

Article

Associations of Land Use and Conservation Measures with Soil Organic Carbon in Small Watersheds of the Black Soil Region of Northeast China

Xiaotong Zheng ¹, Mark Henderson ², Zhengqing Zhu ¹, Jiaqi Zhang ¹, Shang Li ¹, Changlin Zhang ¹,
Tiantian Ren ¹ and Binhui Liu ^{1,*}

¹ College of Forestry, The Northeast Forestry University, Harbin 150040, China; zhengxt@nefu.edu.cn (X.Z.); 229@nefu.edu.cn (Z.Z.); z1234516668@nefu.edu.cn (J.Z.); 1455291368@nefu.edu.cn (S.L.); 2024120142@nefu.edu.cn (C.Z.); rtt@nefu.edu.cn (T.R.)

² Mills College, Northeastern University, Oakland, CA 94613, USA; ma.henderson@northeastern.edu

* Correspondence: binhui@nefu.edu.cn; Tel.: +86-131-0088-1689

Abstract

Soil organic carbon (SOC) is a critical indicator for soil fertility and ecosystem stability, yet its spatial distribution in slope croplands remains poorly understood at the small watershed scale. This study compared SOC content and its associated factors in two small watersheds in the hilly black soil region of Northeast China that share similar topographic and climatic conditions but differ in the adoption of slope cropland conservation measures. Surface soil samples (0–20 cm) were collected across both watersheds using a 400 m × 400 m grid, and a random forest model was used to identify the association of each factor with SOC content. The SOC content in forests was higher than that in cropland. The SOC content in cropland with soil and water conservation measures was 51.84% higher than that in cropland without such measures. SOC tended to be lower on steeper slopes. For slopes of 5–8°, cropland with conservation measures had SOC 76.98% higher than cropland without measures. Random forest analysis showed that the relative importance of SOC predictors varied among different management types. The contribution of total nitrogen (TN) and slope was higher on cropland without conservation measures, while the importance of soil pH and slope was relatively higher in cropland with measures. These findings suggest avenues for research to optimize conservation measures to improve soil quality in black soil regions.

Keywords: black soil; small watersheds; soil erosion; soil and water conservation measures; soil organic carbon; land use



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1. Introduction

Population growth and declining arable land resources pose serious challenges to global food security, especially in the context of climate change. Efforts to improve cropland quality, agricultural ecosystem stability, and crop production resilience are important to ensuring national food security and reducing risks to the global food system [1]. Soil organic carbon (SOC), an essential measure of soil fertility and soil quality, serves as an important part of the carbon cycle of terrestrial ecosystems [2]. SOC plays a key role in stabilizing soil structure, improving the retention of water and nutrients, and enhancing erosion resistance [3]. The accumulation and loss of SOC are regulated by land use, topographic conditions, and soil erosion processes [4]. In particular, erosion directly leads

to the migration and loss of organic carbon, destroys the structure of soil aggregates, and accelerates its mineralization and decomposition [5]. Compared with other ecosystems, cropland is repeatedly affected by disturbances from long-term tillage, water erosion, and crop growth, and thus it displays more complicated surface SOC migration and redistribution processes [6].

To date, many studies of the ecological benefits of soil and water conservation measures have been focused on a single land use type [7] and at the scale of individual slopes or fields. SOC in slope croplands undergoes varying degrees of loss under different intensities of soil erosion. Accelerated decomposition of soil organic matter driven by high-emission climates further exacerbates substantial regional SOC depletion [8]. Increasing terrain gradient and topographic fragmentation intensify soil erosion on slope croplands; the transport of soil mass directly removes topsoil SOC and results in net SOC loss [9]. Conversion of forest to slope croplands degrades soil aggregate structure. Coupled with erosion-induced continuous depletion of organic carbon and nitrogen, bound in aggregates of different particle sizes, this process ultimately triggers severe SOC loss [10].

In northeast China, soil erosion is thought to be a major threat to soil stability on low hills and mountains, especially for slope cropland [11]. Given the obvious spatial heterogeneity of soil erosion and its impact on SOC, research is needed at a spatial scale that can comprehensively reflect the interaction of topography, land use, and hydrological processes. Small watersheds can integrate a variety of land use types and topographic conditions, making this the most appropriate scale to reflect the spatial patterns of soil erosion and SOC change [12]. For example, land use and soil and water conservation measures have been shown to be the main drivers of SOC storage in small watersheds in Mexico [13]. In a small watershed study in the Argentine Pampas region, slopes and sedimentation were found to affect the distribution of soil water content (SWC) and SOC [14]. Previous studies have shown that different land uses have different associations with soil characteristics within small watersheds; slope position also significantly affects erosion intensity and, thus, the spatial heterogeneity of soil properties [15,16].

Black soil is one of the most important soil resources in the world. Although it only accounts for about one-sixth of the global cropland area, it stores about 30% of the carbon in cropland soils and is valued for its high organic matter content and productivity [17]. In addition to Northeast China, black soil is widely distributed in Ukraine and Russia [18] and the humus soil region of the Great Plains of the central United States, all high-fertility farming areas of global significance [19]. The black soil region in Northeast China, covering about 1.09 million km², is an important commodity grain production area that is key to China's food security [20]. 86% of the cropland in the black soil region of Northeast China is slope cropland with slope >0.5°, characterized by gentle, long slopes and large catchment areas [21].

In recent years, soil and water conservation measures such as terrace construction and ridge planting have been widely used in the black soil region of Northeast China. In one small watershed in that region, a study of SOC change between two dates (2005 and 2016) found that engineering and agronomy practices have contributed to alleviating slope erosion, improving soil structure over time, and promoting SOC content [22]. However, it is unclear how soil and water conservation measures are associated with the spatial distribution of soil organic carbon under different topographic conditions. Different environmental factors may drive the variation in soil organic carbon in different land uses. In response, we propose the following research questions:

- (1) Comparing two small watersheds of low mountains and hills in the black soil region of Northeast China with similar topography and climate, is the implementation

of conservation measures associated with significant differences in soil organic carbon content?

- (2) How are land use and slope related to the spatial differentiation of soil organic carbon within these small watersheds?

2. Materials and Methods

2.1. Overview of the Study Area

The experimental site is located in Dongliao County, Liaoyuan City, Jilin Province in Northeast China. It occupies a transition zone between the Changbai Mountains and the Songliao Plain (42°37'09"~43°13'44" N, 124°50'17"~125°30'41" E), with topography consisting of low mountains and hilly landforms (Figure 1). The area has a semi-humid temperate monsoon climate zone with four distinct seasons; the annual average temperature is 5.2 °C, and the annual total sunshine duration is 2497.9 h. The average annual precipitation is 658.1 mm, mainly concentrated in summer. Erosive rainfall (defined as daily rainfall ≥ 12 mm [23]) from April to September accounts for 77.44% of the total annual rainfall, accounting for most of the region's soil erosion and surface runoff (Figure 2). The soil is predominantly degraded black soil, classified as Phaeozems according to the World Reference Base (WRB) and Mollisols under the U.S. Soil Taxonomy (USST) [24,25]. The topsoil texture is predominantly clay loam or loam, with quartz and feldspar as the primary minerals, and montmorillonite and illite as the dominant secondary minerals. More than 90% of the cropland is on slopes greater than 5°, and the average annual soil erosion modulus is as high as 2085 t/km²·a [26]. Non-crop vegetation coverage in the area includes natural secondary forests (*Quercus mongolica*, *Juglans mandshurica* Maxim), plantation forests (*Pinus koraiensis*, *Larix gmelinii*), and herbs (*Poaceae*, *Carex tristachya* Thunb).

Within the study area, two small watersheds were selected for comparison. The Shuangfu small watershed, geographical location 43°02'50"~43°04'51" N, 125°13'55"~125°16'31" E, covers 686.12 ha. About 10 km away, the Xingmu small watershed, geographical location 42°59'42"~43°01'16" N, 125°23'35"~125°26'04" E, encompasses 584.10 ha. The study area is a traditional agricultural region. The land use type is mainly cropland, with forests on some steep slopes. Cropland is planted with corn (maize) or a corn-soybean rotation with contour ridge tillage. Fertilizers applied include N (210 kg·ha⁻¹), P₂O₅ (90 kg·ha⁻¹), and K₂O (90 kg·ha⁻¹). The tillage methods and fertilization practices have been consistent between the two watersheds for many years.

While the two small watersheds share similar climates and soil-forming environments, they display different proportions of land uses and rates of adoption of conservation measures. There is more cropland in Shuangfu and more forest land in Xingmu. Conservation measures, typically on slopes in the range of 5–8°, have been implemented more in Shuangfu (Table 1). Terraces and ridge plant belts were constructed on about 66.30 hectares of Shuangfu's slope cropland around 2014.

Table 1. Number of samples by land use and conservation measures. Value in parentheses is the number of sample sites with soil and water conservation measures.

Watershed	Land Use	Slope	Sample Sites	Area (ha)	Percentage in Watershed
Shuangfu	Cropland	0~5°	17	448.31	65.34
		5~8°	8 (6)		
		8~15°	5		
	Forest		13	155.61	22.68
	Other		-		11.98

Table 1. Cont.

Watershed	Land Use	Slope	Sample Sites	Area (ha)	Percentage in Watershed
Xingmu	Cropland	0~5°	13	362.32	62.03
		5~8°	6 (2)		
		8~15°	5		
	Forest		13	185.04	31.68
	Other		-		6.29

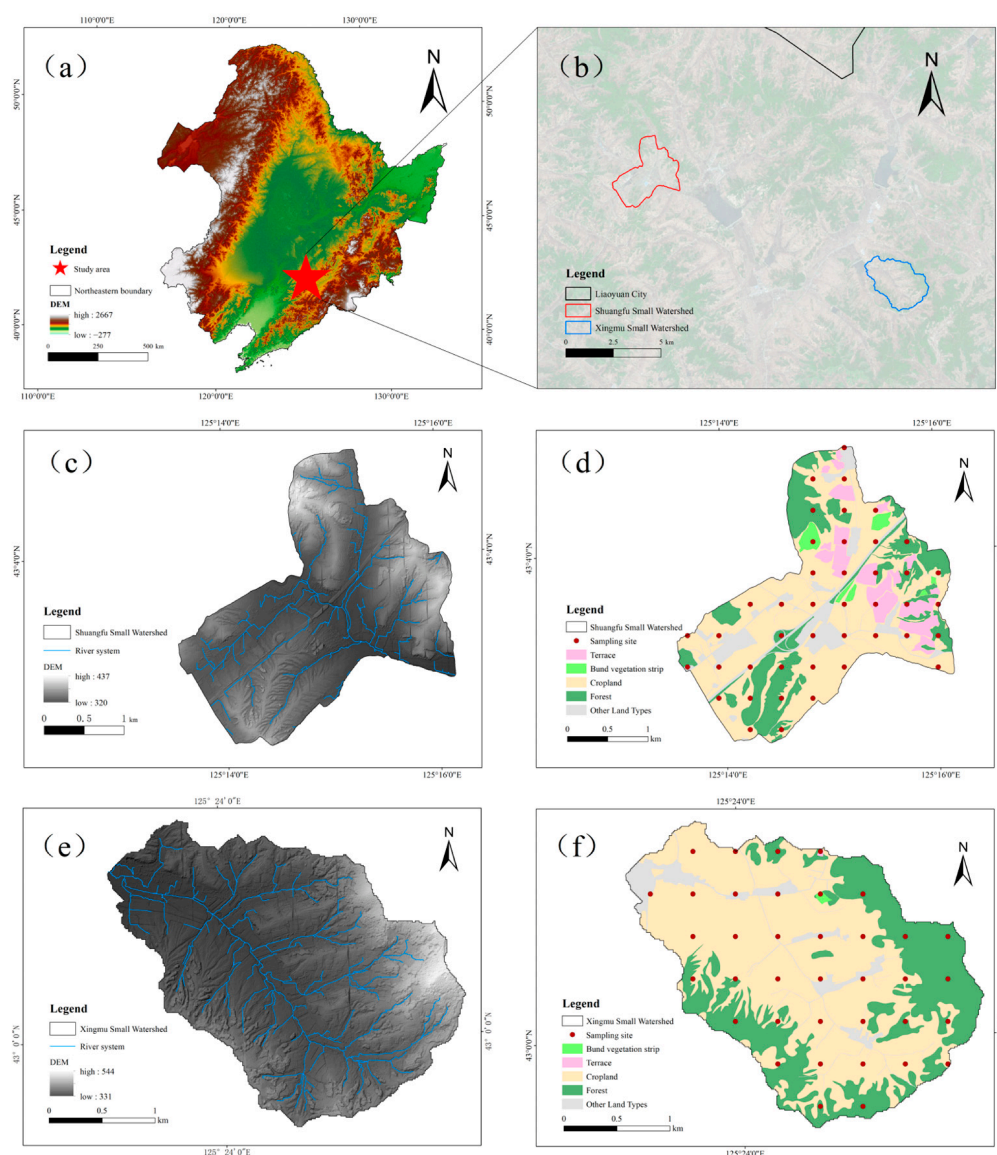


Figure 1. Shuangfu and Xingmu small watersheds in the context of (a) Northeast China and (b) Liaoyuan City; (c,e) terrain and hydrography; (d,f) land uses and sampling sites.

Both watersheds are generally oriented westward. The overall topography of Shuangfu is higher in the north and east, and relatively flat in the middle and south (Figure 1c). Slopes range from 0.43° to 11.31° , and elevations span 320 m to 437 m. The stream network forms a dendritic drainage pattern along the lower slope areas. In contrast, Xingmu generally descends from the east and south, with the stream network draining toward the northwest (Figure 1e). Slopes range from 0.18° to 14.89° , and elevations span 331 to 544 m.

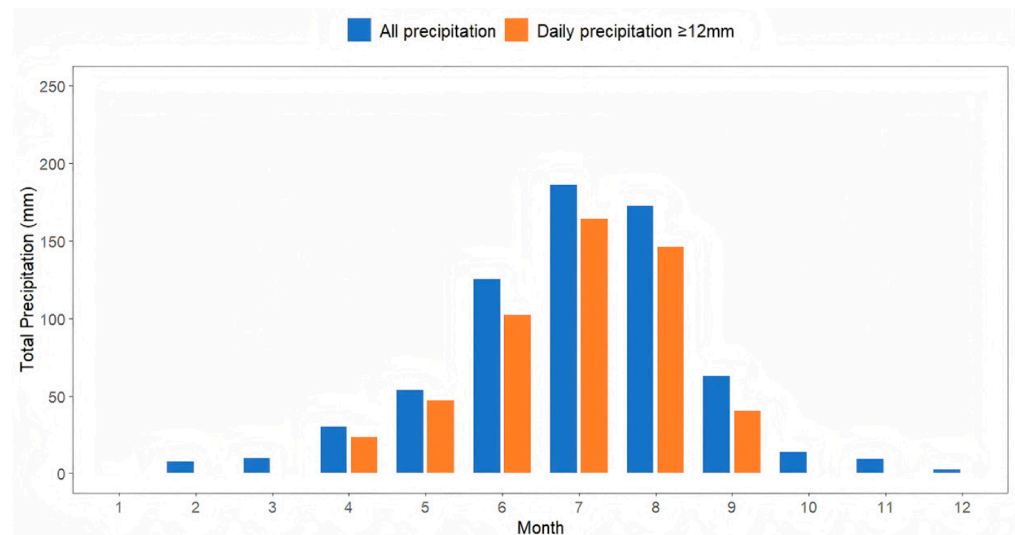


Figure 2. Ten-year average monthly total precipitation and monthly precipitation recorded on heavy rainfall days (12 mm). Data from Xingmu Small Watershed Water Erosion Observation Station, Dongliao County, Jilin Province (2015–2025).

2.2. Research Design and Sampling

Following the paradigm of comparing paired small watersheds as described in prior studies [27,28], this study selected two small watersheds (Shuangfu and Xingmu) for fixed-point observation and analysis. Soil sampling was conducted in October 2025, prior to crop harvest, to avoid soil disturbance. Sampling points were set at a 400×400 m grid interval [22,29] covering all major land use types in the watersheds. For this study, 37 sampling points were established in Xingmu and 43 in Shuangfu.

In the field, each site was located by GPS (± 0.05 m), and three parallel soil samples from the topsoil (0–20 cm) were taken within about 2 m of each site. In some cases, when sampling sites fell near topographic obstructions or less than 5 m from land-use transitions, the location was adjusted in the field to avoid edge effects. In each watershed, sampling points covered all land use types and slope combinations. The land-use type (mainly forest, cropland with conservation measures, or cropland without measures) and the slope at each sampling point were recorded synchronously. All soil samples were packed in polyethylene bags and stored at low temperature. After being transported to the laboratory, the samples were screened with a 2-mm sieve and divided into two parts: one was refrigerated at -20 °C, and the other was air-dried and passed through 2-mm and 0.149-mm soil sieves in turn. The three soil samples taken at each site were fully mixed to prepare a composite sample. Three replicate measurements were made of the composite sample, and the average values of the three replicate measurements were used for subsequent analysis.

High-resolution Digital Elevation Models (DEMs) with 0.5-m resolution were generated using UAV-based LiDAR scanning (DJI Innovations, Shenzhen, China). A DJI Matrice 300 real-time kinematic (RTK) platform equipped with a Zenmuse L1 LiDAR system was used to conduct aerial surveys over each catchment. Flights were conducted at an altitude of approximately 80–100 m above ground level with forward and side overlaps of 50–70% to ensure full coverage. The LiDAR data were processed using DJI Terra 4.5.0 to produce DEMs used for terrain analysis and catchment delineation and Digital Orthophoto Mapping (DOM, 0.05 m) of land use by visual interpretation.

2.3. Indicator Determination

Soil water content (SWC) was determined using the oven-drying method [30]. Briefly, approximately 30 g of fresh soil was weighed into an aluminum box, followed by oven drying at 100–105 °C for over 24 h. The boxes were then covered immediately after removal from the oven, cooled to room temperature, and reweighed.

Bulk density (BD) was determined by the ring knife method [31]. A 100 cm³ undisturbed soil core was collected using a 100 cm³ ring knife and oven-dried at 105 °C for 6–8 h, and the dry mass was subsequently weighed and recorded.

The mechanical composition of the soil (sand, silt, clay) was determined by the pipette method [32].

The mean weight diameter (MWD) of soil aggregates was measured by wet sieving method [32]. Balances, ovens, and sieves were routinely calibrated; pre-weighed constant aluminum boxes eliminated container blanks. Duplicate subsamples served as internal controls without certified aggregate standards. Masses of stones and plant debris were subtracted, and a water blank was run for impurity correction. Soil aggregates were wet-sieved into >2, 1~2, 0.5~1, 0.25~0.5 and 0.053~0.25 mm fractions. MWD was calculated as:

$$\text{MWD} = \sum_{i=1}^n R_i W_i$$

where R_i is the average diameter of the grain size of i -grade aggregates, and W_i is the mass percentage of i -grade aggregates.

Soil inorganic carbon was removed by hydrochloric acid fumigation. SOC was measured on treated soil. TN was measured on untreated soil. The soil samples were placed in a desiccator and fumigated with hydrochloric acid at a concentration of 1 mol/L. After fully removing inorganic carbon, the samples were dried to a constant weight at 60 °C, and then the carbon content was determined using an elemental analyzer (NCT ECS4024, Costech, Milan, Italy). Soil pH was measured using a pH meter with a water-to-soil ratio of 2.5:1 [33].

2.4. Data Analysis

All analyses were conducted using SPSS 25.0, ArcMap 10.8.1, and R 4.5.1 software. The Shapiro–Wilk method was used to test the normality of the data. Subsequently, one-way and multi-way ANOVAs were employed to analyze the variability among multiple groups for each indicator, while independent-samples t -tests were used to compare the variability between two groups for each indicator. Box plots were generated using the ggplot2 package to visualize the median, interquartile range, dispersion, and outliers of each soil property across the three land-use types. Pairwise inter-watershed comparisons across slope and management groups were performed using the independent samples t -test for normally distributed data and the Mann–Whitney U test for non-normal data. A Bonferroni correction was used for multiple-comparison adjustment.

Ordinary kriging interpolation was used to predict and visualize the spatial distribution of SOC. The interpolation was performed with the Geostatistical Analyst extension of ArcMap under GCS_WGS_1984. A Power variogram model was fitted with a circular searching neighborhood (10–15 neighbors, radius = 0.012). The prediction grid and uncertainty standard error grid were exported. Leave-one-out cross-validation gave ME = 0.1281, RMSE = 8.1397, ASE = 8.0559, RMSS = 1.0100. A standard-error raster represented prediction uncertainty.

Considering the overestimation risk caused by spatial autocorrelation, block-based spatial cross-validation was further implemented, and a set of complementary indicators (spatial CV- R^2 , RMSE, MAE, and NSE) was combined to comprehensively evaluate model performance. The ‘randomForest’ package was used to perform random forest analysis (ntree = 500, nrep = 1000) for relative importance ranking. All models were set with a

fixed random seed of 123; default untuned hyperparameters ($mtry = 2$, $node\ size = 5$) were applied, and 1000 permutation iterations were conducted to quantify the uncertainty of variable importance. Before random forest modeling, the variance inflation factor (VIF) was used to test the collinearity between predictors to reduce potential redundancy.

3. Results

3.1. Spatial Distribution of SOC

The highest values of SOC in the Shuangfu and Xingmu small watersheds were found in forestland and cropland with conservation measures (Figure 3). Overall, the two small watersheds displayed similar amounts of surface SOC (Figure 4). The average content of SOC in Shuangfu was only slightly and nonsignificantly ($p > 0.05$) higher than that in Xingmu: $19.04\text{ g}\cdot\text{kg}^{-1}$ compared with $18.85\text{ g}\cdot\text{kg}^{-1}$ —a difference of $0.19\text{ g}\cdot\text{kg}^{-1}$. Comparing forest lands, there was no significant difference in soil SOC between Shuangfu ($27.97\text{ g}\cdot\text{kg}^{-1}$) and Xingmu ($27.86\text{ g}\cdot\text{kg}^{-1}$). In both watersheds, the SOC content of cropland was significantly lower than that of forest land: cropland SOC was $15.16\text{ g}\cdot\text{kg}^{-1}$ in Shuangfu and $13.89\text{ g}\cdot\text{kg}^{-1}$ in Xingmu, so the SOC of forest land in those watersheds was, respectively, 84.50% and 100.58% higher than that of slope cropland.

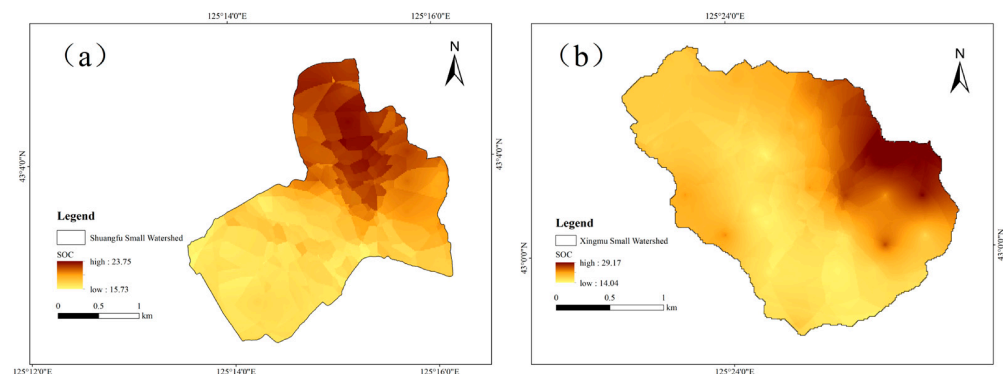


Figure 3. SOC distribution in different small watersheds: (a) Shuangfu, (b) Xingmu.

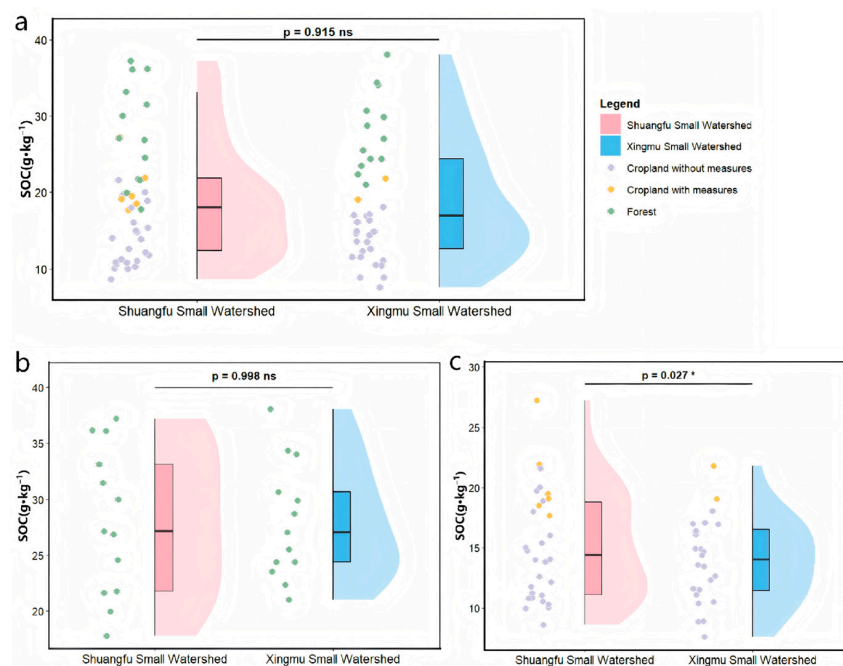


Figure 4. Differences in soil organic carbon (SOC) content between Shuangfu and Xingmu small watersheds. (a) all land cover types. (b) forest. (c) cropland with and without conservation measures. * $p < 0.05$, ns = not significant.

SOC in cropland with conservation measures was associated with a 51.84% higher level of SOC compared with that of cropland without measures. As more of the slope cropland in Shuangfu had soil and water conservation measures, the SOC content of Shuangfu cropland was 9.07% higher than that in Xingmu, $p < 0.05$ (Figure 4).

3.2. Cropland SOC Content by Slope and Soil and Water Conservation Measures

On cropland without conservation measures, lower SOC content was associated with steeper slopes, especially above about 5° (Figure 5). The Shuangfu small watershed has a higher rate of implementation of soil and water conservation measures, such as terraces and ridge-belt planting, mainly on slopes ranging from 5° to 8° , covering 66.30 ha of cropland area. Only 1.22 hm^2 of cropland in the Xingmu small watershed implemented conservation measures, also concentrated on slopes of 5° – 8° . For slope ranges of 0 – 5° , 5 – 8° , and 8 – 15° (Figures 6 and 7), the SOC content in the Shuangfu small watershed was 3.79%, 23.56%, and 6.02% higher than that of Xingmu, respectively. In the 5 – 8° slope gradient range, the SOC content of cropland with measures ($20.59 \text{ g}\cdot\text{kg}^{-1}$) was higher than that of cropland without measures ($11.64 \text{ g}\cdot\text{kg}^{-1}$). The mean difference in SOC between the two types of cropland was $-8.96 \text{ g}\cdot\text{kg}^{-1}$ (95% CI: -11.84 to $-6.08 \text{ g}\cdot\text{kg}^{-1}$, independent samples t -test, $p < 0.001$), and the standardized effect size Cohen's d was -3.66 (95% CI: -5.42 to -1.84).

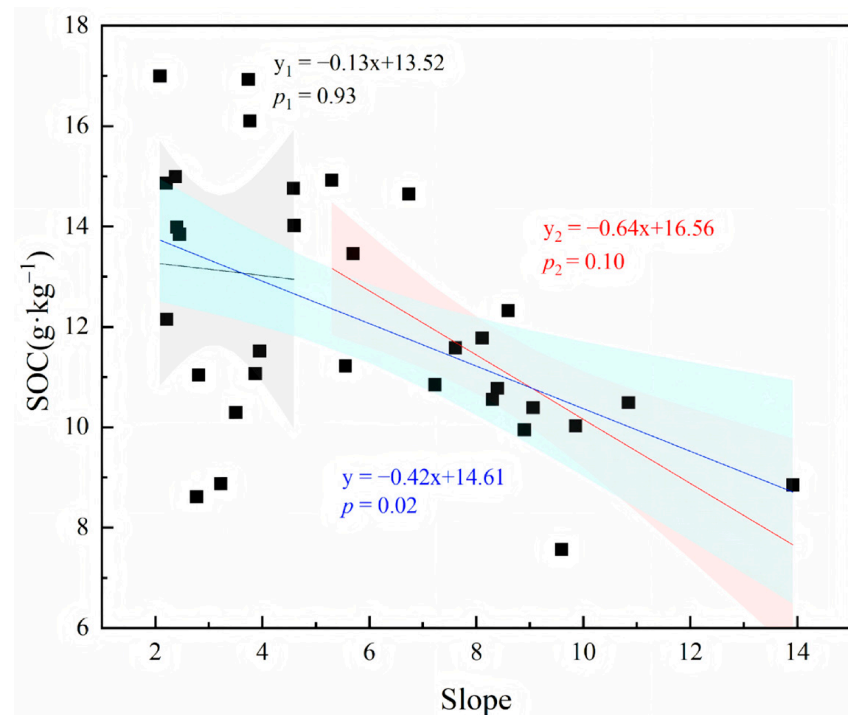


Figure 5. Association of slope gradient with soil organic carbon (SOC) in cropland without conservation measures. Black points represent samples; shadow areas represent 95% confidence intervals; and the linear fitting trends of y_1 , p_1 (gray shadow), y_2 , p_2 (red shadow), and y , p (blue shadow) correspond to 2 – 5° , $>5^\circ$, and $>8^\circ$.

Similarly, slope cropland without conservation measures in the two small watersheds displayed lower SOC content as the slope increased (Figure 7). The SOC content of 5 – 8° slope cropland was 26.71% and 17.66% lower than that of the 0 – 5° slope range, in Shuangfu and Xingmu, respectively. The SOC content of 8 – 15° slope cropland was 3.72% and 5.36% lower than that of the 5 – 8° slope range, respectively. Steeper slopes were associated with lower SOC concentrations at sites without conservation measures.

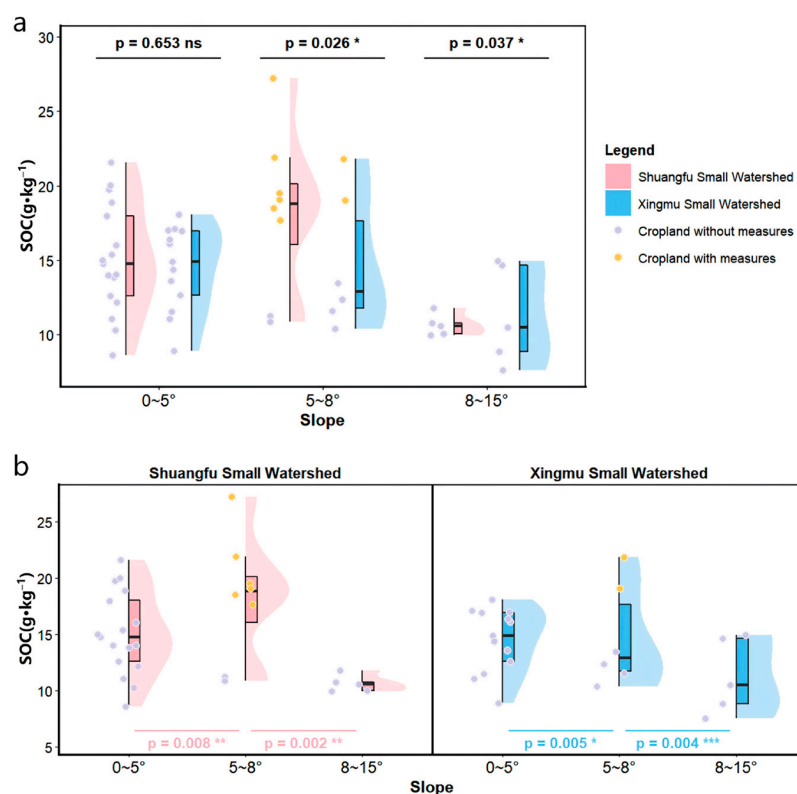


Figure 6. SOC content of cropland with different slopes in the Shuangfu and Xingmu small watersheds. **(a)** Comparison between the two watersheds. **(b)** Comparison within each small watershed. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns = not significant.

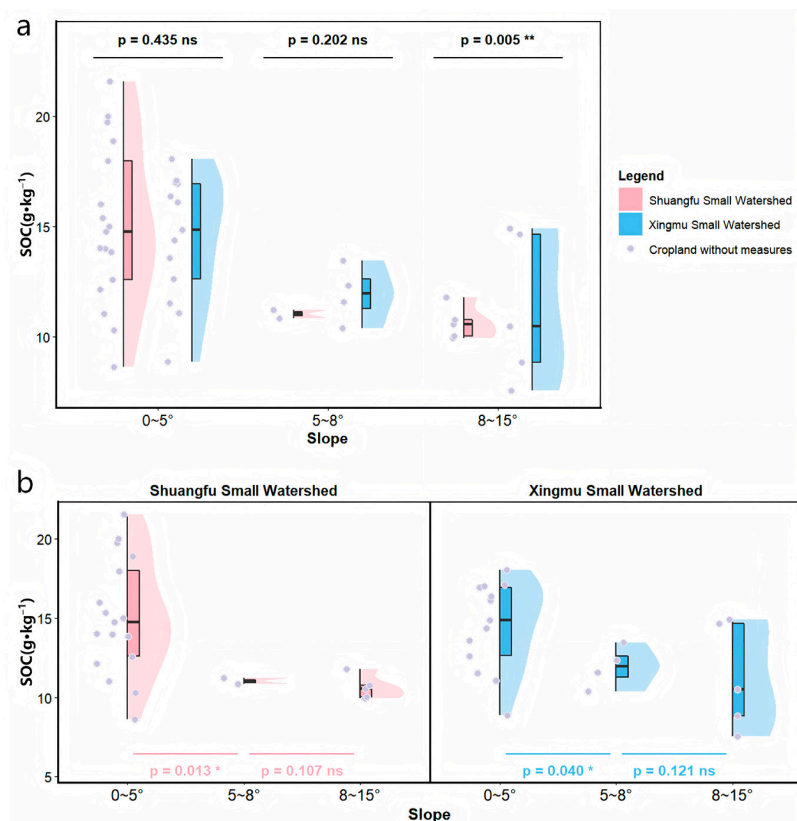


Figure 7. SOC content of cropland without conservation measures with different slopes in Shuangfu and Xingmu small watersheds. **(a)** Comparison between the two small watersheds. **(b)** Comparison within each small watershed. * $p < 0.05$, ** $p < 0.01$, ns = not significant.

Soil and water conservation measures in both small watersheds are concentrated in the 5–8° slope range (Table 1). For slopes greater than 8°, the SOC content of cropland in Shuangfu and Xingmu small watersheds was 29.95% and 18.71% lower than the average level of cropland SOC in their respective watersheds. The cropland area in this slope interval accounts for 17.73% and 25.43% of the total cropland area, respectively. Lower levels of organic matter were more likely to occur in steeper-slope cropland, consistent with greater erosion.

3.3. SOC Associations Under Different Land-Use Regimes

Compared with cropland without measures, the cropland with conservation measures showed significantly ($p < 0.05$) higher levels of SOC (51.84%), TN (28.18%), MWD (23.36%), and clay content (17.53%) (Table 2). The soil carbon:nitrogen ratio (C/N) in cropland with measures was significantly higher ($p < 0.05$) than that of either the forest or the cropland without measures, suggesting that the relative accumulation of organic carbon and nitrogen differs with land use and conservation practices. Although soil and water conservation measures are generally considered to improve soil structure, enhancing rainfall infiltration capacity and water regulation, SWC and BD were 26.16% and 6.02% lower on cropland with conservation measures than on unprotected cropland, both significant differences ($p < 0.05$). There were no significant differences in pH value, sand content, or silt content.

Table 2. Soil properties of different land use types. Values shown are the mean $\pm$ standard deviation (SD) and 95% confidence intervals (CI) for each land use type. Different lowercase letters (a, b, c) in the same row indicate significant differences between different land use types as determined by one-way ANOVA combined with Tukey HSD post hoc test ($p < 0.05$).

Soil Property	Forest		Cropland Without Conservation Measures		Cropland with Conservation Measures	
	Mean $\pm$ SD	95% CI	Mean $\pm$ SD	95% CI	Mean $\pm$ SD	95% CI
SOC (g·kg ^{−1})	27.97 $\pm$ 0.66 a	27.70~28.24	13.56 $\pm$ 0.29 c	13.47~13.65	20.59 $\pm$ 0.27 b	20.39~20.79
TN (g·kg ^{−1})	2.10 $\pm$ 0.48 a	1.91~2.29	1.10 $\pm$ 0.27 c	1.02~1.18	1.41 $\pm$ 0.23 b	1.24~1.58
C/N	13.53 $\pm$ 0.39 b	13.37~13.69	12.59 $\pm$ 0.32 c	12.49~12.69	14.74 $\pm$ 0.18 a	14.61~14.87
SWC (%)	15.54 $\pm$ 0.22 b	15.45~15.63	19.11 $\pm$ 0.21 a	19.05~19.17	14.11 $\pm$ 0.30 c	13.89~14.33
BD (g·cm ^{−3})	1.18 $\pm$ 0.22 b	1.09~1.27	1.33 $\pm$ 0.13 a	1.29~1.37	1.25 $\pm$ 0.10 b	1.18~1.32
pH	5.81 $\pm$ 0.32 a	5.68~5.94	5.68 $\pm$ 0.52 ab	5.52~5.84	5.49 $\pm$ 0.49 b	5.13~5.85
MWD (mm)	1.54 $\pm$ 0.41 a	1.37~1.71	1.07 $\pm$ 0.29 c	0.98~1.16	1.32 $\pm$ 0.19 b	1.18~1.46
Sand (%)	42.40 $\pm$ 0.82 b	42.07~42.73	50.01 $\pm$ 1.79 a	49.47~50.55	48.70 $\pm$ 2.14 a	47.14~50.26
Silt(%)	35.59 $\pm$ 1.21 a	35.10~36.08	31.40 $\pm$ 1.96 b	30.80~32.00	29.44 $\pm$ 1.48 b	28.36~30.52
Clay (%)	22.00 $\pm$ 0.62 a	21.75~22.25	18.60 $\pm$ 0.63 b	18.41~18.79	21.86 $\pm$ 0.75 a	21.31~22.41

To further explore the factors influencing SOC in the study area, two variables (slope and land use type—forest, cropland with conservation measures, and cropland without measures) for two-way analysis of variance. The results of the two-factor general model showed that land use type, slope, and their interaction were significantly associated with SOC content ($p < 0.001$). The model could explain 95.0% of the SOC variation. Land use is the dominant predictor, while slope may affect the distribution of soil organic carbon through the process of erosion and deposition. The significant interaction between the two factors indicates that the association of slope with SOC varies significantly with land-use types.

Before random forest modeling, the variance inflation factor (VIF) was used to test the collinearity between predictors (Table 3). Since the Sand, Silt, and Clay predictors are all components of soil composition that collectively total 100%, there is an inherent

dependence between the three; therefore, this study does not include all three grain-size indicators at the same time and removes the Silt variable to reduce potential redundancy. The VIF test was performed on the remaining predictive variables (Slope, TN, SWC, BD, pH, MWD, Sand, and Clay). Results of $VIF < 10$ indicate a lack of multicollinearity, so all variables were retained for random forest model construction.

Table 3. Variance inflation factors (VIF) of random forest predictors for different land use types. $VIF < 10$ indicates that there is no obvious collinearity between variables.

Soil Property ^t (Predictor)	Forest	Cropland Without Conservation Measures	Cropland with Conservation Measures
TN	1.710	1.383	5.428
Slope	1.692	2.767	1.792
SWC	1.800	2.547	1.798
BD	1.890	1.341	2.135
MWD	1.641	1.311	2.876
pH	1.981	1.362	3.394
Sand	1.638	2.077	1.880
Clay	1.312	1.593	6.247

Eight environmental factors (Clay, Sand, MWD, pH, BD, SWC, TN, and Slope) were evaluated on an exploratory basis for their predictive importance to SOC content. The results of the Random Forest model (Figure 8) show differences among these factors' contributions under different land use types. The OOB- R^2 values for forest land, cropland without measures, and cropland with measures reached 0.820, 0.775, and 0.608, respectively, indicating that the selected environmental factors could explain between 60.8% and 82.0% of the SOC variation under the three land use types.

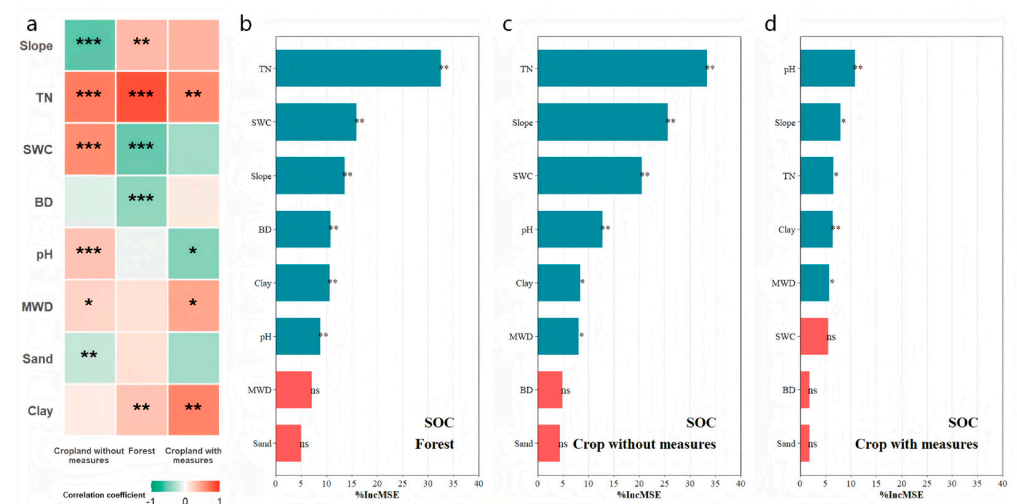


Figure 8. Factors associated with SOC by land use type. (a) Heat map of correlations between each variable and SOC by land-use type. (b–d) Percent increase in mean squared error (%IncMSE) contribution of each variable to the Random Forest model for each land use type. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns = not significant.

In the Random Forest model for forests, TN showed the highest %IncMSE permutation importance (32.58%), indicating that it was the strongest for SOC prediction performance, followed by SWC (15.93%) and slope (13.64%), while Sand showed a relatively low value (5.00%). For cropland without conservation measures, TN and Slope had the strongest %IncMSE values at 33.38% and 25.65%, respectively, followed by SWC (20.58%) and pH (12.83%); Sand had the weakest predictive importance (4.45%). For the cropland with

measures, pH and slope showed high predictive importance with %IncMSE values of 10.86% and 8.04%, respectively. This indicates that within the sample range of this study, the spatial variability of SOC in the cropland with measures is more related to soil pH and slope, while the importance of slope to SOC prediction is relatively low.

4. Discussion

Comparing two small watersheds with different land-use patterns, this study showed that there was no significant difference in soil organic carbon between the watersheds' forest lands, suggesting that SOC at sample points less affected by human disturbance was generally stable under similar climatic and topographic conditions. This finding is similar to that reported in managed and unmanaged forests of the southeastern U.S. [34]. The SOC of cropland was significantly lower than that of forest land in both watersheds [35]; this suggests that land use is a major cause of the SOC differences within these small watersheds. For slope cropland with soil and water conservation measures, SOC content was significantly higher in most respects, consistent with better organic matter retention and environmental conditions. The results imply that differences in SOC within the small watersheds may be influenced not only by the overall land uses but are also affected by slope cropland conservation practices.

Slope is an important topographic factor associated with the spatial distribution of SOC in slope cropland, as previously reported in large- and small-scale studies [36,37]. This study found that on steeper slopes, the SOC content of cropland without conservation measures was significantly lower. As slope increases, the runoff velocity and scouring ability of the slope increase [38], and the fine particles and aggregates rich in organic carbon in the surface layer are preferentially eroded and transported [39], resulting in the continuous loss of SOC. At the same time, the erosion process destroys the structure of soil aggregates, exposes organic carbon to the microbial environment, and accelerates the mineralization and decomposition process [40,41]. By contrast, on gentle slopes, erosion is relatively weak, and the sediment and organic matter carried by the runoff are more likely to deposit on the lower slope area [42].

The spatial distribution pattern of SOC at the small watershed scale reflects the long-term interaction of erosion, transport, and deposition processes. Studies on SOC control by slope erosion have generally concluded that soil and water conservation measures can significantly weaken SOC differences at different slope positions [43,44]. This study shows that the implementation of soil and water conservation measures in slope cropland in low-hill areas is associated with higher SOC content.

Soil and water conservation measures like terracing and ridge planting aim to mitigate erosion by reshaping the hydrological processes on slope surfaces, mainly by altering the slope gradient [45,46]. Along with TN, slope has been identified as the primary determinant of increases in SOC in a meta-analysis of soil conservation measures implemented across China [47]. In this study area, the conservation measures on slope cropland are mainly concentrated in the 5–8° slope range; on unprotected cropland, SOC content was lower on steeper slopes, suggesting that implementing conservation measures on such slopes could be an appropriate response. Measures such as terraces and ridge plant belts can improve precipitation infiltration efficiency and reduce sediment output by changing slope micro-topography, shortening slope length, and reducing runoff speed [48–50]; at the same time, vegetation cover and root soil fixation can effectively weaken the erosion process and increase the input of organic matter [51,52], associated with reducing the loss of SOC. This association is more pronounced in the middle and high slope areas with the greatest erosion risk [53].

Conservation measures were not only predictive of the average level of SOC in slope cropland, but also changed the spatial distribution characteristics of SOC under different slope positions and slope gradients. The implementation of conservation measures changes the pattern of runoff collection and sediment migration, altering the process of redistribution of organic matter and fine particulate matter on the slope [54]. It was observed that the cropland with soil and water conservation measures showed better soil physical and chemical properties. The SOC, TN, clay content, and aggregate concentrations were better in the cropland with conservation measures, whereas bulk density was lower. The higher C/N ratio indicates that more carbon than nitrogen is found in the cropland with conservation measures, which may reflect the role of conservation measures in reducing soil erosion, promoting organic matter accumulation, and increasing plant residue inputs. The lower C/N ratio in unprotected cropland may be related to the loss of organic carbon due to long-term tillage and erosion as well as agricultural nitrogen inputs. In such a case, SOC would decrease to a greater extent than TN, thus reducing the soil C/N ratio. This again suggests that cropland with measures could experience better soil nutrient accumulation, structure, and erosion resistance, consistent with prior research [55,56]. At the same time, the variation in SOC and TN was higher than that of aggregate stability and soil texture index, indicating that conservation measures may have a stronger association with soil carbon and nitrogen accumulation, while soil structural properties could be affected by factors such as soil parent material, texture composition, and formation process [57].

The results of the Random Forest analysis further showed that conservation measures were associated with high SOC, with differences in the correlation patterns between SOC and environmental factors under different land management types. In the cropland without conservation measures, SOC is mainly associated with slope and soil moisture content, indicating that the erosion process is still the dominant factor of SOC change [58]. On cropland with conservation measures, the association of slope with SOC is markedly weaker, and SOC appears more dependent on pH [59]. Studies have shown that fine particles, especially clay particles, can enhance the stability of organic carbon by forming organic-mineral complexes while improving the structure of aggregates and promoting the physical protection of carbon [60]. However, the Random Forest model in this study only supports an exploratory analysis; the OOB-R² and variable importance rankings here cannot support generalizable conclusions. Further work with larger sample sizes relative to the number of predictors should be conducted to produce more robust results to guide the adoption of conservation measures for cropland.

This study elucidated the spatial distribution patterns of SOC in small watersheds with different land-use and conservation measures, but several limitations still exist. The two small watersheds are basically consistent in terms of topographic conditions, tillage years, soil parent material development process, and climate. This suggests that the difference in the SOC content of cropland may be influenced by the differing implementation of soil and water conservation measures. To quantitatively characterize SOC variations across diverse land-use types and systematically elucidate the regulatory mechanisms of slope-scale soil and water conservation measures on SOC dynamics, follow-up controlled field experiments should be set up on adjacent plots with consistent underlying conditions. The experimental treatments can cover forestland, cropland with measures, and cropland without measures.

Furthermore, this investigation only sampled and tested the topsoil layer of 0–20 cm, which cannot adequately represent the vertical stratification characteristics of the overall soil carbon pool along the full soil profile. Future research is recommended to integrate deep soil profile sampling with long-term fixed-site monitoring trials to track the dy-

namic changes in SOC and its labile organic carbon fractions. Such efforts will deepen understanding of the spatial heterogeneity and stability control mechanisms of SOC at the small-watershed scale.

5. Conclusions

This study compared soil organic carbon in a pair of typical small watersheds in the black soil hilly region of Northeast China with similar topography and climatic conditions but different slope cropland management regimes. The spatial distributions of SOC, terrain, and other associated factors were systematically analyzed at the small watershed scale. The associations of soil and water conservation measures with SOC and soil quality characteristics in slope cropland were evaluated. The main conclusions are as follows:

- (1) The topography and climatic conditions of Shuangfu and Xingmu small watersheds are similar; there are no significant differences in SOC content in the watersheds overall or their forest lands. In croplands, SOC in Shuangfu was significantly higher than that in Xingmu by 9.07% ($p < 0.05$). This difference is mainly due to the higher proportion of cropland with conservation measures in Shuangfu.
- (2) Slope is an important topographic factor associated with SOC differences on slope cropland. In the slope cropland without conservation measures, SOC content was lower. Conservation measures were mostly concentrated on slopes of 5–8°, and in that slope range, the cropland with conservation measures had higher SOC than unprotected cropland.
- (3) A Random Forest analysis showed that total nitrogen content, slope gradient, and soil water content were relatively more important for predicting SOC in cropland without conservation measures. Soil pH and slope gradient had relatively higher variable importance for cropland with measures.

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References

1. Liu, R.; Zhang, M.; Wang, Y.; Zou, F.; Lu, W. The Impact of Farmland Property Rights Stability on China’s Food Production Resilience: Evidence from the New Round of Land Ownership Clarification Reform. *Front. Sustain. Food Syst.* **2026**, *10*, 1726373. [CrossRef]
2. Georgiou, K.; Jackson, R.B.; Vindušková, O.; Abramoff, R.Z.; Ahlström, A.; Feng, W.; Harden, J.W.; Pellegrini, A.F.A.; Polley, H.W.; Soong, J.L.; et al. Global Stocks and Capacity of Mineral-Associated Soil Organic Carbon. *Nat. Commun.* **2022**, *13*, 3797. [CrossRef] [PubMed]
3. Pan, J.; Liu, C.; Li, H.; Wu, Q.; Dong, Z.; Dou, X. Soil-Resistant Organic Carbon Improves Soil Erosion Resistance Under Agroforestry in the Yellow River Flood Plain, of China. *Agrofor. Syst.* **2022**, *96*, 997–1008. [CrossRef]

4. Wiesmeier, M.; Urbanski, L.; Hobley, E.; Lang, B.; Von Lützow, M.; Marin-Spiotta, E.; Van Wesemael, B.; Rabot, E.; Ließ, M.; Garcia-Franco, N.; et al. Soil Organic Carbon Storage as a Key Function of Soils—A Review of Drivers and Indicators at Various Scales. *Geoderma* **2019**, *333*, 149–162. [\[CrossRef\]](#)
5. Bai, L.; Duan, J.; Shi, P.; Xiao, J.; Li, Z.; Li, P. Erosion-Deposition Processes Drive Soil Organic Carbon Mineralization Through Aggregate Breakdown and Buildup. *CATENA* **2025**, *260*, 109432. [\[CrossRef\]](#)
6. He, Z.; Xu, H.; He, S.; Liang, X.; Zheng, Z.; Luo, Z.; Wang, Y.; Zhang, Y.; Tan, B. Characteristics of Soil Organic Carbon (SOC) Loss with Water Erosion in Sloping Farmland of Southwestern China during Maize (*Zea mays* L.) Growth Stages. *Agronomy* **2023**, *13*, 738. [\[CrossRef\]](#)
7. Zhang, W.; Li, L.; Liu, B.; Liu, J.; Chen, F.; Ni, J.; Wei, C.; Zhong, S. Effect of Ridge Tillage with Rice-Rape Rotation on the Root System and Yield of Crops. *Plant Soil* **2025**, *510*, 291–304. [\[CrossRef\]](#)
8. Wang, S.; Zhang, X.; Zhuang, Q.; Yang, Z.; Wang, Z.; Li, C.; Jin, X. Spatio-Temporal Variations in Soil Organic Carbon Stocks in Different Erosion Zones of Cultivated Land in Northeast China Under Future Climate Change Conditions. *Agronomy* **2025**, *15*, 2459. [\[CrossRef\]](#)
9. Zhu, Y.; Li, W.; Wang, D.; Wu, Z.; Shang, P. Spatial Pattern of Soil Erosion in Relation to Land Use Change in a Rolling Hilly Region of Northeast China. *Land* **2022**, *11*, 1253. [\[CrossRef\]](#)
10. Li, H.; Zhu, H.; Liang, C.; Wei, X.; Yao, Y. Soil Erosion Significantly Decreases Aggregate-Associated OC and N in Agricultural Soils of Northeast China. *Agric. Ecosyst. Environ.* **2022**, *323*, 107677. [\[CrossRef\]](#)
11. Li, M.; Wang, B.; Wang, W.; Chen, Z.; Luo, S. Hydrological Connectivity Response of Typical Soil and Water Conservation Measures Based on SIMulated Water Erosion Model: A Case Study of Tongshuang Watershed in the Black Soil Region of Northeast China. *Water* **2024**, *16*, 2568. [\[CrossRef\]](#)
12. Tang, Z.; Li, R. Small Watersheds Are the Best Control and Management Unit for Improving Soil Conservation Services in Karst Areas. *Sci. Total Environ.* **2024**, *953*, 176162. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Aguirre-Salado, O.; Pérez-Nieto, J.; Aguirre-Salado, C.; Monterroso-Rivas, A. Factors regarding the spatial variability of soil organic carbon in a Mexican small watershed. *Rev. Fac. Agron. Univ. Zulia* **2023**, *41*, e244101. [\[CrossRef\]](#)
14. Kraemer, F.B.; Ares, G.; Mozo, J.; Chagas, C. Topographical Effects on the Interplay Between Soil Organic Carbon Fractions, Aggregate Stability and Water Repellency at a Small Watershed Scale. *CATENA* **2025**, *258*, 109182. [\[CrossRef\]](#)
15. Gao, H.; Li, Z.; Li, P.; Jia, L.; Zhang, X. Quantitative Study on Influences of Terraced Field Construction and Check-Dam Siltation on Soil Erosion. *J. Geogr. Sci.* **2012**, *22*, 946–960. [\[CrossRef\]](#)
16. Luo, Y.; Wei, J.; Tang, Q.; Gan, F.; Li, J. Water Seepage and Retention in Purple Soil Bunds on Sloping Farmland in the Three Gorges Reservoir Area, China. *Land Degrad. Dev.* **2022**, *33*, 1410–1422. [\[CrossRef\]](#)
17. Liao, X.; Li, Y.; Wang, J.; Dong, J.; Yao, Q.; Li, J.; Hou, R.; Li, Z.; Zhang, Y.; Jia, X.; et al. Governing Black Soils for Food and Climate Security. *Nat. Commun.* **2026**, *17*, 1488. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Qi, Q.; Shengkui, C.; Liang, W.; Xiaojie, L.; Aimin, L. A Study on the Spatial Distribution of China's Potential Foreign Cooperation on Grain from Geographical View. *J. Resour. Ecol.* **2018**, *9*, 585–591. [\[CrossRef\]](#)
19. Kwang, J.S.; Thaler, E.A.; Larsen, I.J. The Future of Soils in the Midwestern United States. *Earths Future* **2023**, *11*, e2022EF003104. [\[CrossRef\]](#)
20. Wang, H.; Yang, S.; Wang, Y.; Gu, Z.; Xiong, S.; Huang, X.; Sun, M.; Zhang, S.; Guo, L.; Cui, J.; et al. Rates and Causes of Black Soil Erosion in Northeast China. *CATENA* **2022**, *214*, 106250. [\[CrossRef\]](#)
21. Zhang, X.; Liu, X. Key issues of mollisols research and soil erosion control strategies in China. *Bull. Soil Water Conserv.* **2020**, *40*, 340–344. [\[CrossRef\]](#)
22. Hu, W.; Xu, J.; Li, J.; Zhang, X. The Effect of Soil and Water Conservation Measures on Soil Organic Carbon in a Typical Small Watershed in the Mollisol Region of Northeast China. *CATENA* **2022**, *208*, 105744. [\[CrossRef\]](#)
23. Zhao, Y.; Zhu, D.; Wu, Z.; Cao, Z. Extreme Rainfall Erosivity: Research Advances and Future Perspectives. *Sci. Total Environ.* **2024**, *917*, 170425. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Schad, P. World Reference Base for Soil Resources, 4th Edition: Field Guide and Fundamental Definitions. *Soil Sci. Plant Nutr.* **2026**, *72*, 229–235. [\[CrossRef\]](#)
25. Castellón Meyrat, A.; O'Sullivan, L.; Holloway, P.; Wall, D.; Bondi, G. Impact of Management Intensity of Agricultural Systems and Soil Intrinsic Characteristics on Soil Organic Carbon Stocks. *Agric. Ecosyst. Environ.* **2026**, *410*, 110547. [\[CrossRef\]](#)
26. Wei, S.; Fu, Y.; Liu, B.; Zhang, Y.; Shao, S.; Zhang, X. Characteristics of Soil Physical Properties and Spatial Distribution of Soil Erosion on Ridge-Slope Farmland in the Black Soil Areas of Northeast China. *Water* **2024**, *16*, 2353. [\[CrossRef\]](#)
27. Kang, T.-H.; Sharma, A. A State-Controlled Hypothesis Test for Paired-Watershed Experiments. *J. Hydrol.* **2024**, *640*, 131664. [\[CrossRef\]](#)
28. Law, J.Y.; Long, L.A.; Kaleita, A.; Helmers, M.; Brendel, C.; Van Der Woude, K.; Soupir, M. Stacked Conservation Practices Reduce Nitrogen Loss: A Paired Watershed Study. *J. Environ. Manag.* **2022**, *302*, 114053. [\[CrossRef\]](#) [\[PubMed\]](#)

29. Zhai, Y.; Fang, H.; Wu, Z. Enhancing Understanding of Soil Redistribution and Sediment Budgets in Three Contrasting Agricultural Catchments, Northeast China: Using the ^{137}Cs Technique. *Soil Tillage Res.* **2026**, *255*, 106773. [[CrossRef](#)]
30. State Bureau of Standards of the People's Republic of China. *Method for the Determination of Soil Water Content*; China Standards Press: Beijing, China, 1987.
31. Ministry of Agriculture of the People's Republic of China. *Soil Testing Part 4: Method for Determination of Soil Bulk Density*; China Agriculture Press: Beijing, China, 2006.
32. Ministry of Agriculture of the People's Republic of China. *Soil Testing Part 3: Method for Determination of Soil Mechanical Composition*; China Agriculture Press: Beijing, China, 2006.
33. Ministry of Ecology and Environment of the People's Republic of China. *Soil—Determination of pH—Potentiometry*; China Environment Press: Beijing, China, 2018.
34. Nave, L.E.; DeLyser, K.; Domke, G.M.; Holub, S.M.; Janowiak, M.K.; Ontl, T.A.; Sprague, E.; Viau, N.R.; Walters, B.F.; Swanston, C.W. Soil Carbon in the South Atlantic United States: Land Use Change, Forest Management, and Physiographic Context. *For. Ecol. Manag.* **2022**, *520*, 120410. [[CrossRef](#)]
35. Sun, J.; Shao, D.; Han, F.; Chen, Q.; Zhu, Y. Spatial Distribution Characteristics of Soil Organic Carbon Under Different Land Use Types. *Soil Use Manag.* **2025**, *41*, e70130. [[CrossRef](#)]
36. Ai, S.; Chen, M.; Sheng, M.; Ai, X. Slope Aspect Influences the Organic Carbon Content and Stock in Soil Aggregates of Cut Slopes in the Alpine Region of Southwest China. *Land Degrad. Dev.* **2026**, *37*, 3455–3465. [[CrossRef](#)]
37. Li, Y.; Zheng, S.; Meng, X.; Wang, L.; Yu, Y.; Zhang, Y.; Zhang, G.; Zhang, S.; Dai, X.; Ruan, W.; et al. Climatic and Topographic Controls on Soil Organic Carbon Distribution across Continents. *CATENA* **2025**, *260*, 109435. [[CrossRef](#)]
38. Feng, R.; Wang, F.; Ban, Y.; Chen, C. Method for Estimating Overland Flow Velocity on Sandified Slopes from Measured Solute Transport Process with Bias Errors. *J. Hydrol.* **2020**, *589*, 125116. [[CrossRef](#)]
39. Li, S.; Sheng, M.; Yuan, F.; Yin, J. Effect of Land Cover Change on Total SOC and Soil PhytOC Accumulation in the Karst Subtropical Forest Ecosystem, SW China. *J. Soils Sediments* **2021**, *21*, 2566–2577. [[CrossRef](#)]
40. Zhang, N.; Xia, Z.; Li, P.; Chen, Q.; Ke, G.; Yue, F.; Xu, Y.; Wang, T. The Impact of Rainfall and Slope on Hillslope Runoff and Erosion Depending on Machine Learning. *Front. Environ. Sci.* **2025**, *13*, 1580149. [[CrossRef](#)]
41. Plotnikova, O.O.; Demidov, V.V.; Farkhodov, Y.R.; Tsymbarovich, P.R.; Semenov, I.N. Influence of Water Erosion on Soil Aggregates and Organic Matter in Arable Chernozems: Case Study. *Agronomy* **2024**, *14*, 1607. [[CrossRef](#)]
42. Zhang, P.; Li, L.; Wang, J.; Zhang, S.; Zhu, Z. Effects of Hydraulic Erosion on the Spatial Redistribution Characteristics of Soil Aggregates and SOC on Pisha Sandstone Slope. *Sustainability* **2023**, *15*, 13276. [[CrossRef](#)]
43. Xie, Y.; Tang, J.; Li, R.; Chen, P. Redistribution of SOC Driven by Erosion and Deposition in Cultivated Black Soils of Northeast China. *CATENA* **2025**, *258*, 109268. [[CrossRef](#)]
44. Liu, H.; Zhou, L.; Fan, H.; Zhang, Y.; Jia, Y. Decoupling Analysis of Soil Properties and Slope-Position Interactions Affecting Erosion Rates on Long Gentle Slopes. *Soil Tillage Res.* **2026**, *256*, 106875. [[CrossRef](#)]
45. Yang, H.; Wang, T.; Yang, D.; Yan, Z.; Wu, J.; Lei, H. Runoff and Sediment Effect of the Soil-Water Conservation Measures in a Typical River Basin of the Loess Plateau. *CATENA* **2024**, *243*, 108218. [[CrossRef](#)]
46. He, Q.; Zhang, P.; Li, B.; Shen, N.; Yang, M.; Zhang, F. Regional Mechanisms of Hillslope Erosion and Soil and Water Conservation Pathways on the Loess Plateau. *J. Hydrol.* **2026**, *668*, 135023. [[CrossRef](#)]
47. Zhang, J.; Zhang, Y.; Zhang, X.; Zhao, Y.; Liu, S.; Miao, J.; Han, X. Spatiotemporal Effects of Soil and Water Conservation Measures on Soil Organic Carbon Enhancement in China: A Meta-Analysis. *J. Hydrol.* **2026**, *664*, 134373. [[CrossRef](#)]
48. Hancock, G.R.; Gibson, A.; Kirk, E.; Conway, I.; Parrod, A. Soil Erosion and Carbon Export: A Case Study in a Steep Slope Grazing Landscape. *Geoderma Reg.* **2024**, *36*, e00751. [[CrossRef](#)]
49. Liu, S.; Seybold, H.; Van Meerveld, I.; Wang, Y.; Kirchner, J.W. Tree Planting and Soil Conservation Measures Have Strongly Attenuated Storm Runoff Responses on the Chinese Loess Plateau. *J. Hydrol.* **2025**, *662*, 134039. [[CrossRef](#)]
50. Long, L.; Cang, Q.F.; Xueling, Y.; Lina, J.; Yu, D.X.; Tong, R.X. Relationship Between the Slope Microtopography and the Spatial Redistribution Pattern of Soil Organic Carbon Under Water Erosion. *J. Soil Water Conserv.* **2021**, *76*, 435–445. [[CrossRef](#)]
51. Yin, Q.; Liu, Y.; Li, J.; Wu, J.; Wang, Y.; Zhang, H.; Liu, H.; Jiang, L.; Yang, J.; Wang, Y.; et al. Soil Organic Carbon Formation in Grassland Ecosystems: Higher Efficiency of Roots than Shoots and Rhizodeposition. *Soil Tillage Res.* **2025**, *250*, 106523. [[CrossRef](#)]
52. Moore, J.A.M.; Sulman, B.N.; Mayes, M.A.; Patterson, C.M.; Classen, A.T. Plant Roots Stimulate the Decomposition of Complex, but Not Simple, Soil Carbon. *Funct. Ecol.* **2020**, *34*, 899–910. [[CrossRef](#)]
53. Cheng, M.; Xiang, Y.; Xue, Z.; An, S.; Darboux, F. Soil Aggregation and Intra-Aggregate Carbon Fractions in Relation to Vegetation Succession on the Loess Plateau, China. *CATENA* **2015**, *124*, 77–84. [[CrossRef](#)]
54. Dangiso, Y.; Wolka, K. Fanya Juu Terraces Improve Soil Properties of Cultivated Land in Erosion-Prone Semi-Arid Area of Ethiopia. *Sci. Rep.* **2024**, *14*, 25485. [[CrossRef](#)] [[PubMed](#)]
55. Nang, Y.W.; Onodera, S.; Wang, K.; Shimizu, Y.; Saito, M. Slope Gradient Effects on Sediment Yield of Different Land Cover and Soil Types. *Water* **2024**, *16*, 1419. [[CrossRef](#)]

56. Li, Z.; Fan, Y.; Zhang, R.; Chen, P.; Jing, X.; Lyu, C.; Zhang, R.; Li, Y.; Liu, Y. Synergistic Impacts of Landscape, Soil, and Environmental Factors on the Spatial Distribution of Soil Aggregates Stability in the Danjiangkou Reservoir Area. *CATENA* **2024**, *237*, 107840. [[CrossRef](#)]
57. Mahajan, G.R.; Das, B.; Manivannan, S.; Manjunath, B.L.; Verma, R.R.; Desai, S.; Kulkarni, R.M.; Latore, A.M.; Sale, R.; Murgaonkar, D.; et al. Soil and Water Conservation Measures Improve Soil Carbon Sequestration and Soil Quality Under Cashews. *Int. J. Sediment Res.* **2021**, *36*, 190–206. [[CrossRef](#)]
58. Zhang, J.; Lan, Z.; Li, H.; Jaffar, M.T.; Li, X.; Cui, L.; Han, J. Coupling Effects of Soil Organic Carbon and Moisture Under Different Land Use Types, Seasons and Slope Positions in the Loess Plateau. *CATENA* **2023**, *233*, 107520. [[CrossRef](#)]
59. He, Z.; He, S.; Zheng, Z.; Yi, H.; Qu, S.; Liu, X. Change in Soil Organic Carbon After Slope Cropland Changed into Terrace in Southwest China. *CATENA* **2025**, *248*, 108580. [[CrossRef](#)]
60. Halder, M.; Ahmad, S.J.; Rahman, T.; Joardar, J.C.; Siddique, M.A.B.; Islam, M.S.; Islam, M.U.; Liu, S.; Rabbi, S.; Peng, X. Effects of Straw Incorporation and Straw-Burning on Aggregate Stability and Soil Organic Carbon in a Clay Soil of Bangladesh. *Geoderma Reg.* **2023**, *32*, e00620. [[CrossRef](#)]

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