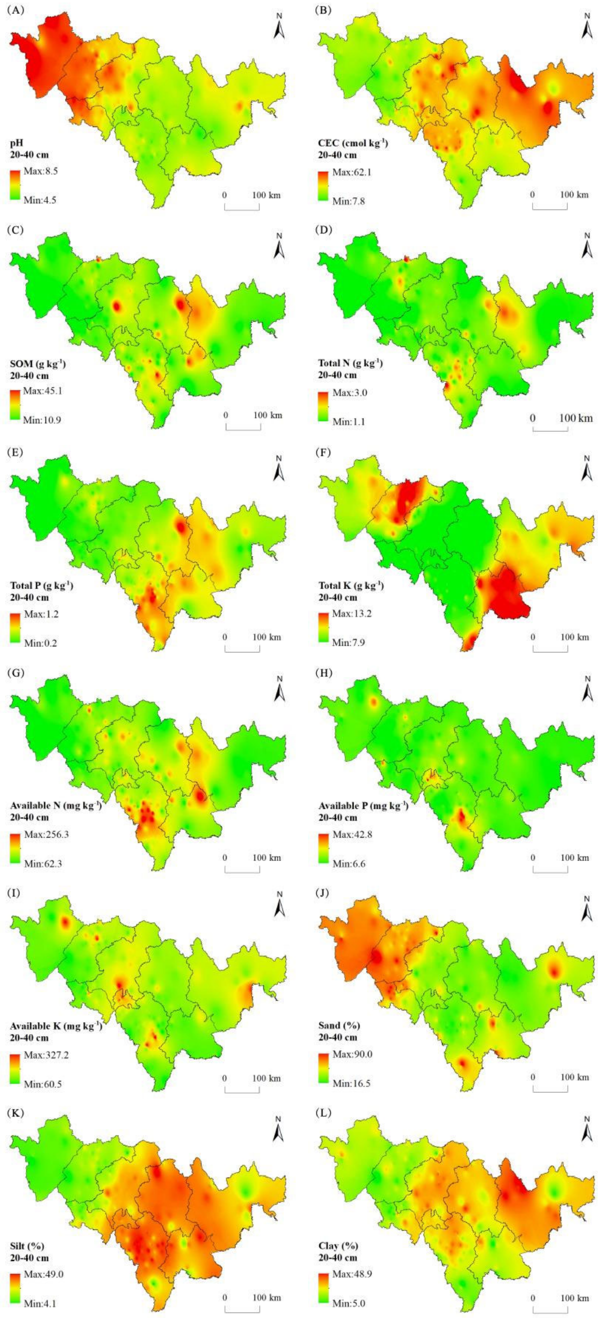

Figure 3. Spatial distribution of soil physicochemical properties of the sub-tillage layer (20–40 cm) in Jilin Province, China. (**A**) pH, (**B**) cation exchange capacity, (**C**) soil organic matter, (**D**) total nitrogen, (**E**) total phosphorus, (**F**) total potassium, (**G**) available nitrogen, (**H**) available phosphorus, (**I**) available potassium, (**J**) sand, (**K**) silt, and (**L**) clay.

Table 8. Regional distribution characteristics of sub-tillage soil fertility in Jilin Province, China.

Region	City (State)	pH	CEC (cmol kg^{-1})	SOM (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	Sand (%)	Silt (%)	Clay (%)
Western	Baicheng	8.5 ± 0.8 a	24.2 ± 8.2 d	10.8 ± 3.9 b	1.1 ± 0.3 b	0.2 ± 0.2 e	9.7 ± 1.0 c	63.2 ± 24.1 c	11.8 ± 10.8 abc	128.4 ± 85.3 abc	63.4 ± 11.0 a	13.5 ± 5.1 d	23.0 ± 7.0 de
	Songyuan	7.4 ± 0.8 b	25.3 ± 11.3 d	17.7 ± 7.9 ab	1.5 ± 0.7 ab	0.5 ± 0.2 cd	12.4 ± 1.8 b	103.4 ± 45.2 bc	10.4 ± 6.8 abc	146.1 ± 73.1 abc	59.0 ± 12.8 a	19.5 ± 6.8 d	21.4 ± 6.8 e
	Average	7.6 ± 0.9 A	25.1 ± 10.7 B	16.4 ± 7.8 B	1.5 ± 0.7 AB	0.4 ± 0.2 B	11.9 ± 2.0 A	96.1 ± 44.7 B	10.6 ± 7.6 A	142.9 ± 74.7 A	59.8 ± 12.5 A	18.4 ± 6.9 B	21.7 ± 6.8 B
Central	Changchun	6.6 ± 0.9 c	39.8 ± 15.9 bc	19.2 ± 10.0 a	1.3 ± 0.4 ab	0.4 ± 0.1 d	7.4 ± 0.6 d	118.0 ± 45.9 b	10.1 ± 5.0 abc	168.0 ± 50.2 a	39.1 ± 16.4 bc	29.9 ± 8.9 c	31.0 ± 8.5 abc
	Siping	6.8 ± 1.2 bc	31.6 ± 14.7 cd	16.2 ± 7.4 ab	1.3 ± 0.5 b	0.4 ± 0.3 cd	7.5 ± 0.6 d	104.1 ± 51.6 bc	15.6 ± 16.5 ab	155.7 ± 87.6 ab	45.1 ± 19.0 b	29.6 ± 11.4 c	25.3 ± 8.7 cde
	Liaoyuan	5.9 ± 0.4 d	42.9 ± 12.0 ab	20.2 ± 8.9 a	1.5 ± 0.5 ab	0.6 ± 0.2 bc	7.6 ± 1.0 d	139.5 ± 69.6 ab	6.8 ± 1.9.0 c	100.8 ± 29.8 bc	27.7 ± 15.2 cd	43.6 ± 9.3 a	28.7 ± 6.3 bcd
	Jilin	5.7 ± 0.5 d	40.0 ± 14.0 bc	19.6 ± 10.7 a	1.2 ± 0.5 b	0.6 ± 0.3 bc	7.2 ± 0.6 d	113.1 ± 57.5 b	10.4 ± 6.0 abc	127.9 ± 36.6 abc	25.6 ± 14.3 d	41.9 ± 8.5 a	32.5 ± 8.5 ab
	Average	6.4 ± 1.0 B	37.9 ± 15.0 A	18.5 ± 9.2 AB	1.3 ± 0.5 B	0.5 ± 0.2 B	7.4 ± 0.7 C	116.3 ± 54.7 B	11.3 ± 10.3 A	145.3 ± 63.7 A	36.3 ± 18.2 B	34.5 ± 11.4 A	29.2 ± 8.6 A
Eastern	Tonghua	5.6 ± 0.6 d	32.0 ± 11.8 cd	23.4 ± 14.3 a	1.7 ± 0.8 a	0.9 ± 0.3 a	7.9 ± 1.8 d	175.9 ± 77.9 a	18.1 ± 15.3 a	146.0 ± 92.3 abc	34.3 ± 17.9 bcd	40.0 ± 10.2 ab	25.7 ± 9.6 cde
	Baishan	5.8 ± 0.8 d	29.2 ± 6.8 d	17.2 ± 13.8 ab	1.2 ± 0.3 b	0.7 ± 0.3 ab	13.9 ± 0.6 a	134.5 ± 79.2 ab	10.3 ± 3.8 abc	98.7 ± 45.5 c	38.4 ± 23.2 bcd	36.5 ± 13.7 abc	25.1 ± 10.2 cde
	Yanbian	6.2 ± 0.8 cd	52.2 ± 18.8 a	19.5 ± 11.5 a	1.5 ± 0.7 ab	0.6 ± 0.3 bc	10.6 ± 1.2 c	98.7 ± 58.1 bc	8.0 ± 2.8 bc	172.7 ± 70.3 a	28.9 ± 18.9 cd	33.8 ± 11.0 bc	37.3 ± 11.4 a
	Average	5.7 ± 0.7 C	36.1 ± 15.6 A	21.4 ± 13.6 A	1.6 ± 0.7 A	0.8 ± 0.3 A	9.7 ± 2.7 B	150.4 ± 79.6 A	14.3 ± 12.6 A	143.3 ± 83.0 A	33.8 ± 19.0 B	37.9 ± 11.1 A	28.2 ± 11.1 A
Province	Average	6.4 ± 1.0	33.7 ± 14.0	19.4 ± 10.5	1.4 ± 0.6	0.6 ± 0.3	8.8 ± 2.7	127.3 ± 63.5	12.5 ± 10.9	144.6 ± 71.3	40.1 ± 19.6	33.0 ± 12.4	26.9 ± 9.0

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK denote cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively. Different capital letters in the same column mean significant differences between regions at $p < 0.05$, and different lowercase letters mean significant differences between cities at $p < 0.05$.

3.3. Top-Tillage Soil Minimum Data Set

The factor loadings results of the 12 soil quality indicators in the top-tillage layer after principal component analysis (PCA) showed that the eigenvalues of the four principal components were all greater than one, and the cumulative contribution rate was 76.11%, which could reflect the soil quality condition better (Table 9). The four principal components explained more than 60% of the variability of AP and silt, 70% of the variability of SOM and TN, 80% of the variability of CEC, TP, TK, and sand, and 90% of the variability of AK and clay, which indicate that the four principal components can represent the variability of most indicators.

Table 9. Top-tillage soil evaluation indexes principal component factor loadings.

Parameters	PC1	PC2	PC3	PC4	Grouping	Common Factor Variance	Weights	Norm Value
pH	−0.57	−0.38	0.12	−0.38	1	0.63	0.069	1.81
CEC	0.04	0.80	0.10	−0.10	2	0.67	0.073	1.99
SOM	0.88	−0.02	0.27	0.00	1	0.84	0.092	2.86
TN	0.77	0.13	0.18	−0.20	1	0.67	0.074	2.25
TP	0.72	0.33	−0.05	−0.22	1	0.68	0.074	2.26
TK	−0.23	−0.07	0.00	0.84	4	0.76	0.083	0.97
AN	0.79	0.14	−0.19	−0.06	1	0.69	0.075	2.38
AP	0.50	0.01	0.65	0.36	3	0.79	0.087	1.61
AK	−0.08	0.10	0.90	−0.12	3	0.84	0.092	1.21
Sand	−0.37	−0.89	0.00	−0.01	2	0.93	0.102	2.91
Silt	0.57	0.67	−0.06	−0.02	2	0.78	0.086	2.55
Clay	0.02	0.92	0.06	0.03	2	0.85	0.093	2.58
Eigenvalue (λ)	3.39	3.08	1.50	1.16				
Variance contribution (%)	28.28	25.65	12.48	9.70				
Cumulative contribution (%)	28.28	53.93	66.41	76.11				

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK represent cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively.

According to the minimum data set (MDS) selection criteria, soil quality evaluation indicators with absolute factor loadings higher than 0.5 were selected, and the criteria for entering the MDS were that the correlation coefficients between the indicators were less than 0.3. PC1 contains pH, SOM, TN, TP, AN, AP, and silt indicators, and the factors have a good correlation (Figure 4A). SOM, with the largest Norm value, was selected to enter the MDS. PC2 contains CEC, sand, and clay, with a correlation coefficient between factors > 0.6. Sand, with the largest Norm value, was selected to enter the MDS. PC3 contains AP and AK, and its correlation coefficient is 0.57. AP, with a higher Norm value, was selected to enter the MDS. TK, with absolute values of load more significant than 0.5, was chosen to enter the MDS in PC4. Finally, four indicators, SOM, sand, AP, and TK, were determined to enter the MDS.

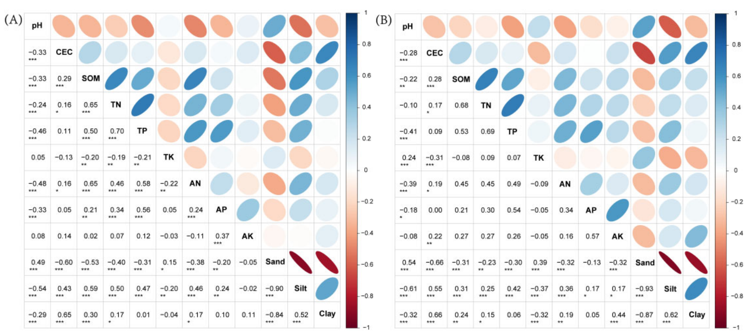

Figure 4. Pearson's correlation analysis of soil physicochemical indexes in top-tillage (**A**) and sub-tillage (**B**) soils. The CEC, SOM, TN, TP, TK, AN, AP, and AK represent cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively. *, **, and *** represent $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

3.4. Sub-Tillage Soil Minimum Data Set

The PCA analysis results of soil quality indicators in the sub-tillage layer showed that the eigenvalues of the four principal components were all greater than one, and the cumulative contribution rate was 76.84%, which could better reflect the soil quality status (Table 10). The four principal components could explain more than 60% of the variability of silt, 70% of TP, 80% of pH, CEC, SOM, AP, AK, and sand variability, and 90% of TN and clay variability. It can be seen that the four principal components can represent most of the indicator variability.

Table 10. Sub-tillage soil evaluation indexes principal component factor loadings.

Parameters	PC1	PC2	PC3	PC4	Grouping	Common Factor Variance	Weights	Norm Value
pH	−0.29	−0.12	−0.81	−0.04	3	0.76	0.083	1.42
CEC	0.82	0.18	0.00	−0.03	1	0.71	0.077	2.26
SOM	0.24	0.83	0.02	0.05	2	0.74	0.081	1.93
TN	0.07	0.91	0.01	0.13	2	0.85	0.092	2.15
TP	−0.06	0.71	0.45	0.33	2	0.82	0.089	1.82
TK	−0.48	0.22	−0.31	−0.04	1	0.37	0.040	1.03
AN	0.07	0.55	0.49	0.13	3	0.56	0.061	1.22
AP	−0.10	0.20	0.29	0.86	4	0.87	0.095	1.50
AK	0.33	0.13	−0.15	0.86	4	0.88	0.096	1.65
Sand	−0.87	−0.17	−0.38	−0.10	1	0.93	0.101	2.76
Silt	0.69	0.21	0.48	0.03	1	0.85	0.092	2.03
Clay	0.91	0.08	0.02	0.17	1	0.86	0.094	2.74
Eigenvalue (λ)	3.23	2.55	1.68	1.66				
Variance contribution (%)	26.94	21.26	14.86	13.79				
Cumulative contribution (%)	26.94	48.19	63.05	76.84				

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK represent cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively.

In each principal component analysis, the indicators included in PC1 were CEC, sand, and clay. The loading value of TK in each principal component was less than 0.5, so it was classified into the group with the highest loading value, i.e., group 1. The correlation coefficients among CEC, sand, clay, and TK were all greater than 0.3 (Figure 4B), and sand, with the highest Norm value, was selected to enter the MDS. The indicators included in PC2 were SOM, TN, TP, and AN, and there was a significant correlation among the factors, so TN, with the largest Norm value, was selected to enter the MDS. pH was selected to enter the MDS in PC3, and AK was selected to enter the MDS in PC4. Finally, four indicators, sand, TN, pH, and AK, were determined to enter the MDS.

3.5. Minimum Data Set Rationality Verification

The MDS method was used to evaluate the soil quality characteristics of the whole tillage layer, and the accuracy of the evaluation was ensured by precision verification (Table 11). The total dataset soil quality index (SQI-TDS) of the top-tillage layer ranged from 0.22 to 0.80, with an average value of 0.49 and a coefficient of variation of 20.6%. The minimum dataset soil quality index (SQI-MDS) ranged from 0.22 to 0.98, with an average value of 0.46 and a coefficient of variation of 25.5%. The SQI-TDS in the sub-tillage layer ranged from 0.22 to 0.83, with an average of 0.51 and a coefficient of variation of 19.7%, and the SQI-MDS ranged from 0.23 to 0.93, with an average of 0.55 and a coefficient of variation of 20.6%. The SQI-TDS and SQI-MDS of both the top-tillage and sub-tillage layers showed significant positive correlations (Figure 5), indicating that the selected MDS indicators could represent the TDS indicators better and that the SQI of the top-tillage and sub-tillage layers, and that calculations based on MDS could be used for the evaluation of the whole tillage soil quality in Jilin Province. To further verify the magnitude of influence of the selected indicators of soil quality, the multiple regression analysis of MDS indicators and soil quality was used to determine the standardized coefficients, which were SOM (0.58) > TK (0.53) > AP (0.33) > sand (0.31) in top-tillage soils, and sand (0.73) > pH (0.49) > AK (0.23) > TN (0.16) in sub-tillage soils.

Table 11. Common factor variance and index weights.

Soil Index	0–20 cm				20–40 cm			
	Common Factor Variance		Weights		Common Factor Variance		Weights	
	TDS	MDS	TDS	MDS	TDS	MDS	TDS	MDS
pH	0.632		0.069		0.761	0.513	0.083	0.281
CEC	0.665		0.073		0.708		0.077	
SOM	0.839	0.758	0.092	0.267	0.743		0.081	
TN	0.673		0.074		0.847	0.275	0.092	0.151
TP	0.678		0.074		0.820		0.089	
TK	0.760	0.847	0.083	0.299	0.373		0.040	
AN	0.689		0.075		0.564		0.061	
AP	0.791	0.807	0.087	0.285	0.874		0.095	
AK	0.841		0.092		0.881	0.326	0.096	0.179
Sand	0.931	0.424	0.102	0.150	0.933	0.710	0.101	0.389
Silt	0.782		0.086		0.852		0.092	
Clay	0.851		0.093		0.864		0.094	

Notes: CEC, SOM, TN, TP, TK, AN, AP, and AK represent cation exchange capacity, soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium, respectively.

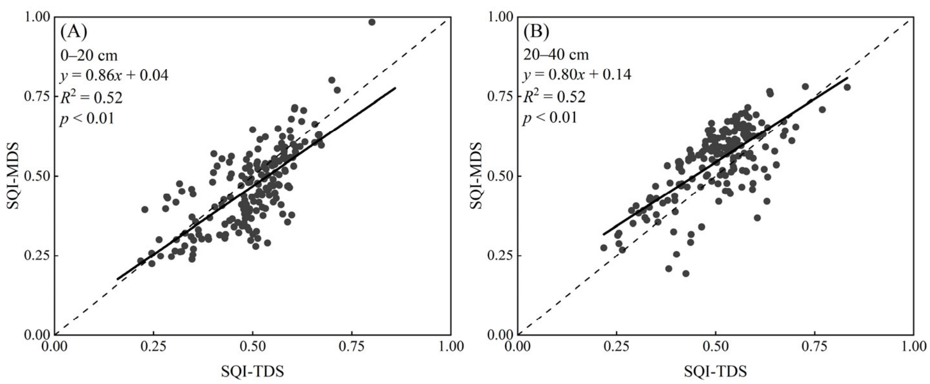

Figure 5. Linear regression analysis of soil quality index in different data sets for top-tillage (**A**) and sub-tillage (**B**) layers.

3.6. Appropriate Range of Soil Parameters for Reasonable Whole Tillage

The SQI of the top-tillage and sub-tillage layers varied in different regions (Figure 6) and was generally at the "medium and above (SQI > 0.4)" level. The SQIs of the top-tillage and sub-tillage layers were better in the central semi-humid and eastern humid regions than in the western semi-arid region. The distribution frequencies of SQI-MDS at medium and above levels in the top-tillage and sub-tillage layers were 81.7% and 87.1% in the central region, 75.0% and 89.6% in the eastern region, and 27.3% and 88.6% in the western region, respectively.

According to the corresponding relationship between the SQI and the affiliation function (Table 1), the soil is in a relatively reasonable state when the cropland quality grade is "better (SQI > 0.6)". Therefore, when SQI > 0.6, the corresponding affiliation function value is $K > 0.6$, and the appropriate range thresholds of the corresponding evaluation indexes were calculated by back-stepping based on the affiliation function u(x). The results showed that the appropriate ranges of the MDS parameters for a reasonable whole tillage layer in Jilin Province were, for the top-tillage layer, SOM $\geq$ 34.5 g kg^{-1}, 31.5% $\leq$ sand $\leq$ 53.5%, AP $\geq$ 32.1 mg kg^{-1}, TK $\geq$ 15.18 g kg^{-1}; and for the sub-tillage layer, 31.3% ≤ sand ≤ 51.2%, TN ≥ 1.48 g kg^{-1}, 6.4 ≤ pH ≤ 7.1, and AK ≥ 157.6 mg kg^{-1} (Table 12). The above appropriate ranges of soil parameters can be used as a standard for reasonable whole tillage layer diagnosis of cropland in Jilin Province.

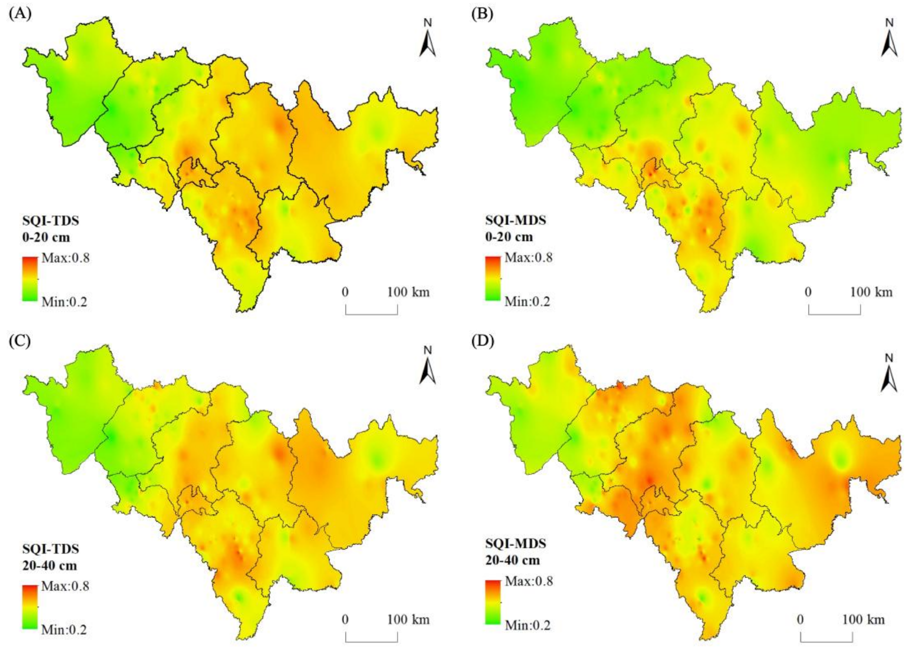

Figure 6. Spatial distribution characteristics of soil quality index in Jilin Province, China. (**A**) Top-tillage whole data set soil quality index, (**B**) top-tillage minimum data set soil quality index, (**C**) sub-tillage whole data set soil quality index, and (**D**) sub-tillage minimum data set soil quality index.

Table 12. Threshold values and appropriate ranges of MDS soil indexes in reasonable tillage.

Soil Layer	Index	Membership Function Type	Membership Function	Threshold	Appropriate Range
Top-tillage	SOM (g kg^{-1})	Type S	u(x) = 0.1029 + 0.0144x	34.5	≥34.5
	Sand (%)	Type parabola	u(x) = −0.074 + 0.034x − 0.0004x^2	31.5–53.5	31.5–53.5
	AP (mg kg^{-1})	Type S	u(x) = 0.2118 − 0.0121x	32.1	≥32.1
	TK (g kg^{-1})	Type S	u(x) = 0.0898 + 0.0336x	15.18	≥15.18
Sub-tillage	Sand (%)	Type parabola	u(x) = 0.2793 + 0.0165x − 0.0002x^2	31.3–51.2	31.3–51.2
	TN (g kg^{-1})	Type S	u(x) = 0.1957 + 0.2724x	1.48	≥1.48
	pH	Type parabola	u(x) = −1.4574 + 0.6116x − 0.0453x^2	6.4–7.1	6.4–7.1
	AK (mg kg^{-1})	Type S	u(x) = 0.2375 + 0.0023x	157.6	≥157.6

Notes: SOM, TN, TK, AP, and AK represent soil organic matter, total nitrogen, total potassium, available phosphorus, and available potassium, respectively.

4. Discussion

4.1. Soil Fertility Characteristics of the Whole Tillage Layer in Jilin Province

Combining the soil factor properties of the top-tillage and sub-tillage layers in Jilin Province, the whole tillage soil pH increased in acidification compared with the Second National Soil Survey [32], and the top-tillage soil pH decreased by an average of 0.34 compared with that in 2018 [33]. Top-tillage soil was severely acidified by fertilization and crop root secretions [34], while sub-tillage pH changed less, and soil pH was more suitable for crop root growth. The top-tillage soil organic matter (SOM) and total and available nutrient contents were relatively rich, and there was a significant enhancement in soil nutrient status compared with 2005–2010, which was related to the increasing input of chemical and organic fertilizers in agriculture in recent years [35]. Tillage and land preparation disturbed the soil shallowly, as the upper layer of the soil profile was enriched in nutrients due to fertilizer application and crop root uptake, and soil nutrient content decreased with increasing soil depth [36].

The nutrient status of cropland soils in Jilin Province has obvious regional characteristics. Farmland soils in the western semi-arid plains area have high sand content; annual precipitation is lower than evapotranspiration, soil types are dominated by black calcareous soils and sandy soils, and with the increase of sand, the SOM content decreases [37]. Meanwhile, the gradual increase in calcium carbonate content in the soil caused a significant increase in pH. It led to a decrease in available phosphorus (AP) content through calcium phosphate salt adsorption [38]. The central semi-humid plains are mostly loamy, with black soil and black calcium soil as the main soil types, and the soil is neutral with high nutrient content, with climatic and geographic characteristics intermediate between the west and the east. In contrast, the eastern humid mountainous soils are mostly clay soils, and the soil types are dominated by dark brown loam and white slurry soils. The forest vegetation cover in this region is high, and the cultivation time is short, so the farmland soils are weakly acidic and have high nutrient content [35]. As a result, soil pH in Jilin Province showed a decreasing distribution from West to East [39], and the soil SOM, AP, and other nutrient contents showed an increasing distribution from West to East [37].

4.2. Soil Quality Evaluation of the Whole Tillage in Jilin Province

In this study, the whole tillage soil in the maize continuous cropping area of Jilin Province was taken as the research object, and a whole tillage quality evaluation index system was constructed using 12 soil physical and chemical characteristics indexes. The applicability of the minimum data set (MDS) method in soil quality evaluation of this study area was verified by comparing it to the total data set (TDS) [1,29,30]. The top-tillage soil indicators screening by the MDS method included the SOM, sand, AP, and total potassium (TK) content. In contrast, the indicators of the sub-tillage layer included sand, total nitrogen (TN), pH, and available potassium (AK) content, and the sieve filtration of the indicators was more than 50%. The selected indicators were consistent with the results of most domestic and international studies [3,8,15,16,23,24,29,40], which confirmed that SOM was a key indicator of soil health [41]. Organic carbon promotes higher microbial volume and activity, and microbial-mediated pathways, as the core of soil nutrient cycling, further improve soil nitrogen and phosphorus availability through the regulation of key enzyme activities and carbon, nitrogen, and phosphorus stoichiometric ratios [42]. Increased soil SOM, AP, TK, and AK content positively affect crop yield [43]. Whereas sand influences soil moisture content and limits soil nutrient transport, soil pH explains more than 50% of the variation in soil multifunctionality and influences the adsorption and desorption of soil nutrient elements (especially phosphorus), and appropriate sand and pH indirectly contribute to crop yield and soil health [44,45]. This showed that both TDS and MDS evaluation index systems were well represented in this study. The significant correlation between TDS and MDS soil quality index (SQI) further indicated that MDS could be a better alternative to the TDS indicators for evaluating the SQI of the whole tillage layer in Jilin Province.

The SQI of the top-tillage layer in Jilin Province calculated based on MDS in this study ranged from 0.22 to 0.98, with a mean value of 0.46, which was slightly lower than the 0.54 evaluated by Mei Nan et al. [8] for the soil quality of the black soil top-tillage layer in Jilin Province in 2018. This was attributed to the fact that black soil has high fertility characteristics, while the maize planting area in Jilin Province contains a variety of soil types such as black calcareous soil, dark brown loam, and white slurry soil at the same time, resulting in SQI differences. There were differences in SQI among different soil layers, with the sub-tillage layer SQI (0.55) being better than the top-tillage layer. The longer the duration of continuous cropping, the lower the SQI. Long-term continuous cropping leads to continuous cropping disorders and mainly occurs in the top-tillage layer, resulting in soil nutrient imbalance and quality degradation. In addition, the SQI of the sub-tillage layer consists of sub-tillage MDS, which has different compositional indicators than the top-tillage layer, and the relatively suitable pH in the sub-tillage MDS may be responsible for the increased SQI.

Different regions in Jilin Province have obvious differences in soil quality characteristics, and the SQI of the whole tillage is generally at a moderate level. It shows an increasing trend from West to East, which is consistent with the spatial distribution characteristics of the evaluation indexes such as the SOM, AP, TK, TN, and AK, which are high in the East and low in the West [8]. Most of the unhealthy areas were located in the west of Jilin Province (Figure 6), which serves as a major contributor to maize production in Jilin Province, with a high intensity of continuous cropping. The ecological environment was fragile, especially with inadequate agricultural hydrology conditions, severe wind erosion and salinization of soils, as well as reduced soil water and fertilizer retention capacity. The MDS index thresholds for reasonable tillage layers in Jilin Province were explored, with SOM $\geq$ 34.5 g/kg, 31.5% $\leq$ sand $\leq$ 53.5%, AP $\geq$ 32.1 mg/kg, TK $\geq$ 15.18 g/kg in the top-tillage layer, and 31.3% $\leq$ sand $\leq$ 51.2%, TN $\geq$ 1.48 g/kg, 6.4 $\leq$ pH $\leq$ 7.1, AK $\geq$ 157.6 mg/kg in the sub-tillage layer. Among them, the soil SOM, AP, and TN contents were consistent with the research results of the northeast dryland area [46]. The soil SOM content threshold was much higher than that of the southern dryland area, which was mainly due to the high background value of soil SOM in the study area. The unique climatic conditions also promoted the accumulation of soil SOM in the region [29]. Nutrient content is the main limiting factor in the threshold indicators for top-tillage soils, and long-term high-intensity utilization of regional soils has led to soil fertility degradation and reduced SOM content [4]. Reduced microbial phosphorus turnover caused by carbon limitation has led to limited phosphorus effectiveness enhancement [47]. Most of the soil conditions in the study area did not reach the threshold range, and there is a long way to go to improve soil quality. The dominant endogenous cause of black soil degradation is emphasized in the black soil conservation policy issued in China as a decrease in organic matter [3,4]. Anthropogenic soil management (organic matter returned with tillage practices) plays a vital role in increasing soil organic carbon and available nutrient content [48]. Also, the large amount of organic matter resources (straw and manure) in the Northeast offers the possibility of improving the top-tillage soil quality [49]. Fertilizer use of straw allows straw resource management, optimizes soil structure, and regulates soil pH. Meanwhile, straw returned to the field brings in a variety of elements, and the stimulating effect of exogenous carbon makes a great contribution to nutrient activation. Conservation tillage (no-tillage with straw mulching) measures were applied in the western region of Jilin Province to protect the black soil by reducing wind erosion, improving soil fertility, increasing crop yields, and lowering operating costs [5]. The deep soil structure and pH in the central and eastern regions limit the sub-tillage soil quality. Straw deep plowing can improve the nutrient content of the sub-tillage soil and alleviate the soil acidification problem [25]. Compared with traditional rotary tillage, increasing the tillage depth can break the plow subsoil layer, increase water storage and water supply capacity, and create a better growing environment for the crop root system [50], improving crop yields.

In summary, the SQI and evaluation indicators of the top-tillage and sub-tillage layers in different ecological zones are varied, and the evaluation indicator thresholds need to be adjusted in combination with the actual conditions to establish a more accurate system of evaluation indicators for soil quality in the whole tillage layer. In this study, data from 185 sites were collected, and 12 physical and chemical indicators were utilized to assess the soil quality status in Jilin Province. Soil biological indicators, crop yields, seasonal or climatic changes, and socio-economic factors were not taken into account. Thus, it is necessary to further refine and optimize the evaluation system in future extensive research and future extension to the practice of implementing sustainable development in black soil.

5. Conclusions

This study comprehensively analyzed the soil physical and chemical indicators of the top-tillage and sub-tillage soils in the maize continuous cropping area of Jilin Province, constructed a whole tillage soil quality index evaluation system based on the minimum data set (MDS), evaluated the soil quality, and explored the suitability of reasonable tillage indicators.

The results showed that the top-tillage and sub-tillage soil pH in Jilin Province were 6.06 and 6.36, respectively. The physicochemical indicators were overall in the moderate and above grade. The inter-regional performance showed that pH decreased and nutrient content increased from West to East.

The SQI-MDS of the top-tillage layer and the sub-tillage layer were 0.46 and 0.55, respectively, which were overall at a moderate level and showed an increasing trend from West to East among regions. The appropriate ranges of MDS parameters for reasonable tillage layer in Jilin Province were as follows: SOM $\geq$ 34.5 g/kg, 31.5% $\leq$ sand $\leq$ 53.5%, AP $\geq$ 32.1 mg/kg, TK $\geq$ 15.18 g/kg for the top-tillage layer, and 31.3% $\leq$ sand $\leq$ 51.2%, TN $\geq$ 1.48 g/kg, 6.4 $\leq$ pH $\leq$ 7.1, AK $\geq$ 157.6 mg/kg for the sub-tillage layer. To achieve reasonable tillage layer construction, it is necessary to take targeted fertilization and tillage measures for the above indicators. Straw return measures, together with deep plowing, are effective measures to improve soil structure and optimize soil nutrient reservoirs, and optimizing field management is an important way to perform black soil protection and sustainable agricultural development.

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