Assessment of the degree of sloped cropland degradation in typical black soil region

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Abstract

A comprehensive evaluation indicator system is needed to provide a integrated assessment of the degree of sloped cropland degradation. We employed bibliometrics on research studies involving cropland degradation. Frequency analysis was then used to identify high-frequency indicators with which to construct a total index set (TIS). In addition, soil measurement data from sloped cropland in Baiquan and Keshan Counties, Heilongjiang province, China, were used as a basis to construct a minimum index set (MIS). The TIS included A-horizon thickness, clay content, organic matter content, pH, slope gradient, ridge-slope angle, gully density, bulk density, large water-stable aggregate content, soil cation exchange capacity, and crop yield. The first six of these were included in the MIS. In the studied area, undegraded soil, mildly degraded soil, and moderately degraded soil and above accounted for 7%, 48% and 45% of investigated sloped croplands, respectively. Slope gradient is one of the main factors affecting soil degradation. Soil degradation mainly presented as worsening of soil physicochemical characteristics. In addition, downslope and small-angle ridge cultivation are benefit for soil organic matter maintenance and the soil structure and nutrient retention capacity is better than soil with contour or large-angle ridge cultivation. The reason might be that downslope and small-angle ridge cultivation are usually employed on soil with small slope. The study results provide a scientific basis for improving the quality and productivity of sloped cropland in black soil region.

Keywords: slope gradient/ridge-slope angle/gully density/evaluation system/land degradation/ bibliometrics

1. Introduction

Soil is an indispensable component of the ecosystem and is a medium and substrate for growth and survival of organisms. Soil degradation refers to a reduction of functions or intensity of functionality as compared to functions under natural conditions (Kuzyakov et al., 2019). Soil degradation seriously threatens food production and agricultural sustainable development.

In typical black soil region in Northeast China, cropland area is approximately 167,000 km^2. Sloped cropland with a slope gradient of >0.25° accounts for 46.7% of the total cultivated land (Liu et al., 2021). Sloped cropland consists mainly of gentle and long slopes, with slope gradients of 1-8° and slope lengths of 500–2000 m (Fan et al., 2004). The unique terrain, climate, and unsuitable human cultivation management have caused serious degradation in sloped cropland in black soil region (Sang et al., 2020; Zhai et al., 2020). The first national water conservancy census showed that there are nearly 300,000 erosion gullies in black soil region in Northeast China, with a mean gully density of 0.21 km/km^2 (Ministry of Water Resources of the People's Republic of China, 2013) and approximately 400,000 hm^2 of cropland area has been eroded (Wang et al., 2017). The soil A-horizon has been lost completely in severely eroded sloped cropland, appearing as a broken and yellow surface. Most of these croplands have since become low-productivity fields (Yan et al., 2009). Soil degradation caused by gully erosion has become an important problem for ecological restoration in black soil region (Liu and Yan, 2009). Improving productivity of degraded sloped cropland is crucial in black soil region (Zhang et al., 2010), for which the evaluation of the degree of sloped cropland degradation are prerequisites (Jin et al., 2019).

The soil degradation classification system that is mostly used worldwide classifies the soil degradation processes as water erosion, wind erosion, physical degradation, and chemical degradation (Middleton and Thomas, 1997). Researchers have selected different indicator to evaluate soil degradation based on the actual situation of the region. For example, Zhou et al. (2012) mainly used soil physical (soil moisture content and firmness) and chemical indicators (pH, organic matter, total nitrogen, total phosphorous, ammoniacal nitrogen, nitrate nitrogen, available phosphorus, and available potassium), combined with biodiversity and biomass to evaluate the degree of alpine grassland degradation in the Yellow River Source Region. Zhou et al. (2005) selected physical (A-horizon thickness, depth, clay-silt ratio, soil bulk density, and soil moisture), chemical (soil pH and soil cation exchange capacity (CEC)), and nutrient indicators (organic matter, total nitrogen, available nitrogen, total phosphorous, available phosphorus, total potassium, and available potassium) to assess the soil degradation in upper Yangtze River.

There is few studies focus on the evaluation of the degree of black soil degradation. Sun (2006) found that black soil degradation were mainly shown as the thinness of A-horizon, nutrient deletion, soil bulk density and gully increase, and soil organic matter decline. Liu et al. (2009) and Yan et al. (2009) pointed out that soil erosion is the main driving factor leading to the degradation of sloping cropland in black soil area, causing the thinning of A-horizon and the worsening of soil quality. Therefore, the selection of evaluation indicators for black soil degradation should focus mainly on soil erosion, soil profile characteristics, field productivity, and soil quality.

The objective of this study was to construct an evaluation indicator system that is suitable for assessing the degree of sloped cultivated land degradation in typical black soil region. We employed bibliometrics to screen for studies focused on the degree of cropland degradation evaluation and performed frequency analysis on indicators in these papers. Meanwhile, adding indicators based on the specific environment of sloped cropland in typical black soil region and the associated cultivation management characteristics to construct evaluation indicator system. In addition, soil measurement data from sloped cropland in Baiquan and Keshan Counties, Heilongjiang province, China, were used as a basis to construct a minimum index set. This study provides an evaluation system to determine the degree of sloped cropland degradation in typical black soil region and provides support for improving the productivity of sloped cropland.

2. MATERIALS AND METHODS

2.1. Soil sampling and measurements

Soil samples were taken from sloped cropland in Baiquan and Keshan Counties, Qiqihar, Heilongjiang province (125°30′E–126°31′E, 47°20′N–47°55′N), which are both located in typical black soil region (Liu et al., 2021). The climate is temperate continental climate. Strong winds are frequent in spring and summers are hot. Rainfall is high and concentrated in summers, while winters are frigid. The cropland soil is mainly black soil (Luvic Phaeozem, FAO).

According to *Technical Standards for Black Soil Region Soil Erosion Comprehensive Prevention and Control* (Ministry of Water Resources of the People’s Republic of China, 2009) and Liu et al. (2021), farmland in typical black soil region with a slope gradient of >0.25° represents priority targets for soil erosion prevention and control. Therefore, sloped cropland with a slope gradient of >0.25°were selected (0.25°–1.5°, 1.5°–3°, 3°–5°, and >5°) on black soil type to investigate and measure soil degradation evaluation indicators (Figure 1). Samples were collected at 3 positions: top, middle, and bottom of the slope for each site. The A-horizon thickness of each sampling point was measured and 0–20 cm of undisturbed (stored in a hard box) and mixed soil samples (consist of five samples collected in an “S” shape) were collected. Soil samples were delivered to the laboratory as soon as possible for air-drying prior to measurement of soil physicochemical characteristics.

Conventional methods were used to measure soil bulk density, large water-stable aggregate content, soil organic matter content, and pH (Bao, 2013). To determine the clay content, a Microtrac S3500 laser particle size analyzer (Microtrac Inc., USA) was used to obtain the volume ratio, which was converted to mass ratio using an empirical equation (Li et al., 2015). To determine the gully density, satellite images of Baiquan and Keshan Counties acquired in Summer 2018 were used to identify the erosion gullies at each sampling site and its surroundings, and calculating the ratio of the length of these gullies to the total area of the sampling site. The ridge-slope angle was calculated by using remote sensing images for ridge interpretation, a digital elevation model for generation of the slope raster image layer of sampling points, before the ArcGIS 10.2 raster calculator (ESRI) was used to calculate the ridge-slope angle. A ridge-slope angle of 0–10°, 10–80°, and 80–90° are known as downslope tillage, ridge tillage, and contour tillage, respectively (Guan et al., 2019). The crop yield (maize) was obtained based on a farmer survey.

2.2. Construction of a soil degradation evaluation indicator system

2.2.1 Construction of a total index set (TIS) for soil degradation evaluation indicators

Bibliometrics and a frequency analysis method were used to conduct a literature search and screen for indicators. The screening principles of dominance, accuracy, practicality, independence, and stability were used to construct the TIS.

A subject term search was used for bibliometrics using the China National Knowledge Infrastructure (CNKI) and Web of Science databases. All the subject terms were shown in Table 1. Papers in the CNKI database and Web of Science databases were indexed from 1979 to 2019 and 1950 to 2019, respectively. Using "soil degradation-evaluation indicator" as an example, the search method was as follows: "soil degradation" was input as the subject term search and searched within the results for "evaluation indicators." Combined the usage frequency if different indicator with the same meaning, such as 'soil moisture' and 'soil water content'. After screening, we obtained 451 papers that were mainly focused on cropland soil degradation and 85 indicators were extracted. Among which 78 papers studied on typical black soil region and 63 indicators were extracted.

The usage frequency of each indicator was calculated as follows (Wang et al., 2019):

$$F_i=T_i/S \quad (1)$$

where F_i represents the usage frequency for indicator i, T_i represents the number of times that indicator was used, and S represents the total number of papers.

2.2.2 Construction of a minimum index set (MIS) for soil degradation evaluation indicators

Cluster analysis was used to construct the MIS to evaluate the degree of sloped cultivated land degradation in typical black soil region. The squared Euclidean distance method was used for R cluster analysis in SPSS 22.0 (SPSS Inc., Chicago, Illinois, USA). The corresponding cluster level was selected based on the objective of the study and the evaluation indicators were classified into several groups of soil attributes (usually 4–6 groups). The indicators can replace each other if a significant correlation between indicators in the same group. In addition, based on the results of previous studies and field investigations, redundant indicators were excluded, and representative and relatively independent indicators were selected to create the MIS.

The soil degradation index (SDI) is an integrated index composed of soil degradation evaluation indicators and the threshold value is [0–1]. Higher SDI means more severe soil degradation. A five-grade system was used in this study to classify the degree of sloped cropland degradation: undegraded ($0 \leq \mathrm{SDI} < 0.2$), mild degradation ($0.2 \leq \mathrm{SDI} < 0.4$), moderate degradation ($0.4 \leq \mathrm{SDI} < 0.6$), severe degradation ($0.6 \leq \mathrm{SDI} < 0.8$), and extremely severe degradation ($0.8 \leq \mathrm{SDI} \leq 1$) (Jin et al., 2018). The calculation formula for soil degradation is as follows:

$$\mathrm{SDI} = \sum_{i=1}^{n} W_i N_i \qquad (2)$$

$$N_i = \mu(x_i) \qquad (3)$$

where W_i represents the weight of the ith indicator, N_i represents the membership of the ith indicator. N_i is calculated using the function $\mu(x_i)$, where x_i represents the actual measurement for indicator i.

The positive and negative effects of various indicators on the SDI were used to classify $\mu(x_i)$ as an "S" type function or reverse S type function (Xu, 2003), and approximated as semi-increasing trapezoid and semi-decreasing trapezoid distributions (Figure 2). The mean value of soil with higher fertility in Baiquan and Keshan Counties in the second national soil census was used as a criterion to determine whether soil degradation has occurred (i.e., the upper limit of the membership function threshold). Soil data from region with the most severe degradation in field investigation were used as the lower limit for the membership function threshold. The calculation formula for membership was as follows:

$$\mu(x)=\begin{cases} 1,\ x\geq b\,(\mathrm{S}\ type\ function)\ or\ x\leq a\,(reverse\ \mathrm{S}\ type\ function) \\ \dfrac{x-a}{b-a}(\mathrm{S}\ type\ function)\vee\dfrac{x-b}{a-b}(reverse\ \mathrm{S}\ type\ function),\ a<x<b \\ 0,\ x\leq a\,(\mathrm{S}\ type\ function)\vee x\geq b\,(reverse\ \mathrm{S}\ type\ function) \end{cases} \quad (4)$$

where μ(x) represents indicator membership, x represents the indicator measurement, a represents the lower limit of threshold, and b represents the upper limit of threshold.

In Equation (2), W_i was obtained by principal component analysis (Jin et al., 2018). SPSS 22.0 was used to extract the common factor variance for each indicator (range: 0–1). The ratio of the common factor variance of an indicator to the total common factor variance was the weight of that indicator. The higher the indicator weight, the greater its contribution to SDI.

The calculation formulas for E_f and E_r were as follows:

$$E_f=1-\frac{\sum(R_0-R_{cal})^2}{\sum(R_0-\overline{R_0})^2} \quad (5)$$

$$E_r=\left|\sum_{i=1}^{n}R_{0i}-\sum_{i=1}^{n}R_{cali}\right|\div\sum_{i=1}^{n}R_{0i} \quad (6)$$

where R_0 and $\overline{R_0}$ represent the SDI (SDI-TIS) and mean calculated using TIS, respectively, and R_{cal} represents the SDI (SDI-MIS) calculated using MIS. The closer the E_f is to 1 and the closer E_r is to 0, the smaller the deviation between SDI-MIS and SDI-TIS, and the more precise the results for soil degradation evaluation with MIS.

3. RESULTS

3.1 TIS construction

The literatures on evaluation of the degree of sloped cropland degradation in black soil region were classified into the following five categories: erosion indices, profile indices, physical indices, chemical indices, and biological indices. Each indicator was ranked according to frequency and the high-frequency indicators were then selected (Figure 3). A total of 17 high-frequency indicators were obtained: soil texture, bulk density, clay content, Ap-horizon thickness, effective soil thickness, A-horizon thickness, soil erosion degree, soil erosion modulus, organic matter content, pH, available-N, available-P, available-K, total N, total P, CEC, and microbial biomass C/N. By analyzing the correlation between different indicators and combining regional characteristics and principles of indicator screening, we finally confirmed 11 indicators to form the TIS to evaluate soil degradation in sloped cropland in black soil region (Figure 4).

3.2 MIS construction

Cluster analysis classified the evaluation indicators into four categories (Figure 5). Category 1 consists of gully density, slope, ridge-slope angle, and bulk density, which mainly characterize the terrain characteristics of sloped cropland. Soil pH is in Category 2 and characterizes the soil environment. Category 3 consists of A-horizon thickness and crop yield, which characterizes soil production performance. Category 4 consists of organic matter, CEC, clay content, and large water-stable aggregate content and mainly characterizes soil nutrient retention capacity. By analyzing the correlation between indicators, we finally confirmed the following six indicators in MIS for evaluating the degree of sloped cropland degradation in black soil region: A-horizon thickness, CEC, organic matter content, pH, slope gradient, and ridge-slope angle.

In TIS, bulk density, gully density, slope, and ridge-slope angle have positive relationship with the degree of soil degradation. Therefore, they belong to the S-shaped curve and membership degree was determined according to Equation (4). Large water-stable aggregate content, organic matter content, CEC, A-horizon thickness, crop yield, pH, and clay content have negative relationship with the degree of soil degradation and belonged to the reverse S-shaped function. Their membership was determined using Equation (5). The weight of indicators in TIS and MIS were shown in Table 2.

The SDI-TIS distribution range was 0.128~0.841 and the SDI-MIS distribution range was 0.157~0.836. E_f was 0.886 and E_r was 0.037. Regression analysis showed a strong linear correlation between SDI-MIS and SDI-TISand R^2 was 0.895 (Figure 6). The SDI-MIS results showed that in the studied area, undegraded soil, mildly degraded soil, moderately degraded soil and above accounted for 7%, 48%and 45% of investigated sloped cropland sites, respectively.

3.3 Soil characteristics for sloped cropland with varying degrees of degradation

Correlation analysis showed that SDI has significant positive correlations with slope gradient, ridge-slope angle, soil bulk density and gully density (Table 3). The mean slope gradient of undegraded soil was 0.75°, while severely degraded soil and above was >4° (Table 4). The SDI showed a significant negative correlation with organic matter, CEC, large water-stable aggregate, clay content and A-horizon thickness but was not correlated with pH and crop yield (Table 4). Undegraded soil had an A-horizon thickness of 80–110 cm (mean: 100 cm) and organic matter content of 64 g/kg. In contrast, the mean A-horizon thickness of extremely severely degraded soil was only 5 cm and the organic matter content was one third of that of undegraded soil. All soil pH (5-6) was much lower than that (around 7) in the second national soil census in the studied area.

4. DISCUSSION

4.1 Construction of indicator system for evaluating the degree of sloped cropland

degradation in typical black soil region

Bibliometrics was used to screen for TIS indicators to evaluate the degree of sloped cropland degradation in typical black soil region and indicators in the literature were classified into five categories. The usage frequency of each indicator was then analyzed. Soil bulk density directly affected soil porosity and water retention and shows a good response to soil degradation (Wang, 2016). Erosion is one of the main causes of black soil degradation in Northeast China, which mainly results in the loss of clay particles and breaking up of large aggregates (>0.25 mm). The large water-stable aggregate content is one of the key indicators of fertility decline in black soil (Lu et al., 2016). Therefore, we still included large water-stable aggregate content in TIS to evaluate the degree of soil degradation, even though its usage frequency in the searched papers was only 6.4%. Thinning of A-horizon is the directly reflection of soil degradation in sloped cropland in black soil region and A-horizon thickness can be used to characterize the degree of soil erosion. Therefore, the degree of soil erosion in the erosion index was replaced by A-horizon thickness. Soil available nutrients were used to characterize soil nutrient supply. However, it is easily affected by fertilizer application and other environmental factors (Wang, 2015). Besides, soil available nutrients usually have positive correlation with organic matter content. Therefore, it was not included in TIS. Microbial biomass C/N has a significant positive correlation with organic matter in black soil (Wang et al., 2015). Based on the principles of dominance and independence, soil organic matter was used to replace soil microbial biomass C/N in biological indicators. In addition, literature review and field surveys have found that ridge cultivation significantly affects sloped cropland degradation (Zhao et al., 2014; Guan et al., 2019). In the current study, by taking into account the regional characteristics and referencing evaluation indicator systems for sloped cropland degradation in other region, the ridge-slope angle, slope gradient, and gully density were included in the TIS. In summary, we selected TIS comprising 11 indicators to evaluate soil degradation in sloped cropland in black soil region.

Cluster analysis was used to simplify TIS and construct the MIS for evaluating the degree of sloped cultivated land degradation in black soil region. The slope gradient of cropland in black soil region mostly ranged from 1° to 5° but slope length ranged from several hundred meters to kilometers. This provided a good underlying surface for decreasing the impact of rainfall and runoff, and soil erosion was severe (Wang and Li, 2018). Ridges affect runoff, thereby affecting the formation of erosion gullies. Based on the principle of dominance, slope gradient and ridge-slope angle were selected for Category 1 in the cluster analysis. Soil pH in Category 2 is an important characteristic of sloped cropland degradation in black soil region in the study site. A decrease in A-horizon thickness is a major form of soil degradation in sloped cropland in black soil region (Shan et al., 2009). In addition to the soil fertility effects on crop yield, fertilizer application also greatly affects crop yield. Based on the stability and dominance principles, A-horizon thickness were selected for Category 3. Clay in a major inorganic colloid in soil and has important effects on CEC and formation of water-stable aggregates. However, we found a significant correlation between clay content and organic matter content and large water-stable aggregates. There is no relationship between CEC and other indicators in this category. Duo to the independence principles, CEC and organic matter content were selected for Category 4 in MIS. In summary, the MIS for evaluation of the degree of sloped cropland degradation in typical black soil region includes the following six indicators: A-horizon thickness, CEC, organic matter content, pH, slope gradient, and ridge-slope angle.

4.2 Evaluating the degree of sloped cropland degradation in typical black soil region

Undegraded and mildly degraded soil are mainly located in the northwest and southwest plains of the studied site, which is characterized by gentle slope (<1.5°), few erosion gullies, cross ridge or small-angle sloping ridge cultivation, and a thick A-horizon. Moderately degraded soil and above have steep slope, multiple erosion gullies, large-angle sloping ridge or longitudinal ridge cultivation, and a thin A-horizon. These soils are mainly located within the northern rolling hilly region and hills in the southeast region of Baiquan County. We analyzed the relationship between the degree of soil degradation and various indicators. Sloped cropland in the studied black soil region was not only indicated by worsening soil physicochemical characteristics but also a decrease in sloped cropland area due to gully erosion. The significant correlation between slope gradient and other soil characters might indicate that slope is one of the main factors causing cropland degradation. The steeper sloped cropland, with a lower soil organic matter, CEC, large water-stable aggregates and clay content, has a higher degree of soil degradation. In addition, the positive correlation between slope gradient and ridge-slope angle shows that downslope tillage is mainly employed on soil with a gentle slope, while sloping, and contour tillage are mainly employed on soil with a steep slope. The cooperative relationship between slope gradient and ridge-slope angle might be the reason leading to a non-significant correlation between ridge-slope angle and gully density. A-horizon thickness is the main factor affecting crop yield. There is no relationship between crop yield and SDI. The long-term unsuitable land management causes deterioration of soil quality and subsequently influences crop productivity. In order to achieve a high crop yield, huge amount of chemical fertilizers and pesticides have to be applied. Therefore, the crop yield difference between cropland with varying degrees of degradation was small.

5. CONCLUSION

The TIS for evaluation of the degree of soil degradation in sloped cropland in black soil region included the following 11 indicators: gully density, slope gradient, ridge-slope angle, bulk density, large water-stable aggregate content, organic matter, pH, CEC, A-horizon thickness, clay content, and crop yield. The MIS included the following six indicators: A-horizon thickness, clay content, organic matter content, pH, slope gradient, ridge-slope angle. The MIS constructed based on cluster analysis has high accuracy for evaluating the sloped cultivated land degradation in black soil region. In this study, high-frequency indicators which were used by previous studies for evaluating cropland degradation in black soil region were employed, relevant indicators for evaluating sloped cropland degradation in other region were referenced, and indicators reflecting the characteristics of black soil region were added based on field surveys. This study provides a useful summary and an improvement from previous studies.

The study sites, Baiquan and Keshan Counties, are located in a rolling hilly region, with complex terrain. Slope gradient has a significant effect on sloped cropland degradation. Ridged-cultivation causes considerable complexity in soil erosion in sloped cropland. Soil degradation in the studied sites mainly presented as worsening of soil physicochemical characteristics such as severe loss of the A-horizon, soil compaction, severe structural destruction, and a decline in soil fertility. Downslope and small-angle ridge cultivation are benefit for soil organic matter maintenance and the soil structure and nutrient retention capacity is better than soil with contour or large-angle ridge cultivation.

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Table 1. Subject terms used for construction of a soil degradation degree indicator system using bibliometrics and the results

Subject term	**Results**	**Number of Studies Selected**	**Number of Studies in typical black soil region**
Soil degradation—evaluation indicators	346	14	**4**
Cropland quality evaluation—indicators	386	144	**17**
Cropland quality evaluation—black soil	14	6	**6**
Cropland fertility evaluation—indicators	303	187	**19**
Cropland fertility evaluation—black soil	25	2	**2**
Soil quality assessment—black soil	29	12	**12**
Soil erosion	253	16	**3**
Cropland degradation	109	16	**5**
soil quality assessment—cropland	84987	36	**10**
soil degradation evaluation	14972	18	—
total	—	**451**	**78**

Table 2. Weight of indicators in the total index set (TIS) and minimum index set (MIS)

TIS	Soil organic matter	A-horizon thickness	Clay content	pH	Slope gradient	Ridge-slope angle	Bulk density	Large water-stable aggregates	CEC	Crop yield	Gully density
Weight	0.08	0.08	0.09	0.07	0.11	0.09	0.10	0.08	0.09	0.12	0.09

MIS	Soil organic matter	A-horizon thickness	pH	CEC	Slope gradient	Ridge-slope angle
Weight	0.17	0.15	0.16	0.13	0.24	0.15

Table 3. Correlation analysis between soil degradation index (SDI) and soil characteristics

	Soil organic matter	A-horizon thickness	pH	CEC	Slope gradient	Ridge-slope angle	Bulk density	Large water-stable aggregates	Clay content	Crop yield	Gully density
SDI	-0.721**	-0.497**	-0.093	-0.526**	0.777**	0.622**	0.652**	-0.376**	-0.526**	0.021	0.653**

**: extremely significance;

Table 4. Distribution range and mean value of soil characteristics for sloped cropland with varying degrees of degradation

	Undegraded soil		Mild degradation		Moderate degradation		Severe degradation		Extremely severe degradation	
	Distribution range	Mean	Distribution range	Mean	Distribution range	Mean	Distribution range	Mean	Distribution range	Mean
Organic matter/（g/kg）	62.2~65.6	64.0	37.3~64.3	52.2	20.2~56.0	45.4	14.0~41.1	29.2	21.8	21.8
A-horizon thickness/cm	80~110	100	15~80	60	20~50	32.5	5~60	22.5	5	5
pH	4.9~5.5	5.3	4.9~6.1	5.5	4.9~5.7	5.3	3.7~5.9	5.3	5.2	5.2
CEC	37.3~52.0	43.1	31.3~43.6	37.2	24.4~38.2	33.6	15.4~42.3	30.0	26.9	26.9
Slope gradient/°	0.7	0.7	0.9~1.8	1.4	1.4~5.6	2.9	3.0~5.6	4.6	4.0	4.0
Ridge-slope angle /°	0	0	0~74.3	24.5	14.5~82.6	53.6	21.9~82.6	54.6	21.9	21.9

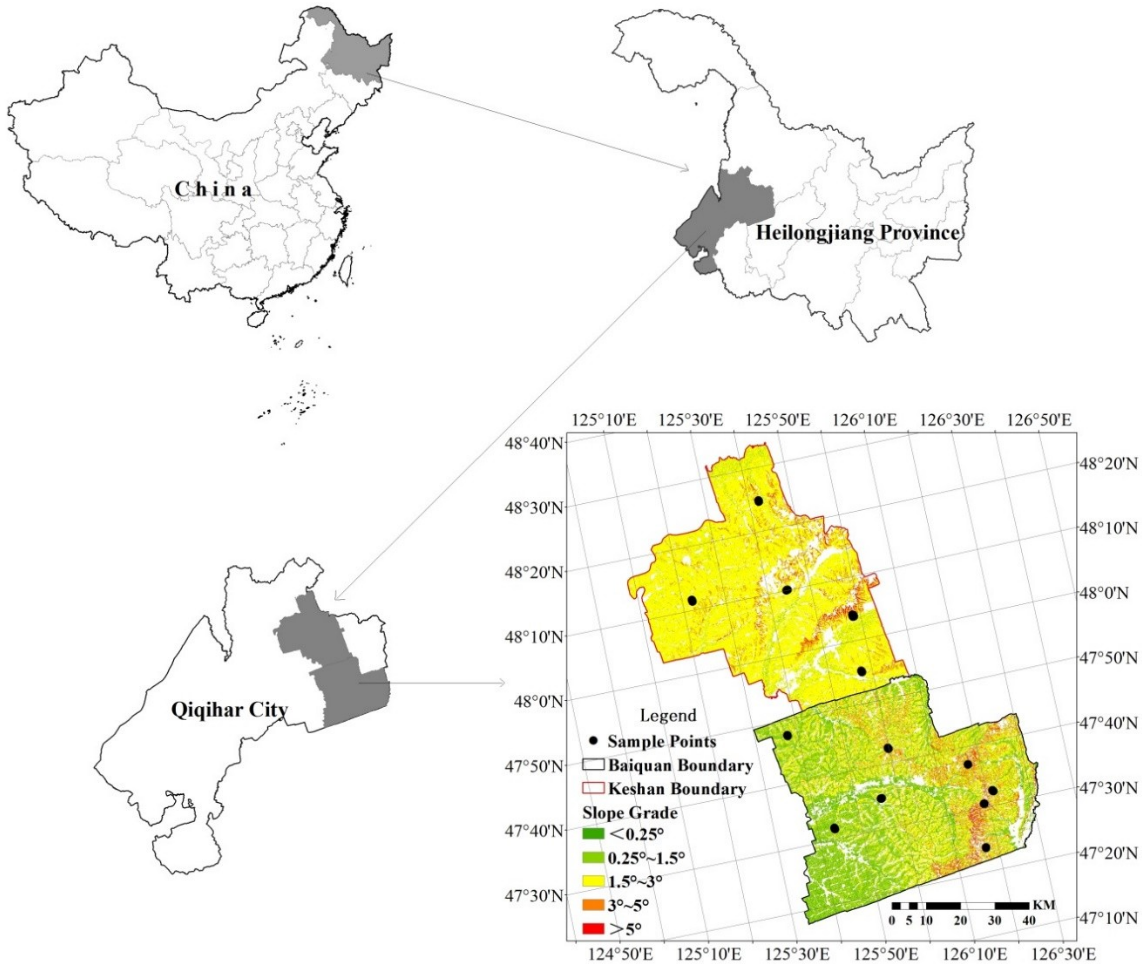


Fig. 1 Geographical location of the study sites and distribution of sampling points

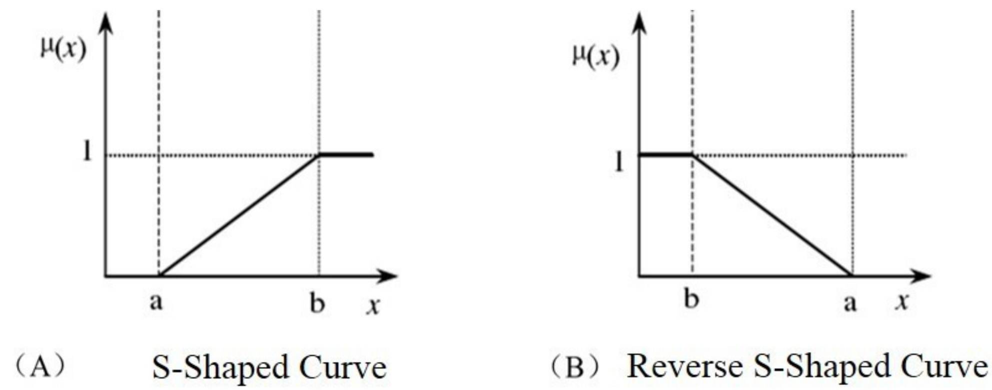
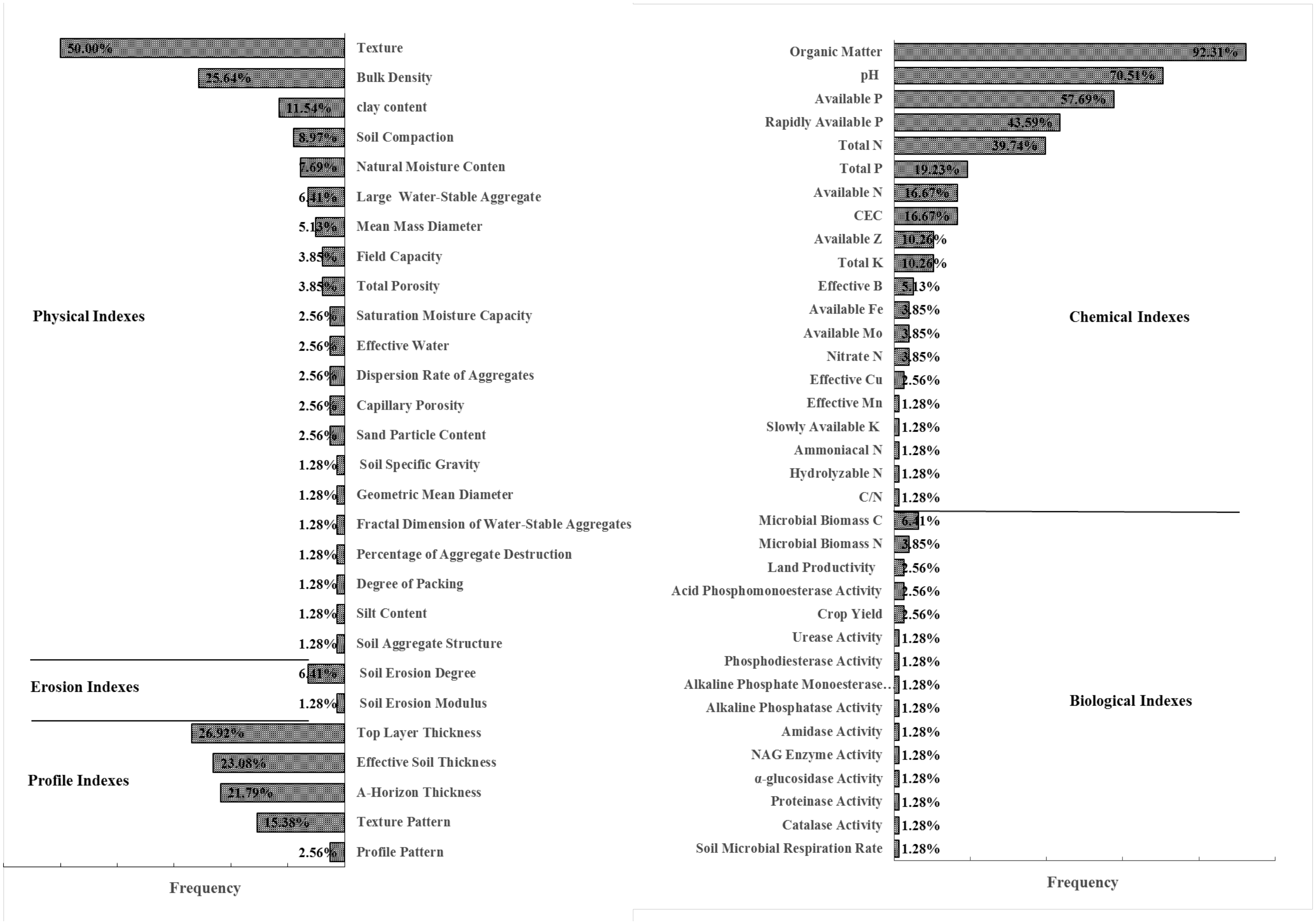


Fig. 2 Schematic diagram of membership function between soil degradation index (vertical axis) and soil characteristics (horizontal axis). a, the lower limit of threshold; b, the upper limit of threshold.



50.00% Texture
25.64% Bulk Density
11.54% clay content
8.97% Soil Compaction
7.69% Natural Moisture Conten
6.41% Large Water-Stable Aggregate
5.13% Mean Mass Diameter
3.85% Field Capacity
3.85% Total Porosity
Physical Indexes
2.56% Saturation Moisture Capacity
2.56% Effective Water
2.56% Dispersion Rate of Aggregates
2.56% Capillary Porosity
2.56% Sand Particle Content
1.28% Soil Specific Gravity
1.28% Geometric Mean Diameter
1.28% Fractal Dimension of Water-Stable Aggregates
1.28% Percentage of Aggregate Destruction
1.28% Degree of Packing
1.28% Silt Content
1.28% Soil Aggregate Structure
Erosion Indexes
6.41% Soil Erosion Degree
1.28% Soil Erosion Modulus
Profile Indexes
26.92% Top Layer Thickness
23.08% Effective Soil Thickness
21.79% A-Horizon Thickness
15.38% Texture Pattern
2.56% Profile Pattern
Frequency
Organic Matter 92.31%
pH 70.51%
Available P 57.69%
Rapidly Available P 43.59%
Total N 39.74%
Total P 19.23%
Available N 16.67%
CEC 16.67%
Available Z 10.26%
Total K 10.26%
Effective B 5.13%
Available Fe 3.85%
Available Mo 3.85%
Nitrate N 3.85%
Effective Cu 2.56%
Effective Mn 1.28%
Slowly Available K 1.28%
Ammoniacal N 1.28%
Hydrolyzable N 1.28%
C/N 1.28%
Chemical Indexes
Microbial Biomass C 6.41%
Microbial Biomass N 3.85%
Land Productivity 2.56%
Acid Phosphomonoesterase Activity 2.56%
Crop Yield 2.56%
Urease Activity 1.28%
Phosphodiesterase Activity 1.28%
Alkaline Phosphate Monoesterase.. 1.28%
Alkaline Phosphatase Activity 1.28%
Amidase Activity 1.28%
NAG Enzyme Activity 1.28%
α-glucosidase Activity 1.28%
Proteinase Activity 1.28%
Catalase Activity 1.28%
Soil Microbial Respiration Rate 1.28%
Biological Indexes
Frequency

Fig. 3 Frequency distribution of indicators to evaluate the degree of soil degradation based on the frequency analysis method

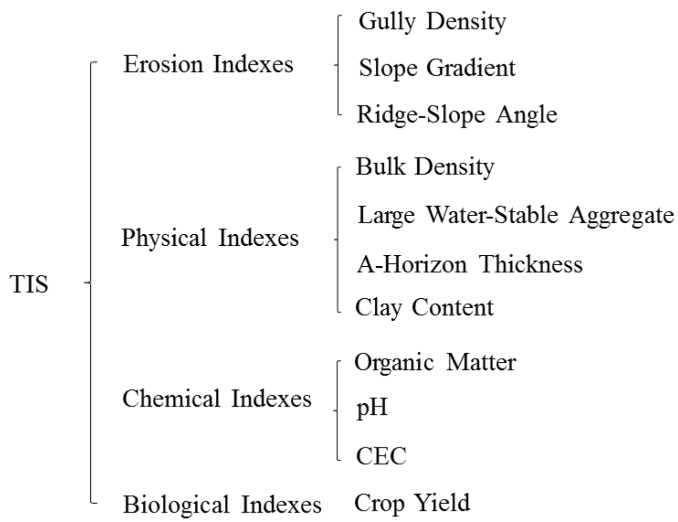


Fig. 4 Total index set (TIS) for degree of sloped cropland degradation in typical black soil regions

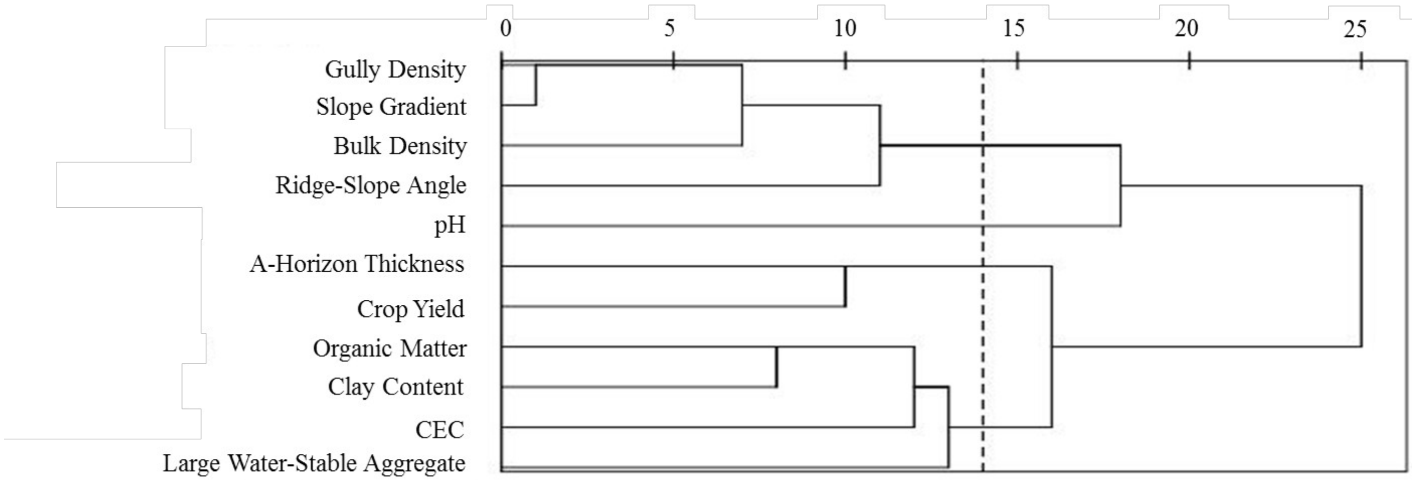


Fig. 5 Cluster analysis for evaluation indicators of the degree of sloped cropland degradation in typical black soil region.

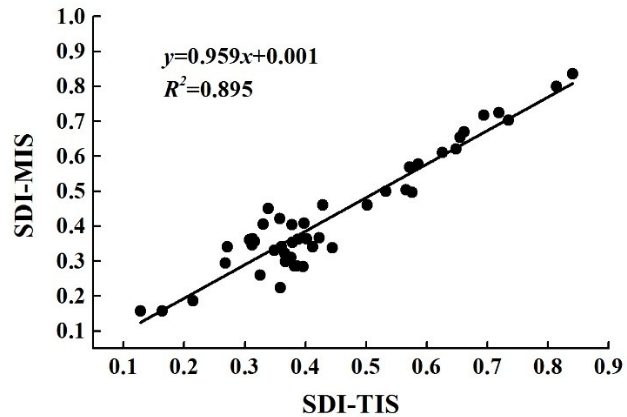


Fig. 6 Regression analysis of soil degeneration index (SDI) based on total index set (SDI-TIS) and minimum index set (SDI-MIS)